

Pre-final STRUBIAS Report

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DRAFT STRUBIAS recovery rules and market study for precipitated phosphate salts & derivates, thermal oxidation materials & derivates and pyrolysis & gasification materials in view of their possible inclusion as Component Material Categories in the Revised Fertiliser Regulation

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SYNOPSIS

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243 1 Executive summary

244 The European Commission envisages a revision of the **Fertiliser Regulation** expanding its
245 scope to secondary raw material based fertilising products. This report explores the technical
246 and market conditions for a possible legal framework for the manufacturing and placing on
247 the market of specific safe and effective fertilising products derived from biogenic wastes and
248 other secondary raw materials. The acronym **STRUBIAS** (**STRU**vite, **B**iochar, or
249 incineration **A**Shes) was initially chosen as the working title for this project to reflect the
250 targeted fertilising materials. Throughout the course of the STRUBIAS project, the scope of
251 these materials has however been further refined and significantly expanded. The work
252 delivered within this project should contribute to making the recovery of nutrients, organic
253 matter and liming materials from secondary raw materials a more attractive practice across
254 Europe. "Closing the loop – An EU action plan for the **circular economy**", as adopted by the
255 European Commission¹, has identified the Fertilisers Regulation revision as a key legislative
256 proposal to boost the market for secondary raw materials, and the revised Waste Framework
257 Directive² establishes ambitious targets for recycling. Several STRUBIAS materials show a
258 substantial potential to provide safe sources of **phosphorus** (P) that can constitute an
259 alternative for the primary raw material phosphate rock. Both phosphorus and phosphate rock
260 have been identified by the European Commission as critical raw materials, based on its
261 supply risk and the economic importance for EU operators in particular.

262
263 The **proposal for the revised Fertiliser Regulation** includes provisions for CE marked
264 fertilising products that contain requirements at two levels in accordance with their *intended*
265 *function* ("Product Function Category", PFC), and for the *component materials* contained in
266 the CE fertilising product ("Component Material Categories", CMC). Specific requirements
267 for each of the CMCs apply because different component materials warrant different process
268 requirements and control mechanisms adapted to their different potential hazardousness and
269 variability, in turn dependent on the quality of the input materials applied, production process
270 conditions, etc. Component materials for CE marked fertilising products should, therefore, be
271 divided into different categories. Several STRUBIAS materials have the potential to become
272 **component materials** in the revised Fertiliser Regulation. STRUBIAS materials might be
273 used to produce fertilising materials with different intended functions, including inorganic
274 and organic fertilisers, liming materials, growing media, soil improvers, plant biostimulants,
275 and fertilising product blends.

276
277 The **objectives** of this report are twofold. Firstly, it collects and assesses information to make
278 **technical proposals** on eligible input materials and process conditions for STRUBIAS
279 production pathways, quality requirements for STRUBIAS materials, and quality
280 management systems, which might form the basis for the legal requirements that those
281 candidate materials shall comply with if they become regulated under the revised Fertiliser
282 Regulation. Secondly, the report studies the possible impacts in order to shed a light on the

¹ More information on: http://ec.europa.eu/environment/circular-economy/index_en.htm

² Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste

283 **possible added value** that the STRUBIAS materials could provide for food security, food
284 safety, environmental protection, and the European fertilising and agricultural sector.

285

286 The information laid down in this document has been collated and assessed by the **European**
287 **Commission's Joint Research Centre in Seville** (JRC - Seville) who led the work on the
288 STRUBIAS project, guided by the principles of technical expertise, transparency and
289 neutrality. The JRC has been supported in the process by a **technical working group**
290 ("STRUBIAS sub-group") that constitutes a sub-group of the Commission expert group on
291 Fertilisers, which includes representatives from EU Member States, EU
292 trade/business/professional associations, as well as from other institutions such as think tanks,
293 research and academic institutions. The role of the subgroup is to participate in the process of
294 sharing knowledge and providing non-binding expert advice to the European Commission on
295 manufacturing and use aspects for STRUBIAS materials. The STRUBIAS sub-group has
296 been requested to provide techno-scientific data that contributed to the information collected
297 in this report, and has been consulted through meetings and written consultation rounds on
298 previous versions of this report. The work of the STRUBIAS sub-group and all other
299 contributors is gratefully acknowledged.

300

301 The **technical proposals** for the STRUBIAS materials ("STRUBIAS recovery rules") are
302 based on the **principles** that - to the best possible extent - they: (i) shall provide an avenue for
303 the agricultural valorisation of recovered materials in high-quality fertilisers that do not pose
304 overall adverse environmental impacts or human health risks, (ii) create a level playing field
305 for CE marked fertilising products derived from primary and secondary raw materials that
306 offers simplicity and clarity to producers and consumers that are active on the European
307 fertilising market, (iii) shall be set in a sufficiently flexible manner to encourage industry to
308 undertake nutrient recycling actions, (iv) apply a neutral stance towards all existing and
309 future technological systems operating on the market and input materials available, (v) shall
310 be clear, concise and enforceable to support a stable legal framework.

311

312 Throughout the project, the **candidate material scope and names** have been refined. The
313 scope of the STRUBIAS material originally referred to as "struvite" has been widened to
314 include the broad spectrum of phosphate salts that could be produced through a precipitation
315 process, and can be used according to their intended function as P fertilisers. The scope of
316 "ash-based materials" and "biochar" has been refined to cover the entire spectrum of
317 thermochemical material transformation processes, and separates materials based on their
318 degree of pollutant destruction. The oxygen supply during the thermochemical process
319 distinguishes "thermal oxidation materials" from those that have undergone "gasification"
320 (partial oxidation) and "pyrolysis" (thermal degradation of organic material in the absence of
321 oxygen). Precipitated phosphate salts and thermal oxidation materials can also be used as
322 precursors or intermediates to produce fertilising materials of a different chemical
323 composition ("derivates"; e.g. superphosphates, di-ammonium phosphates, potassium
324 chlorides). Accordingly, the names of the STRUBIAS materials have been changed to
325 "precipitated phosphate salts & derivates", "thermal oxidation materials & derivates", and

326 "pyrolysis & gasification materials". The STRUBIAS acronym has, however, been
327 maintained for simplicity and recognisability.

328

329 The work of developing the technical proposals for STRUBIAS materials that could be used
330 as components in CE fertilising products has been guided by the following **fundamental**
331 **criteria**:

332 I. *The use of the STRUBIAS materials will not lead to overall adverse*
333 *environmental or human health impacts;*

334 II. *The STRUBIAS material shall provide plants with nutrients or improve their*
335 *nutrition efficiency, either on its own or mixed with another material;*

336 III. *Trade on the internal market can be expected for STRUBIAS materials, based*
337 *on the current market and the future market and trade forecasts.*

338

339 Regarding the first criterion, the assessment of the available evidence shows that the potential
340 negative health impacts associated to the manufacturing and use of STRUBIAS materials
341 identified relate to risks of both **recycling contaminants** contained in the eligible
342 STRUBIAS input materials and the **de novo production of specific contaminants**. The
343 technical proposals pay special attention to these risks and the approach followed is to
344 propose a set of different types of requirements to be included in the recovery rules. The
345 eligible input materials have been delimited for all three STRUBIAS material groups,
346 excluding for instance mixed municipal waste as feedstock for STRUBIAS production
347 processes. Moreover, specific requirements are proposed on, for instance, conditions for
348 thermal oxidation to effectively destroy organic contaminants. In some cases, the
349 demonstrated relationship between specific contaminants of concern with easily measurable
350 product quality properties is used to indirectly limit contaminants (e.g. volatile organic
351 compounds for pyrolysis and gasification materials that are tightly related to the H:C ratio of
352 the materials). These requirements impose effective control mechanisms for the wide-ranging
353 and heterogeneous group of organic contaminants. Many of these compounds are identified
354 as "contaminants of emerging concern" because the risk they pose to human health and the
355 environment is not yet fully understood (e.g. pharmaceutical compounds and personal care
356 products, antibiotic resistance genes, specific biocides). For those emerging contaminants,
357 often no "safe" environmental limit concentrations can be established, and their monitoring
358 would imply high material testing and compliance costs for STRUBIAS manufacturers. Still,
359 particular contaminants of concern were identified that could be present in the STRUBIAS
360 materials. This refers specifically to biological pathogens, specific persistent organic
361 pollutants (e.g. polycyclic aromatic hydrocarbons, dioxins and dioxin-like compounds),
362 macroscopic impurities, macroelements (e.g. chlorine) and metals. Therefore, direct product
363 quality requirements are proposed to restrict those compounds in the STRUBIAS materials as
364 part of cost-effective compliance testing schemes. Implementing and applying a **quality**
365 **management system** based on quality of the design and production phase is required to
366 ensure full compliance with the complex and extensive legislative requirements that apply to
367 the handling, transport, and operating conditions of the STRUBIAS production processes. A

368 conformity assessment procedure has been proposed that requests manufacturers of
369 STRUBIAS materials to operate an approved quality management system - assessed by a
370 notified body - in order to ensure conformity to legislative requirements, including the
371 inspection of the STRUBIAS material quality ("module D1"). Altogether, the technical
372 requirements for the different Component Material Categories should ensure that the use of
373 the STRUBIAS materials does not lead to overall adverse environmental or human health
374 impacts, thus safeguarding food and animal safety.

375

376 Regarding the second criterion, the availability of nutrients contained in STRUBIAS
377 materials and effects on plant nutrition efficiency were assessed by carrying out and
378 interpreting meta-analyses results based on studies relevant for European settings. Meta-
379 analysis techniques enable establishing whether the findings on **agronomic efficiency** are
380 consistent and generalisable across European settings and facilitate understanding the reasons
381 why some studies differ in their results. For these reasons, a meta-analysis of similar, well-
382 conducted, randomised, controlled trials has been considered one of the highest levels of
383 evidence. The JRC assessment results indicated that many STRUBIAS materials that meet
384 the proposed STRUBIAS recovery rules provide plants with nutrients, especially P, with a
385 similar agronomic efficiency to mined phosphate rock and processed P-fertilisers. These
386 results are especially consistent for precipitated phosphate salts & derivatives in different soil
387 and plant types, and are thus not restricted to specific agricultural settings within a European
388 context. Similar results are found for thermal oxidation materials & derivatives, although
389 feedstock applied and the length of the growing season impact upon the aggregated results for
390 specific thermal oxidation materials. The results confirmed that post-combustion
391 manufacturing steps applied on incineration ashes improve agronomic efficiencies to values
392 similar to those of mined phosphate rock and processed P-fertilisers. For P-rich pyrolysis &
393 gasification materials, it was indicated that plant responses can vary widely depending on the
394 feedstock and production conditions. Some pyrolysis & gasification materials show similar
395 efficiencies to mined phosphate rock and processed P-fertilisers, whereas others are not as
396 effective relative to the latter in every agronomic environment. Nonetheless, responsible use
397 practices for such fertilisers can also contribute to reducing the reliance on primary raw
398 materials under specific situations and agronomic settings, as part of targeted agricultural
399 practices to increase nutrient use efficiency in the EU. STRUBIAS materials of a low nutrient
400 content may serve other fertilising functions (e.g. soil improver, liming material, growing
401 media, plant biostimulant), thus contributing to improving plant nutrient uptake efficiency in
402 the short or long-term under specific situations. For carbon-rich pyrolysis & gasification
403 materials derived from vegetable residues, the added value for the European agricultural
404 sector varies widely across settings as a function of soil type, climate and targeted application
405 (e.g. growing media versus open field spreading). It is concluded that all three STRUBIAS
406 material groups provide plants with nutrients or improve their nutrition efficiency, although
407 the latter may only hold true under specific European settings for some pyrolysis &
408 gasification materials. STRUBIAS materials are not only an added value material for the
409 conventional European agriculture, but also for the expanding organic farming sector in
410 Europe.

411

412 Regarding the third criterion, **market demand and trade** is expected for all three
413 STRUBIAS material groups in different segments of the EU agricultural sector.
414 Quantitatively assessing the expected trade of STRUBIAS materials on the internal market is
415 challenging, partly because many STRUBIAS materials are often a co-product of a process
416 that has a different primary aim (e.g. waste management and control, biogas production,
417 manure hygienisation, etc.). It is expected that the overall share of the STRUBIAS materials
418 will be used as fertilisers that can be used to provide nutrients, mostly P, to the conventional
419 European agricultural sector. As a best estimate for the year 2030, the opening of the P-
420 fertiliser market to STRUBIAS materials will result in a substitution effect of mined rock
421 phosphate and processed P-fertilisers by fertilising products containing precipitated
422 phosphate salts & derivatives, and thermal oxidation materials & derivatives of 17 to 31%.
423 STRUBIAS materials expected to be on the market in 2030 will be mostly derived from
424 municipal waste waters and sludges and manure, with the former being a more important
425 feedstock than the latter. Most P-recovery in the form of STRUBIAS materials is likely to
426 take place in Western Europe due to increasing concerns associated to the landspreading of
427 unprocessed biogenic materials and the region-situation specificity of high animal and human
428 population densities. As a consequence, some biogenic materials, such as sewage sludge, are
429 increasingly being incinerated and the resulting ashes are transferred to landfills and
430 construction materials. Moreover, possible unbalanced nutrient stoichiometry and spatial
431 constraints to landspreading of manure often hamper sustainable circular nutrient
432 management through enhancing P accumulation in soils and eutrophication under these
433 regional conditions. A certain market demand is also expected for STRUBIAS materials to be
434 used as liming materials, soil improvers or growing media in specific agricultural sectors. For
435 specific fertiliser materials, including pyrolysis & gasification materials, the organic farming
436 sector could be a potential trade market. The development of STRUBIAS production
437 pathways is partly dependent on production costs. Based on the momentary evaluation,
438 STRUBIAS production costs are for most – but not for all - pathways more expensive
439 compared to mined rock phosphate and processed P-fertilisers. The supplementary life cycle
440 cost of P-recycling through STRUBIAS pathways is lowest in regions characterised by
441 nutrient surpluses. Nonetheless, also feedstock availability and decisions that impact upon the
442 use routes for eligible input materials for STRUBIAS materials will determine the market for
443 STRUBIAS materials. With the intention to promote a more circular and resource-efficient
444 economy, policy targets, financial incentives or financial disincentives for the handling of
445 biogenic materials will impact upon the STRUBIAS market outlook. Specifically, the EU and
446 national legislative framework and policies for waste management, ground and surface water
447 quality, and renewable energy targets are expected to greatly influence the STRUBIAS
448 market and trade potential.

449
450 In order to better understand the trade-offs between **resource management and health and**
451 **environmental protection** life cycle analyses were performed. Scenario modelling was
452 applied for nine selected STRUBIAS materials of high technological readiness level that
453 show significant market potential. The life cycle stages include transport, feedstock material
454 transformation and STRUBIAS manufacturing stages, transport to use on land, storage at the
455 farm, land application, and use on land. The analyses identified sector opportunities and

456 mechanisms that maximise the socio-environmental benefits of emerging P-recovery
457 pathways. Because the P contained in biogenic materials is to a large extent dissipated in
458 nutrient surplus regions, the greatest opportunities for P recycling through STRUBIAS
459 pathways occur in those EU areas. The implementation of specific STRUBIAS pathways to
460 reduce the dependence on phosphate rock can provide coinciding benefits for human health
461 and environmental protection relative to mined rock phosphate and processed P-fertilisers.
462 For other STRUBIAS pathways, the analysis confirmed that trade-offs between impacts on
463 phosphate rock depletion, global warming, eutrophication and human health occur. Also
464 those pathways for producing STRUBIAS materials provide thus opportunities for addressing
465 critical environmental and/or human health issues, although at the expense of adverse impacts
466 on other matters. This implies that the implementation of STRUBIAS pathways is likely to
467 depend on the needs and priorities of local stakeholders, and thus the nexus of costs and
468 impacts upon human health, agronomic yields, water quality, energy balances, resource
469 depletion, climate regulation and long-term food security. The main mechanisms that
470 contribute positively to the environmental and human health savings relate to increasing the
471 bio-availability of the nutrients contained in the biogenic input materials and reducing the
472 metals contained therein. There are also risks of adverse and unintended negative effects,
473 however, in processes involving the removal of other valuable materials in the biogenic input
474 materials (e.g. nitrogen, organic carbon), reduced levels for contaminant removal from the
475 biogeochemical cycle relative to counterfactual feedstock handling scenarios, and effects
476 related to additional manufacturing steps that are associated to high chemical or energetic
477 demands. Relative to the counterfactual scenarios of the direct landspreading of unprocessed
478 and digested biogenic materials, STRUBIAS production pathways mitigate nitrogen
479 eutrophication at all times and may show reduced impacts on human health by effectively
480 removing biological pathogens, pharmaceutical and personal care compounds, and other
481 persistent and emerging organic pollutants, and possibly metal removal.

482
483 The possible opening of the EU fertilising market to STRUBIAS materials might be
484 associated to **economic benefits and challenges**. Harmonisation of the legislation concerning
485 all fertilising materials at EU level will increase the transparency on product quality within
486 the EU fertilising market and thus decrease cross-border transaction costs for STRUBIAS
487 materials. The possibility of producing STRUBIAS materials under the EU legislative
488 framework might prevent additional costs for producers of eligible input materials for
489 STRUBIAS pathways, thus reducing costs for disposal and waste compliance, especially for
490 sewage sludge and manure. The addition of STRUBIAS materials as possible component
491 material for CE marked fertiliser products might also stimulate industry innovation to
492 possibly develop new fertilising products, including those with a tailored chemical and
493 physical composition. A major challenge lies in the fact that actors belonging to different
494 sectors form part of the transformation cascade of biogenic materials into STRUBIAS
495 materials (e.g. agriculture, waste water treatment sector, waste management sector, food
496 processing industry, etc.) and will have to establish agreements in order to synchronise
497 material streams, considering both quantitative and qualitative aspects.

498

499 Overall it is concluded that the implementation of the manufacturing and use of STRUBIAS
500 materials in the EU agricultural sector is closely linked to progression towards a more
501 circular economy, and a reduced dependence on phosphate rock as a finite primary raw
502 material that is essential to sustain food production. STRUBIAS materials that meet the
503 proposed technical requirements offer an avenue to enhanced food security and sustainable
504 fertilisation, while respecting the environment and its natural resources in the EU and
505 elsewhere. **A stable legal framework for all three STRUBIAS material groups is
506 therefore desirable to promote trade and use of these materials in the EU agricultural
507 sector, and to provide a material quality benchmark for producers and consumers of P-
508 fertilising products containing STRUBIAS materials.**
509

DRAFT - WORK IN PROGRESS

510 **2 Draft proposals for STRUBIAS recovery rules**

511 **2.1 CMC XX: Precipitated phosphate salts & derivates**

512 A CE marked fertilising product may contain precipitated phosphate salts exclusively
513 obtained through precipitation of one or more of the following input materials:

- 514 a) wastewaters and sludges from municipal wastewater treatment plants;
515 b) manure, non-mineralised guano, and digestive tract content pursuant to Regulation
516 (EC) No 1069/2009;
517 c) animal by-products and derived materials from Category 2 or Category 3 material of
518 Regulation (EC) No 1069/2009, other than manure, non-mineralised guano, and
519 digestive tract content, provided that:
- 520 o they have been hygienised in accordance with the conditions for pressure
521 sterilisation or with other conditions to prevent risks arising to public and
522 animal health, in accordance with the requirements laid down pursuant to
523 Article 15 of Regulation (EC) No 1069/2009, or
 - 524 o they are digestion residues from transformation into biogas as set out in Annex
525 V of (EU) No 142/2011;
- 526 d) wastewaters from food processing industries, unless the food processing steps involved
527 contact with any of the following:
- 528 o detergents other than those permitted pursuant Regulation (EC) No 648/2004,
 - 529 o oxidising and non-oxidising biocides, or
 - 530 o animal by-products of category 1 or derived products falling within the scope
531 of Regulation (EC) No 1069/2009;
- 532 e) bio-waste within the meaning of Directive (EU) 2018/851 amending Directive
533 2008/98/EC resulting from separate bio-waste collection at source, other than those
534 materials included in point c);
- 535 f) living or dead organisms or parts thereof, which are unprocessed or processed only by
536 manual, mechanical or gravitational means, by dissolution in water, by flotation, by
537 extraction with water, by steam distillation or by heating solely to remove water, or
538 which are extracted from air by any means, except
- 539 o materials originating from mixed municipal waste,
 - 540 o sewage sludge, industrial sludge or dredging sludge,
 - 541 o animal by-products or derived products falling within the scope
542 Regulation (EC) No 1069/2009, and
 - 543 o materials separately mentioned in points a) - e); or
- 544 g) chemical substances and fluidised bed substrates, other than:
- 545 o those listed under a) - f),
 - 546 o waste within the meaning of Directive 2008/98/EC,
 - 547 o non-biodegradable polymers, and
 - 548 o animal by-products or derived products falling within the scope of Regulation
549 (EC) No 1069/2009.

550 In addition, a CE marked fertilising product may contain precipitated phosphate salts
551 obtained through precipitation of any material listed in points (a)-(g), or combination thereof,
552 processed by manual, mechanical or gravitational means, by solid-liquid fractionation using
553 biodegradable polymers, by dissolution in water, by flotation, by extraction with water, by
554 steam distillation or by heating solely to remove water, by thermal hydrolysis, by anaerobic
555 digestion or by composting as long as the temperature of such processes is not raised above
556 275°C.

557

558 [Note: The exclusion of a material from a lettered item does not prevent it from being an
559 eligible component material by virtue of another lettered item]

560

561 2. The precipitation process shall take place under controlled conditions in a reactor, which
562 only processes input materials referred to in paragraph 1 above. Physical contacts between
563 input and output materials must be avoided in the treatment plant, including during storage.

564

565 3. Regardless of the input material applied, the precipitated phosphate salt shall contain:

- 566 a) a minimum P₂O₅ content of 16% of the dry matter content³;
- 567 b) a maximum organic carbon content of 3% of the dry matter content⁴;
- 568 c) no more than 5 g/kg dry matter of detectable macroscopic impurities in the form of
569 organic matter, glass, stones, metal and plastics above 2 mm;
- 570 d) no presence of *Salmonella* spp. in a 25 g sample; and
- 571 e) no presence of *Escherichia coli* or *Enterococcaceae* in a concentration of more than
572 1000 CFU/g fresh mass.

573

574 Precipitated phosphate salts derived from materials listed under point a) of paragraph 1
575 shall have:

- 576 f) no more than 6 mg/kg dry matter of PAH₁₆⁵.

577

578 Precipitated phosphate salts derived from materials listed under point a) and b) of
579 paragraph 1 shall have:

- 580 g) no presence of *Clostridium perfringens* in a concentration of more than 100 CFU/g
581 fresh mass; and
- 582 h) no presence of *Ascaris* sp. eggs in a 25 g fresh mass.

583 By way of derogation from point d), e), g) and h), testing shall not be necessary for materials
584 that have undergone following conditions:

- 585 i. Pressure sterilisation through the heating to a core temperature of more than
586 133°C for at least 20 minutes without interruption at a pressure (absolute) of at
587 least 3 bars. The pressure must be produced by the evacuation of all air in the
588 sterilisation chamber and the replacement of the air by steam ('saturated
589 steam'); or
- 590 ii. Processing in a pasteurisation/hygienisation unit that reaches a temperature of
591 70 °C during a time of at least one hour.

592

593 4. A CE marked fertilising product may contain derivates from precipitated phosphate salts
594 compliant with paragraphs 1 to 3 as produced through a chemical manufacturing step that
595 reacts the precipitate with intermediates within the meaning of Regulation (EC) No
596 1907/2006 listed under point g) of paragraph 1.

597

598 5. Precipitated phosphate salts & derivates incorporated into the CE marked fertilising
599 product shall have:

- 600 o a maximum sum of elemental Al and elemental Fe that does not exceed 10% of the
601 dry matter content; and
- 602 o a minimum dry matter content of 90% and be stored under dry conditions.

³ As measured using vacuum drying at 40°C, CEN method under development.

⁴ As measured using vacuum drying at 40°C, CEN method under development.

⁵ Sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene, dibenzo[a,h]anthracene and benzo[ghi]perylene

603 **2.2 CMC YY: Thermal oxidation materials & derivates**

604 1. A CE marked fertilising product may contain thermal oxidation materials exclusively
605 obtained through thermochemical conversion under non-oxygen-limiting conditions from one
606 or more of the following input materials:

- 607 a) living or dead organisms or parts thereof, which are unprocessed or processed only by
608 manual, mechanical or gravitational means, by dissolution in water, by flotation, by
609 extraction with water, by steam distillation or by heating solely to remove water, or which
610 are extracted from air by any means, except:
- 611 ○ materials originating from mixed municipal waste,
 - 612 ○ sewage sludge, industrial sludge or dredging sludge,
 - 613 ○ animal by-products or derived products falling within the scope
614 Regulation (EC) No 1069/2009, and
 - 615 ○ materials separately listed under points c) – g);
- 616 b) animal by-products or derived products of category 2 and 3 falling within the scope of
617 Regulation (EC) No 1069/2009;
- 618 c) bio-waste within the meaning of Directive (EU) 2018/851 amending Directive
619 2008/98/EC resulting from separate bio-waste collection at source;
- 620 d) residues from composting, anaerobic digestion, pyrolysis or gasification as a pre-
621 treatment technique of the input materials listed under point (a) - (c);
- 622 e) waste and by-products within the meaning of Directive 2008/98/EC with the exception of:
- 623 ○ materials which display one or more of the hazardous properties listed in
624 Annex III of Directive 2008/98/EC,
 - 625 ○ materials originating from mixed municipal waste,
 - 626 ○ bio-waste within the meaning of Directive (EU) 2018/851 amending Directive
627 2008/98/EC resulting from separate bio-waste collection at source, and
 - 628 ○ animal by-products of category 1 or derived products falling within the scope
629 of Regulation (EC) No 1069/2009;
- 630 f) auxiliary fuels (natural gas, liquefied petroleum gas, natural gas condensate, process gases
631 and components thereof, crude oil, coal, coke as well as their derived materials), when
632 used in incineration, co-incineration or biomass combustion plants to process input
633 materials listed under points (a) - (e);
- 634 g) substances which occur in nature to be used in production processes of the iron and steel
635 industry, including non-hazardous by-products generated by this industry; or
- 636 h) chemical substances, with the exception of:
- 637 ○ those listed under points a) - g),
 - 638 ○ wastes within the meaning of Directive 2008/98/EC,
 - 639 ○ animal by-products or derived products falling within the scope of
640 Regulation (EC) No 1069/2009, and
 - 641 ○ non-biodegradable polymers.

642 *[Note: The exclusion of a material from a lettered item does not prevent it from being an*
643 *eligible component material by virtue of another lettered item]*
644

645 2. The thermal oxidation shall take place under non-oxygen limiting conditions in such a way
646 that the gas resulting from the thermal oxidation is raised, after the last injection of
647 combustion air, in a controlled and homogeneous fashion and even under the most
648 unfavourable conditions, to a temperature of at least 850°C for at least two seconds or
649 1100°C for at least 0.2 seconds. These conditions shall apply to all input materials, with the
650 exception of those listed under point a) of paragraph 1 and derived materials resulting from
651 their composting, anaerobic digestion, and pyrolysis as a pre-treatment technique.

652 3. The plant operator shall:
653 o only process input materials referred to in paragraph 1 above,
654 o ensure that the input material is oxidised in such a way that the total organic carbon
655 content of the slags and bottom ashes is less than 3%, and
656 o ensure that physical contact between input and output materials is avoided, including
657 during storage phases.

658
659 4. The thermal oxidation materials shall have:
660 o no more than 6 mg/kg dry matter of PAH₁₆⁶, and
661 o no more than 20 ng WHO toxicity equivalents/kg dry matter of PCDD/F⁷.

662
663 5. A CE marked fertilising product may contain derivates from thermal oxidation materials
664 that have been produced from the input materials listed in paragraph 1 and compliant with
665 paragraph 4 and that have been manufactured according to a thermal oxidation process
666 compliant with paragraphs 2 and 3. The post-combustion manufacturing process shall be of
667 following nature:

668 a) chemical manufacturing: processes that chemically react thermal oxidation materials
669 with intermediates within the meaning of Regulation (EC) No 1907/2006 listed under
670 point h) of paragraph 1; or
671 b) thermochemical manufacturing: processes that thermochemically react thermal
672 oxidation materials with intermediates within the meaning of Regulation (EC) No
673 1907/2006 listed in paragraph 1. Thermochemical process conditions shall be
674 compliant with paragraph 2 and 3, and the thermal oxidation material derivate shall
675 meet conditions listed in paragraph 4.

676 Thermal oxidation materials that display one or more of the hazardous properties listed in
677 Annex III of Directive 2008/98/EC shall not be mixed, either with waste, substances or
678 materials with the intention of reducing hazardous substances to levels below the limit values
679 for the hazardous property as defined in that Directive. Using a mass balance approach,
680 manufacturers that use thermal oxidation materials with hazardous properties must
681 demonstrate the removal or transformation of the contaminants to levels below the limit
682 values as defined in Annex III of Directive 2008/98/EC.

683
684 6. Thermal oxidation materials & derivates incorporated into the CE marked fertilising
685 product shall:

686 a) have a pH_{H2O} value in the range of 4.0 to 12.0, if solid;
687 b) no more than 3% Cl⁻ on a dry matter basis, only applicable when Cl⁻ is an
688 unintentional substance constituent coming from the starting material(s);
689 c) contain no more than 400 mg kg⁻¹ dry matter of total Chromium (Cr), if derived from
690 materials listed under point e), f) or g) of paragraph 1;
691 d) contain no more than 10 mg kg⁻¹ dry matter of Thallium (Tl), if derived from
692 materials listed under point f) or g) of paragraph 1; and
693 e) contain no more than 600 mg kg⁻¹ dry matter of Vanadium (V), if derived from
694 materials listed under point f) or g) of paragraph 1.

⁶ Sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene, dibenzo[a,h]anthracene and benzo[ghi]perylene

⁷ van den Berg M., L.S. Birnbaum, M. Denison, M. De Vito, W. Farland, et al. (2006) The 2005 World Health Organization Re-evaluation of Human and Mammalian Toxic Equivalency Factors for Dioxins and Dioxin-like Compounds. Toxicological sciences: an official journal of the Society of Toxicology 93:223-241. doi:10.1093/toxsci/kfl055

695 2.3 CMC ZZ: Pyrolysis & gasification materials

696 1. A CE marked fertilising product may contain materials exclusively obtained through the
697 thermochemical conversion under oxygen-limiting conditions of one or more of the following
698 input materials:

- 699 a) animal by-products or derived products of category 2 and 3 falling within the scope
700 Regulation (EC) No 1069/2009;
- 701 b) living or dead organisms or parts thereof, which are unprocessed or processed only by
702 manual, mechanical or gravitational means, by dissolution in water, by flotation, by
703 extraction with water, by steam distillation or by heating solely to remove water, or
704 which are extracted from air by any means, except:
- 705 ○ materials originating from mixed municipal waste,
 - 706 ○ sewage sludge, industrial sludge or dredging sludge, and
 - 707 ○ animal by-products or derived products falling within the scope
708 Regulation (EC) No 1069/2009;
- 709 c) bio-waste within the meaning of Directive (EU) 2018/851 amending Directive
710 2008/98/EC resulting from separate bio-waste collection at source, other than those
711 included above; or
- 712 d) pyrolysis/gasification additives which are necessary to improve the process
713 performance or the environmental performance of the pyrolysis/gasification process,
714 provided that the additives classify as intermediates within the meaning of Regulation
715 (EC) No 1907/2006 and with the exception of:
- 716 ○ those listed under points a) – c),
 - 717 ○ animal by-products or derived products falling within the scope of
718 Regulation (EC) No 1069/2009,
 - 719 ○ waste within the meaning of Directive 2008/98/EC, and
 - 720 ○ non-biodegradable polymers.

721 The total concentration of all additives must not exceed 25 % of the total input
722 material fresh weight.

723 In addition, CE marked fertilising product may contain pyrolysis & gasification materials
724 obtained through thermochemical conversion under oxygen-limiting conditions of any
725 material listed in points (a)-(d), or combination thereof, processed by manual, mechanical or
726 gravitational means, by solid-liquid fractionation using biodegradable polymers, by
727 dissolution in water, by flotation, by extraction with water, by steam distillation or by heating
728 solely to remove water, by composting, or by anaerobic digestion.

729 *[Note: The exclusion of a material from a lettered item does not prevent it from being an*
730 *eligible component material by virtue of another lettered item]*

731

732 2. The thermochemical conversion process of the input materials shall take place under
733 oxygen-limiting conditions in a plant

- 734 ○ which only processes input materials referred to in paragraph 1 above, and
- 735 ○ where physical contacts between input and output materials must be avoided,
736 including during storage.

737

738 3. Animal by-products and derived materials from Category 2 or Category 3 material of
739 Regulation (EC) No 1069/2009, other than manure, non-mineralised guano, and digestive
740 tract content, should undergo one of the following treatments at a stage prior to or during the
741 pyrolysis & gasification material production process:

- 742 ○ pressure sterilisation or with other conditions to prevent risks arising to public and
743 animal health, in accordance with the requirements laid down pursuant to Article 15
744 of Regulation (EC) No 1069/2009,
745 ○ transformation into biogas or compost as set out set out in Annex V of (EU) No
746 142/2011, or
747 ○ Brookes' gasification process as described in point E, section 2, chapter IV, of Annex
748 IV of Regulation (EU) No 142/2011.
749
- 750 4. The pyrolysis & gasification materials shall have:
- 751 ○ have a pH_{H2O} value in the range of 4.0 to 12.0,
752 ○ a molar ratio of H/organic C of less than 0.7, with testing to be performed in the dry
753 and ash-free fraction for materials that have an organic C content of <50%,
754 ○ no more than 6 mg/kg dry matter of PAH₁₆⁸,
755 ○ no more than 20 ng WHO toxicity equivalents/kg dry matter of PCDD/F⁹,
756 ○ no more than 0.8 mg/kg dry matter of PCB¹⁰, and
757 ○ no more than 3% Cl⁻ on a dry matter basis.
758

⁸ Sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene, dibenzo[a,h]anthracene and benzo[ghi]perylene

⁹ van den Berg M., L.S. Birbaum, M. Denison, M. De Vito, W. Farland, et al. (2006) The 2005 World Health Organization Re-evaluation of Human and Mammalian Toxic Equivalency Factors for Dioxins and Dioxin-like Compounds. Toxicological sciences: an official journal of the Society of Toxicology 93:223-241. doi:10.1093/toxsci/kfl055

¹⁰ Sum of congeners PCB 28, 52, 101, 138, 153, 180

759 **2.4 Labelling requirements at PFC level**

- 760 • All product function categories shall have a declaration when the neutralising value > 15
761 (equivalent CaO) or > 9 (equivalent HO-),
762 • CE marked fertilising product that contain more than 50% pyrolysis & gasification
763 materials shall document the instructions for intended use of the CE pyrolysis &
764 gasification materials.
765

766
767 **2.5 Conformity assessment procedure**

768 Module D1 for all three different STRUBIAS CMCs, with the additional elements of the
769 quality assurance process as indicated in section 5.7.2 "Additional elements of the quality
770 management system and auditing".

771

DRAFT - WORK IN PROGRESS

OBJECTIVES AND METHODOLOGY

DRAFT - WORK IN PROGRESS

773 **3 Objectives and methodology of the JRC STRUBIAS work**

774 **3.1 Objectives**

775 The Joint Research Centre (JRC) of the European Commission is assessing the existing
776 techno-scientific evidence in view of a possible inclusion of certain recovered materials as
777 Component Material Categories (CMC) in the **Revised EC Fertiliser Regulation**¹¹. This
778 assessment should form the basis for any technical proposals on the requirements that those
779 candidate materials shall comply with. The acronym chosen for the project is STRUBIAS,
780 based on the scope initially proposed at the launch of the project, namely STRUvite, BIochar
781 and ASh materials. Whereas this scope has been refined during the course of the project, the
782 STRUBIAS acronym has been maintained for simplicity and recognisability.

783
784 The JRC is supported in the process by a technical working group that constitutes a sub-
785 group of the Commission expert group on Fertilisers (hereafter **STRUBIAS sub-group**),
786 which includes representatives from EU Member States, EU trade/business/professional
787 associations, as well as from other institutions such as think tanks, research and academic
788 institutions. The role of the subgroup is to participate in the process of **sharing knowledge**
789 **and providing non-binding expert advice to the European Commission** on possible
790 recovery rules for nutrients from eligible input materials into STRUBIAS materials. If
791 included in the revised Fertiliser Regulation, STRUBIAS materials may be used as
792 **component materials for the different Product Function Categories (PFCs)** included in
793 the proposal for the Revised Fertiliser Regulation, more specifically fertiliser, liming
794 material, soil improver, growing medium, agronomic additive, plant biostimulant, and
795 fertilising product blend.

796
797 The revision of the Fertilisers Regulation revision aims at establishing a **regulatory**
798 **framework enabling production of fertilising products from recycled bio-wastes and**
799 **other secondary raw materials**, in line with the Bioeconomy strategy¹², which encompasses
800 the production of renewable biological resources and the conversion of these resources and
801 waste streams into value added products. In Regulation (EC) No 2003/2003 of 13 October
802 2003 relating to fertilisers, regulatory barriers to market rollout were noted for those
803 materials.

804
805 In 2013, the European Commission organised a **Consultative Communication** that set out
806 for the first time at EU level the issues around the sustainability of P use (European
807 Commission, 2013a). The intention was to launch a debate on the state of play and the actions
808 that should be considered. The European Institutions and all those interested – organisations
809 or private individuals – were invited to submit their comments on the questions set out in the
810 Consultative Communication, as well as on any other issues that they wish to raise
811 concerning the sustainable use of P. Phosphorus recycling has also been addressed by FP7
812 research projects, the results of which have been analysed during the workshop 'Circular
813 approaches to phosphorus: from research to deployment', held in Berlin on 4 March 2015.

¹¹ More information on: http://europa.eu/rapid/press-release_IP-16-827_en.htm

¹² <http://ec.europa.eu/research/bioeconomy/index.cfm>

814 Answers provided by European Institutions on the questions set out in the Consultative
815 Communication and workshop presentations indicated that promising technical progress is
816 being made in the field of recycling of waste. Amongst others, proposed actions included
817 removing of P from waste water in the form of **struvite**, **incinerating** and post-processing of
818 sewage sludge and fertilising product production from animal by-products in the form of
819 **biochar** through pyrolysis processes. This would boost domestic sourcing of plant nutrients
820 which are essential for a sustainable European agriculture, including P. It would also
821 contribute to a better implementation of the waste hierarchy, by minimising landfilling or
822 energy recovery of bio-wastes, and hence to solving related waste management problems.

823
824 Based on this information, the European Commission decided to evaluate a possible legal
825 framework **for the production of safe and effective fertilisers from recovered, secondary**
826 **raw materials, such as struvite, ashes and biochar**. These could possibly be considered as
827 CMCs in the revised Fertiliser Regulation. The acronym STRUBIAS (STRUvite, BIochar, or
828 incineration Ashes)¹³ was initially chosen as the working title for this project. Throughout the
829 course of the STRUBIAS project, the scope of these CMCs has, however, been further
830 refined (see section 5.1).

831
832 STRUBIAS materials are mainly manufactured from specific secondary raw materials,
833 including waste and by-products within the meaning of Directive 2008/98/EC, animal by-
834 products within the meaning of Regulation (EC) No 1069/2009, and biological materials. The
835 work delivered within this project should contribute to making the recovery of nutrients and
836 organic matter from secondary raw materials a more attractive business across Europe.
837 "Closing the loop – An EU action plan for the **circular economy**", as adopted by the
838 European Commission¹⁴, has identified the Fertilisers Regulation revision as a key legislative
839 proposal to boost the market for secondary raw materials, and the revised Waste Framework
840 Directive¹⁵ establishes ambitious targets for recycling.

841
842 Several STRUBIAS materials show a substantial potential to provide safe sources of
843 **phosphorus (P)** that can constitute an **alternative for the primary raw material phosphate**
844 **rock**. Both phosphorus and phosphate rock have been identified by the European
845 Commission as critical raw materials, based on its supply risk and the economic importance
846 for EU operators in particular.

847
848 The JRC assesses STRUBIAS materials incorporated into CE fertilising products against
849 following criteria:

850 IV. *The use of the materials will not lead to overall adverse environmental or*
851 *human health impacts;*

¹³Note that the acronym STRUBIAS was initially chosen as the working title for this project and has been maintained for simplicity reasons, despite a refined possible scope of the different groups agreed at the STRUBIAS Kick-off Meeting (Seville, July 2016)

¹⁴ More information on: http://ec.europa.eu/environment/circular-economy/index_en.htm

¹⁵ Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste

852 V. *The material shall provide plants with nutrients or improve their nutrition*
853 *efficiency, either on its own or mixed with another material [following the*
854 *definition of fertilising products in the proposal for the Revised EC Fertiliser*
855 *Regulation];*

856 VI. *Trade on the internal market can be expected for such a fertilising material,*
857 *based on the current market and the future market and trade forecasts.*
858

859 The following main benefits are expected from the introduction of EU-wide criteria for
860 fertilising materials derived from secondary raw materials:

- 861 ○ A reduced **dependence on primary raw materials**, principally phosphate rock;
- 862 ○ Improved **functioning of the internal fertilising market** by enabling a market
863 entry for safe fertilisers derived from secondary raw materials;
- 864 ○ A **stable legal framework** that provides legal certainty to the industry that
865 manufactures fertilisers derived from secondary raw materials;
- 866 ○ **Reinforcing consumer confidence by ensuring high quality and safety for**
867 secondary raw materials in accordance with the relevant articles of the EU Treaty
868 for the functioning of the EU;
- 869 ○ **Reduction of administrative burdens** related to shipment, transport and trade
870 that are redundant for environmentally safe materials.

871
872 The final JRC report resulting from the STRUBIAS project aims to support the policy
873 making process within the Commission, in particular the revision of the EU Fertiliser
874 Regulation. However, none of the proposals made in this report have any binding character
875 whatsoever. **The final decision on a proposed incorporation of precipitated phosphate**
876 **salts & derivatives, thermal oxidation materials & derivatives, and pyrolysis & gasification**
877 **materials in the revised Fertiliser Regulation will be taken by the Commission and**
878 **could be based on the outcomes of the final JRC report.** However, the Commission is free
879 to make further changes to the proposals in the present document for the legal requirements
880 that those materials shall meet.
881

882 **3.2 Methodology applied and further steps to be taken**

883 JRC embarked the STRUBIAS project by preparing a **Background Document** for the Kick-
884 off Meeting held in July 2016, which included information related to (1) the nature of the
885 possible input materials for the recovery of nutrients, organic matter, and acid neutralising
886 value, (2) the quantitative share of these input materials that is currently dissipated in the EU
887 and could potentially be used for the production of STRUBIAS materials, (3) the technical
888 description of the different production processes as well as any applied pre- and post-
889 processing techniques, (4) the safety and quality of materials that might be incorporated into
890 CE fertilising products as a function of production process conditions and (5) market aspects.

891
892 The Background Document was distributed to the STRUBIAS sub-group for discussion at the
893 Kick-off Meeting and a **written consultation round**. The STRUBIAS sub-group was asked

894 to **correct any obsolete data** within the document, **complement** the document with
895 additional information and to **respond to questions** where supplementary information was
896 requested from the STRUBIAS sub-group on production process conditions and product
897 quality. Moreover, a standardised excel-template for **data collection** was circulated to
898 facilitate the data input from the STRUBIAS sub-group.

899

900 Based on the confidential and non-confidential data received from the STRUBIAS sub-group
901 and complementary information found in scientific literature, the JRC elaborated **a proposal**
902 **for recovery rules for each of the STRUBIAS materials (STRUBIAS Interim Report**
903 **released in May 2017) and a draft report on market aspects (STRUBIAS Interim**
904 **Report released in December 2017)**. These reports included the overall share of the work
905 covered in the STRUBIAS pre-final report, with the exception of the sections on quality
906 management (section 5.7), environmental and human health impacts materials (section 8),
907 compliance costs (section 9.2) and possible economic drawbacks and benefits (section 9.3).
908 The STRUBIAS sub-group then had the opportunity to comment on the STRUBIAS Interim
909 Report, including the possibility to highlight obsolete information, submit further supporting
910 data, and to make proposals to further complement the reports.

911

912 At all times, the option was given to provide data in a **confidential manner**, for which reason
913 neither all the information received by the JRC has been uploaded on the CIRCABC
914 platform, nor will it be cited in the follow-up documents of this project. Such data is
915 interpreted in a qualitative manner with no reference to the source provider or process
916 technology.

917

918 Each of these STRUBIAS sub-group comments has been assessed by the JRC, and **credible**
919 **and relevant information** has been taken into consideration during the drafting of the pre-
920 final STRUBIAS report. Expert judgement by the JRC and the STRUBIAS sub-group has
921 played a key role in each of these steps and the way in which the information is presented.
922 The information laid down in this document has been **collated and assessed by the**
923 **European Commission's Joint Research Centre who led the work on the STRUBIAS**
924 **project, guided by the principles of technical expertise, transparency and neutrality.** The
925 work of the **STRUBIAS sub-group and all other contributors is gratefully**
926 **acknowledged.**

927

928 **3.3 Structure of the report**

929 As to the structure of this report, **part A** focuses on the **technical proposals** for the
930 requirements that STRUBIAS materials shall comply with for their possible incorporation
931 within the Revised EU Fertilisers Regulation. The Commission envisages a revision of the
932 Fertilisers Regulation expanding its scope to secondary raw material based fertilising
933 materials, including fertilisers made from waste. Section 4 outlines the **structure of the**
934 **proposal for the revised Fertiliser Regulation** and indicates how STRUBIAS materials
935 could enter into the framework of that Regulation. For each candidate STRUBIAS material,
936 recovery rules have been proposed that cover (i) the **eligible input materials** that can be

937 applied for the production of STRUBIAS materials, (ii) the **production process conditions**,
938 (iii) the direct **safety and quality requirements** of the end-material of the production process
939 that can be contained in a CE marked fertilising product as well as labelling requirements,
940 and (iv) the **conformity assessment procedures** that shall apply to control points (i) - (iii)
941 (section 5). Section 5.1 indicates the **scope** expansion that of the original proposed candidate
942 materials, and the associated modification of the category names. Sections 5.2 - 5.6 then
943 discuss the technical proposals for each of the STRUBIAS materials for points (i) – (iii)
944 outlined above, followed by the proposed quality management system (section 5.7) and links
945 to other EU legislation of interest (section 5.8).

946

947 **Part B** builds on section A and supplements it by providing for an extensive description of
948 the **impacts of the possible incorporation of STRUBIAS materials in the revised**
949 **Fertiliser Regulation** for European agriculture, the environment and human health, and the
950 fertilisers industry. Section 6 focuses on the **agronomic efficiency** of STRUBIAS materials
951 to support plant yields and nutrient uptake in European agroecosystems using meta-analyses
952 techniques. Section 7 provides an overview of the current **market for STRUBIAS**
953 **materials**, as well as their potential to replace conventional fertilisers resulting from a
954 possible opening of the EU fertilising market to such products. Section 8 relies on the use of
955 life cycle assessment and life cycle costing to assess the **environmental and human health**
956 **impacts** of replacing conventional fertilisers by fertilising products containing STRUBIAS
957 materials, and estimates the production costs for STRUBIAS materials. Section 9 projects
958 possible **impacts on the economy** of replacing conventional fertilisers by recovered
959 fertilising products, and focuses on sales prices and compliance costs for fertilisers on the EU
960 market.

961

962 Finally, section 10 gives **general conclusions** on the possibility of developing STRUBIAS
963 recovery rules to protect environmental and human health safety, the agronomic effectiveness
964 and added-value of STRUBIAS materials for the European agricultural sector, and the trade
965 and on the internal market that can be expected for each of the STRUBIAS materials.

966

967 The report is **annexed** by sections that focus on a detailed description of the **properties and**
968 **the current fate of eligible input materials** for STRUBIAS production processes (section
969 14) and **STRUBIAS production processes and techniques** (section 15). These sections aid
970 to assess the suitability and technical feasibility to recover nutrients, liming material, and
971 organic matter from different input materials and through the different STRUBIAS
972 production pathways. The **chemical properties of the STRUBIAS materials** as per
973 macroelements and contaminant levels are annexed in section 16. Finally, section 17 provides
974 details on specific **methods** applied in the main report.

975

976

PART A: TECHNICAL PROPOSALS

977

DRAFT - WORK IN PROGRESS

978 **4 STRUBIAS as component material categories in the revised Fertiliser Regulation**

979 **4.1 Definition and principles of recovery rules**

980 The proposal for the Revised EC Fertiliser Regulation¹⁶ defines 'fertilising product' as: "*a*
981 *substance, mixture, micro-organism or any other material, applied or intended to be applied,*
982 *either on its own or mixed with another material, on plants or their rhizosphere for the*
983 *purpose of providing plants with nutrient or improving their nutrition efficiency.*"
984 According to the proposal for the Revised Fertiliser Regulation, the provisions **on product**
985 **criteria for CE marked fertilising products** contain requirements for the categories of end-
986 products in accordance with their **intended function ("Product Function Category" –**
987 **PFC)**, as well for the categories of **component materials ("Component Material**
988 **Categories" – CMC)** that can be contained in CE marked fertilising products. It is referred
989 to section 4.2 for a brief introduction on the structure of the proposal for the revised Fertiliser
990 Regulation as laid down by the European Commission on 16 March 2016.

991
992 STRUBIAS materials may be used as *component materials* in EU fertilising products when
993 they are compliant with the specifications contained in the "recovery rules" of the
994 corresponding material. The STRUBIAS recovery rules thus describe possible specific **CMC**
995 **requirements that shall be fulfilled by the STRUBIAS materials which are used as**
996 **ingredients in CE marked fertiliser products.** Such products could bear the CE mark after
997 the relevant conformity assessment procedure has been performed, including the compliance
998 with the criteria laid down at PFC level. CE marked fertilising products could then freely
999 circulate in the single market.

1000
1001 **Where health and safety, the protection of consumers or of the environment, other**
1002 **aspects of public interest, or clarity and practicability so require, detailed technical**
1003 **specifications may be set out in the legislation concerned.**

1004
1005 The STRUBIAS recovery rules shall describe:

- 1006 i. the eligible input materials that can be applied for the production of
1007 STRUBIAS materials as well as any input materials that are excluded from
1008 eligibility;
- 1009 ii. the production process conditions and parameters that shall be applied during
1010 the production phase of the STRUBIAS materials;
- 1011 iii. the direct safety and quality requirements of the end-material of the production
1012 process that can be contained in a CE marked fertilising product;
- 1013 iv. the useful information, where relevant, to be incorporated in the labelling
1014 requirements for the provision of information towards retailers and end-users.
1015 It is noted that labelling requirements only apply at PFC level, but that the

¹⁶ More information on: http://europa.eu/rapid/press-release_IP-16-827_en.htm

1016 framework enables cross-referencing to certain CMCs in the labelling
1017 requirements;

1018 v. the conformity assessment procedures that shall apply to monitor at control
1019 points i.-iv.

1020

1021 The STRUBIAS sub-group proposed that recovery rules should be a set of requirements that
1022 are in line with following general principles:

1023 ○ Agronomic efficacy and limits on contaminants and pathogens must be ensured
1024 for STRUBIAS materials contained in CE fertilising materials so that farmers in
1025 Europe always have access to **high quality products**, and that the use of
1026 secondary raw materials does **not lead to overall adverse environmental**
1027 **impacts or human health risks**. A lack of consideration of these aspects may
1028 reduce farmers' confidence and create low market acceptance for innovative
1029 fertilisers, ultimately undermining the objective of nutrient recycling.

1030 ○ A **level playing field that ensures high-quality standards for CE marked**
1031 **fertilising products** derived from primary and secondary raw materials shall offer
1032 simplicity and clarity to producers and consumers that are active on the European
1033 fertilising market;

1034 ○ At the same time, requirements shall be set in a sufficiently **flexible** manner to
1035 **encourage industry to undertake nutrient recycling actions** that will contribute
1036 to achieving the policy goals set in the framework of the Circular Economy
1037 Action Plan. It is not advisable to put unnecessary restrictions that might block the
1038 emerging STRUBIAS market.

1039 ○ Recovery rules shall, in principle, apply a neutral stance towards all existing and
1040 future technological systems operating on the market and input materials available
1041 **(technologically neutral recovery rules)**. Such an approach stimulates
1042 competition and technological innovation, and takes into consideration that
1043 process conditions and technologies for nutrient recovery on the emergent
1044 STRUBIAS market might require further adjustments, especially if alternative
1045 input materials are used.

1046 ○ Recovery rules have to **be clear, concise and enforceable**, in order to clearly
1047 **delimit** the scope of the CMC in concordance with its name, lead to reasonable
1048 compliance costs, and facilitate straightforward conformity assessments.

1049 This proposal intends to bring forward a set of requirements that takes into account the above
1050 principles.

1051 The CE product status shall only apply to those materials that meet all the requirements for
1052 relevant **PFCs**, in particular the **conformity assessment** requirements applicable to fertilising
1053 products. This implies that materials that meet the requirements of the CMC, but not those of
1054 the PFC, shall still have the same status as the input material from which they have been
1055 manufactured (e.g. waste status for CMCs derived from waste input materials). This is in line

1056 with article 18 of the proposal for a Revised Fertiliser Regulation stating that "A CE marked
1057 fertilising product that has undergone a recovery operation and complies with the
1058 requirements laid down in this Regulation [including the requirements laid down Annexes 1-
1059 5 in that proposal] shall be considered to comply with the conditions laid down in Article 6(1)
1060 of Directive 2008/98/EC and shall, therefore, be considered as having ceased to be waste".
1061 Therefore, the recovery rules proposed in this document **cannot be interpreted as possible**
1062 **"End-of-Waste" criteria**, as they do not go as far as attributing PFC product status, but stop
1063 at providing CMC material status.

1064
1065 STRUBIAS materials have only been entering the market relatively recently, which explains
1066 why so little information might be available for certain pollutants of concern. In some cases,
1067 it remains unclear to what extent the nature of the manufacturing process may aid the
1068 removal or selective exclusion of certain contaminants from the end-material, and to what
1069 extent the nature of the input material influences the quality of the end-material. For this
1070 reason, the **precautionary principle** is important when evaluating environmental and human
1071 health aspects, meaning that sufficient scientific data should be available prior to the
1072 establishment of criteria for STRUBIAS materials.

1073

1074

DRAFT - WORK IN PROGRESS

1075 **4.2 The proposed framework and outline of the Revised EU Fertiliser Regulation**

1076 The proposal for a Revised Fertiliser Regulation was released on 17 March 2016 and is
1077 publically available on the European Commission's website
1078 (<http://ec.europa.eu/DocsRoom/documents/15949>). At the time of writing this document, it
1079 was under discussion with the European Parliament and Council. For a full understanding of
1080 this report and legal requirements that shall be met for EC marked fertilising materials, the
1081 reader is encouraged to review the referenced proposal, as well as the Annexes to the
1082 proposal. In this section, some specific items and articles of the proposal will be highlighted
1083 in order to facilitate a better understanding on the design of the recovery rules.

1084 1085 4.2.1 Component material categories and product function categories

1086 According to the proposal for the Revised EC Fertiliser Regulation¹⁷, the provisions **on**
1087 **product criteria for CE marked fertilising products** contain requirements for the
1088 categories of end-products in accordance with their **intended function (PFC)**, as well for the
1089 categories of **component materials (CMC)**. Specific requirements for each of the CMCs
1090 apply because **different component materials warrant different process requirements**
1091 **and control mechanisms adapted to their different potential hazardousness and**
1092 **variability**, in turn dependent on the quality of the input materials applied, production
1093 process conditions, etc. Component materials for CE marked fertilising products should,
1094 therefore, be divided into different categories.

1095
1096 A fertiliser manufacturer can bring a CE marked fertilising product that is composed of one
1097 single ingredient, belonging to a specific CMC, on the market. A relevant example is struvite.
1098 In this case, the CE marked fertiliser shall have to comply with the requirements laid down
1099 for the CMC "precipitated phosphate salts" as well as for an eligible PFC, in this case PFC 1
1100 C - inorganic fertilisers. It is also possible to put a CE marked fertilising product on the
1101 market that is composed of several component materials from various CMCs, where each
1102 material complies with the requirements of a certain category. A condition is, however, that
1103 **no chemical reaction or transformation takes place between the different CMCs that**
1104 **are contained in the CE marked fertiliser**. Hence, a CE marked fertiliser producer may
1105 start from two or more substances or mixtures, provided that each of them complies with the
1106 description in one or more of the CMCs, and mix them into a final product without any
1107 chemical reaction taking place. The component materials are then "contained" as such in the
1108 final CE marked fertilising product. This follows the presumption that if different component
1109 materials do not show unacceptable risks for human health and the environment, a physical
1110 mix of them constituting the final CE marked product will also be safe, subject to compliance
1111 with certain limit values defined in Annex I (i.e. PFC level) for the final product. A relevant
1112 example is, for instance, the blending of compost (CMC 3) with a triple superphosphate
1113 (CMC 1 – virgin materials) to produce an organo-mineral fertiliser belonging to PFC 1 B.

1114

¹⁷ More information on: http://europa.eu/rapid/press-release_IP-16-827_en.htm

1115 The general framework of the Revised Fertiliser Regulation has important implications for
1116 the design of the recovery rules and the use of STRUBIAS materials used as ingredients for
1117 fertiliser production processes:

1118 • **Treatments usually considered in recovery operations, such as chemical or**
1119 **thermochemical reactions, cannot take place on CMC materials as they would**
1120 **modify the chemical material properties, disqualifying such processed materials**
1121 **from being "contained" as such in the CE fertilising material.** STRUBIAS CMC
1122 materials should, therefore, meet certain quality requirements **so that they can be**
1123 **used directly without any further processing other than normal industrial**
1124 **practice.** Normal industrial practice can include all steps which a producer would
1125 take for a product, such as the material being screened, sized, agglomerated,
1126 pelletized, dried solely to remove free water, or adding materials necessary for further
1127 use through physical mixing without changing the chemical composition of the
1128 material contained in the mixture. A concrete outcome of this provision is that any
1129 materials that pose a risk for human health or the environment can, by no means, be
1130 considered as CMCs (e.g. unprocessed, raw sewage sludge ashes) because further
1131 chemical or thermochemical processing steps are required before such materials could
1132 meet the contaminant levels at PFC level. The STRUBIAS recovery rules shall,
1133 therefore, encompass any manufacturing steps required to produce a material that can
1134 be used as a fertilising material, i.e. to be placed on the market directly without any
1135 further processing other than normal industrial practice. Therefore, **the recovery**
1136 **rules shall describe process and product requirements until the end stage in a**
1137 **manufacturing process of a fertilising material.** Concretely, this implies, for
1138 instance, that recovery rules shall include provisions for manufacturing steps on raw
1139 sewage sludge ashes, and shall place product requirements on a triple superphosphate
1140 material that is, partially or entirely, produced from incinerated sewage sludge. See
1141 section 5.3.3 for a more detailed explanation on the incorporation of such
1142 manufacturing processes that consist of multiple steps.

1143
1144 • Given that CMCs shall meet quality requirements so that they can be used directly
1145 without any further processing other than normal industrial practice, operators -
1146 including those that recover fertilising materials from waste-based materials - **will**
1147 **have the possibility to perform the conformity assessment procedure associated**
1148 **to a selected PFC.** The **CE marking**, indicating the conformity of a fertilising
1149 product, is the visible consequence of a whole process comprising conformity
1150 assessment in a broad sense. Where compliance of such a fertilising product with the
1151 applicable requirements laid down for a CMC and a PFC has been demonstrated,
1152 manufacturers may affix the CE marking. In accordance with Article 18 of the
1153 proposal for the revised Fertiliser Regulation, any possible waste status ceases to
1154 apply and the resulting material can be sold as a product on the internal market. A
1155 company that does not have a permit for transport or treatment of waste materials
1156 can then **buy the CE marked STRUBIAS product** and subsequently use it:

- 1157 i. As an input material to be used by a fertiliser blending company that
1158 **physically mixes** the product into a fertilising product blend of PFC 7, without
1159 any chemical reaction taking place. The intention behind PFC 7 is to allow
1160 manufacturers to rely on conformity assessments already performed by their
1161 suppliers. If the different components are safe for human health and the
1162 environment, then the blend can also be presumed to be safe if the blending
1163 did not change the nature of the components. A relevant example is selling
1164 struvite as a CE marked fertilising product (thus meeting the requirements for
1165 the CMC "precipitated phosphate salts & derivatives" and the PFC inorganic
1166 fertilisers) to a fertiliser blending company to include it into an NPK-fertiliser
1167 blend.
- 1168 ii. As a CE marked product to be used as an intermediate in a **chemical**
1169 **manufacturing process**. According to Regulation (EC) 1907/2006,
1170 intermediates are defined as "a substance that is manufactured for and
1171 consumed in or used for chemical processing in order to be transformed into
1172 another substance". The CE marked product will now be used a precursor for a
1173 chemical process to make a material pertaining to CMC 1, and the new
1174 substance that comes out of this manufacturing process has to comply with the
1175 requirements for CMC 1 since a chemical reaction is involved. However, it is
1176 not because the intermediate has been derived from waste, that the newly
1177 produced material is excluded from CMC 1; the intermediate left the waste
1178 regime by virtue of complying with all conditions (CMC level, PFC level,
1179 labelling requirements, and conformity assessment procedure) to become a CE
1180 marked fertilising product. A relevant example is, for instance, the
1181 STRUBIAS material triple superphosphate (TSP) derived from bone meal ash.
1182 Triple superphosphate is not only registered pursuant Regulation (EC) No
1183 1907/2006 as a fertiliser (EC 232-379-5), but can also be used as an
1184 intermediate to produce a compound NPK fertiliser, i.e. a fertiliser with each
1185 nutrient contained in every granule or prill. In this case, the compound NPK
1186 producer can buy the CE marked TSP derived from bone meal ash (complying
1187 with CMC requirements for "thermal oxidation materials & derivatives" and
1188 PFC 1 C "inorganic fertilisers") on the internal market, use it as an
1189 intermediate, and produce a compound NPK through a chemical reaction that
1190 then requires a REACH registration according to Point 2 of CMC 1.
1191
- 1192 • **Any material of a CMC production process that has not undergone the**
1193 **conformity assessment procedure (for instance, sewage sludge ashes or struvites**
1194 **that have not yet passed through such a procedure) will still be considered a**
1195 **"waste" and must comply with the regulatory provisions for waste** (Waste
1196 Framework Directive (2008/98/EC) and Directive (EU) 2018/851, Waste Shipment
1197 Regulation (96/61/EC), etc.). Hence, fertiliser manufacturers that receive such waste
1198 materials and turn them into CE marked fertilising products will be required to fulfil
1199 all obligations laid down in the legislation on waste. A relevant example is a fertiliser
1200 production plant manufacturing single superphosphate from precipitated calcium

1201 phosphates at a manure processing plant. **As long as the precipitated phosphate salt**
1202 **has not undergone the conformity assessment procedure, the material can be**
1203 **shipped under the waste legislation** to a fertiliser production plant, which will then
1204 be able to affix the CE marking following a conformity assessment procedure.
1205

1206 4.2.2 Status of industrial by-products and polymers

1207 Some STRUBIAS production processes make use of specific polymers and industrial by-
1208 products as defined in Article 5 of Directive 2008/98/EC on waste. Relevant examples
1209 include:

- 1210 • the solid-liquid separation of manure fractions using anionic polyacrylamide to
1211 separate a manure fraction with a higher dry matter content that can be used as an
1212 input material for a pyrolysis process.
- 1213 • the use of by-product from magnesite mining and the MgO production industry to be
1214 used as Mg source in the struvite precipitation process;
- 1215 • the use of sulphuric acid, an industrial by-product from oil refining, to manufacture
1216 single super phosphate from bone meal ashes;
- 1217 • the use of calcite, a by-product from the dissolution of dolomitic aggregates, as an
1218 additive for pyrolysis reactions.

1219 **Whereas industrial by-products can positively contribute to circular practices in the**
1220 **Revised Fertiliser Regulation, criteria are required to ensure a high level of protection**
1221 **of the environment and human health from the use of such materials.** Depending on their
1222 origin, some industrial by-products can reasonably be expected to contain particular organic
1223 and inorganic contaminants that are uncommon in the targeted input materials for the
1224 STRUBIAS CMCs. The same goes for non-biodegradable polymers that may have, for
1225 instance, a negative effect on soil organisms. Hence, a tangible risk exists that organic or
1226 inorganic contaminants present in industrial by-products and polymers could directly be
1227 transferred to the CE marked fertiliser that contains STRUBIAS materials.

1228 **The JRC proposal is to transpose any technical and legal progress made by the**
1229 **Commission on the possible use of industrial by-products and polymers within the**
1230 **framework of the Revised Fertiliser Regulation to STRUBIAS materials.**

1231

1232 4.2.3 The principle of optional harmonisation

1233 In view of the very local nature of certain product markets, the proposal for the Revised
1234 Fertiliser Regulation maintains the possibility that **non-harmonised fertilisers can be made**
1235 **available on the market** in accordance with national law, and the principles of mutual
1236 recognition of the European Union. This implies that the Revised Fertiliser Regulation will,
1237 therefore, not restrict materials already in use in specific Member States that are covered
1238 under national legislation.

1239

1240

1241 5 STRUBIAS recovery rules

1242 5.1 Terminology and scope of STRUBIAS component material categories

1243 The acronym STRUBIAS was initially chosen as the working title for this project because the
1244 initial scope of the project focused on STRUvite, BIochar and ASh-based materials. As a
1245 result of the continuous refinement of the scope and a further expansion of the materials
1246 covered, a modified terminology for the possible component materials categories (CMCs)
1247 covered by the STRUBIAS project is proposed. **The new CMC names are based on the**
1248 **principles that they (1) should make a clear reference to the production process applied**
1249 **to obtain the CMC material, and (2) they should well-reflect any possible materials**
1250 **covered by the CMC.**

1251

1252 5.1.1 "Precipitated phosphate salts & derivatives" instead of "struvite"

1253 **Struvite** is a phosphate mineral that can be precipitated from a liquid solution or slurry and
1254 its name has been used as the general working title for a group of possible recovered
1255 phosphate salts since the beginning of the STRUBIAS project. The precipitation process
1256 involves the **formation of a separable solid substance from a solution by converting the**
1257 **substance into an insoluble form through the addition of chemicals.** It is noted that
1258 mineral struvite (magnesium ammonium phosphate - $\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O}$) can also be
1259 chemically synthesized from virgin chemicals, in which case it is already covered by the
1260 provisions of *Component Material Category (CMC) I - Virgin material substances and*
1261 *mixtures*. This production pathway for struvite is therefore excluded from the present
1262 analysis, and consequently from the newly proposed CMC.

1263

1264 Struvite is generally considered as the preferred phosphate mineral for P-recovery practices
1265 as it is possible to isolate relatively pure minerals of high P-content with only trace amounts
1266 of impurities, and it has a demonstrated value as a P-fertiliser. It is often assumed that
1267 precipitates harvested at a pH range between 9.0 and 10.7 are struvite-like compounds under
1268 appropriate molar ratios of magnesium, nitrogen and phosphate. In some occasions, X-ray
1269 diffraction (XRD) is used to characterise the harvested crystalline precipitates, mainly by
1270 comparing the position and intensity of peaks with the struvite reference (Hao et al., 2008). If
1271 the diffraction patterns match the struvite reference to a certain extent, precipitates are then
1272 "confirmed" as being struvite. However, because XRD is not a quantitative method and
1273 amorphous precipitates are easily overlooked, **the harvested precipitate may be**
1274 **erroneously interpreted as a relatively pure struvite when, in fact, it is not** (Hao et al.,
1275 2008). The apparently fragile equilibrium of struvite in solution leads to the presence of other
1276 crystal phases as well (Andrade and Schuiling, 2001; Bhuiyan et al., 2008). The formation of
1277 other magnesium phosphates such as $\text{MgNH}_4\text{PO}_4 \cdot \text{H}_2\text{O}$ (dittmarite), $\text{MgHPO}_4 \cdot 3\text{H}_2\text{O}$
1278 (newberyite), $\text{MgKPO}_4 \cdot 6\text{H}_2\text{O}$ (K-struvite) and a wide variety of calcium phosphates (e.g.
1279 $\text{CaNH}_4\text{PO}_4 \cdot 7\text{H}_2\text{O}$ (calcium ammonium phosphate), amorphous calcium phosphates, brushite
1280 ($\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$)) through precipitation or dissolution processes has been reported in the
1281 literature (Michalowski and Pietrzyk, 2006; Massey et al., 2009). Hence, it becomes clear that

1282 "struvite-like" materials are in many cases not pure crystals, defined as solid particles in
 1283 which the constituent molecules, atoms or ions are arranged in a fixed and rigid repeating
 1284 three-dimensional pattern or lattice. In line with this observation, the production process can
 1285 best be referred to the more broad-ranging term "**precipitation**" instead of "crystallisation".
 1286 The term precipitated phosphate salts encompasses the broad variety of materials that are
 1287 targeted in recovery or production processes that are intended to be used as fertilising
 1288 materials or as intermediates in manufacturing processes of P-fertilisers.

1289
 1290 Currently, struvite is the most common precipitated phosphate salt for most industrial
 1291 facilities in planned, piloting and operational facilities in Europe (see section 7.1.1).
 1292 Nonetheless, it is noteworthy to mention that besides **struvite, also other calcium**
 1293 **phosphates and magnesium phosphates are registered pursuant to Regulation EC No**
 1294 **1907/2006 (REACH) as fertilisers**. A total of 252 different phosphate salts are registered in
 1295 the REACH registration system, though only some of them are registered as fertilisers.

1296
 1297 **Table 1: Examples of phosphate salts as registered pursuant to Regulation EC No 1907/2006**
 1298 **(REACH) as fertilisers**

EC / List number	regulatory REACH process names	alternative IUPAC names (selected)	CAS number	molecular formula
232-075-2	ammonium magnesium orthophosphate	struvite	7785-21-9	NH ₄ MgPO ₄ ·6H ₂ O (hydrate)
231-826-1	calcium hydrogenorthophosphate	dicalcium phosphate, calcium dihydrogen phosphate	7757-93-9	CaHPO ₄ (anhydrous); CaHPO ₄ ·2H ₂ O (dihydrate)
231-823-5	magnesium hydrogenorthophosphate	dimagnesium phosphate	7757-86-0	MgHPO ₄
235-330-6	pentacalcium hydroxide tris(orthophosphate)	hydroxylapatite, bone ash	12167-74-7	Ca ₅ (PO ₄) ₃ (OH)
231-837-1	calcium bis(dihydrogenorthophosphate)	monocalcium phosphate	7758-23-8	Ca(H ₂ PO ₄) ₂ (anhydrous); Ca(H ₂ PO ₄) ₂ ·H ₂ O (hydrate)
236-004-6	magnesium bis(dihydrogenorthophosphate)	-	13092-66-5	Mg(H ₂ PO ₄) ₂ (anhydrous); Mg(H ₂ PO ₄) ₂ ·4H ₂ O (quadhydrate)
231-840-8	tricalcium bis(orthophosphate)	tricalcium diphosphate, tricalcium phosphate	7758-87-4	Ca ₃ (PO ₄) ₂
231-824-0	trimagnesium bis(orthophosphate)	trimagnesium diphosphate, trimagnesium phosphate, tribasic magnesium phosphate	7757-87-1	Mg ₃ (PO ₄) ₂

1299
 1300
 1301 Some P-recovery processes such as the Budenheim process, P-ROC process, and BioEcoSim
 1302 deliberately target the formation of calcium phosphates, rather than struvite. Based on the
 1303 information received from the STRUBIAS sub-group, there appears to be an interest to
 1304 include these types of recovered P-rich salts under this CMC. More specifically **techno-**
 1305 **scientific information on calcium phosphates** as end-products of P-recovery processes was
 1306 received from the STRUBIAS sub-group for possible inclusion. The input received enabled
 1307 an assessment of the agronomic value and the environmental and human health safety
 1308 aspects.

1309
 1310 The newly proposed CMC aims at covering any acceptable form of **phosphate-based**
 1311 **compounds** produced through a **precipitation process** that is in line with the principles of
 1312 **phosphorus recovery in safe, P-concentrated materials**. Precipitated phosphate salts could
 1313 be **recovered** from waste-based materials (e.g. municipal wastewaters), where the
 1314 precipitation process constitutes a valuable alternative for the incineration and landspreading

1315 of P-rich waste streams. Precipitated phosphate salts could also be **deliberately produced**
1316 from P-rich materials such as processed animal by-products (e.g. co-products of gelatin
1317 production from animal bone material). It is preferable that the end-materials of the
1318 production processes covered are suitable for direct use as a fertiliser on agricultural land as
1319 well as for use as a source or intermediate in existing production processes for P-fertilisers
1320 and fertiliser blends. Therefore, **end-materials should have a high P content, a low level of**
1321 **inorganic metals/metalloids, and a low presence of organic contaminants.**
1322

1323 Based on scientific literature and feedback from the STRUBIAS sub-group, the appreciation
1324 from experts and users indicates that it is unnecessary to orient P-recovery through
1325 precipitation processes exclusively to struvites of high purity as:

- 1326 ○ the production of P-minerals with a high content of struvite is a **technically**
1327 **challenging and costly process**, especially if also calcium- or potassium-rich input
1328 materials are considered (Hao et al., 2008);
- 1329 ○ **struvite is not superior to some other phosphate-based compounds in agronomic**
1330 **efficiency** (Johnston and Richards, 2003; Massey et al., 2009; Hao et al., 2013; ESPP,
1331 2016), nor does struvite of high purity have a superior fertiliser value than other, less
1332 pure compounds;
- 1333 ○ although there is a relationship between struvite purity and struvite contaminant
1334 levels, **precipitated phosphate salts of low organic C content generally show low**
1335 **levels of contamination**, which do not pose unacceptable risks for the environment
1336 and human health (see section 5.4.5);
- 1337 ○ the **fertiliser industry** has no strict preference for particular phosphate salts that will
1338 be used as raw materials. Wet chemical and thermal post-processing processes can
1339 transform phosphate precipitates into water-soluble P-fertilisers (Hao et al., 2013).
1340 Rather than chemical composition, **the content of P** (preferably 30-40%, expressed as
1341 P₂O₅, similar to phosphate rock) **and organic C** (preferably as low as possible) are
1342 major factors that determine the suitability for precipitated phosphate salts to be used
1343 as an intermediate raw material for the fertiliser industry.
1344

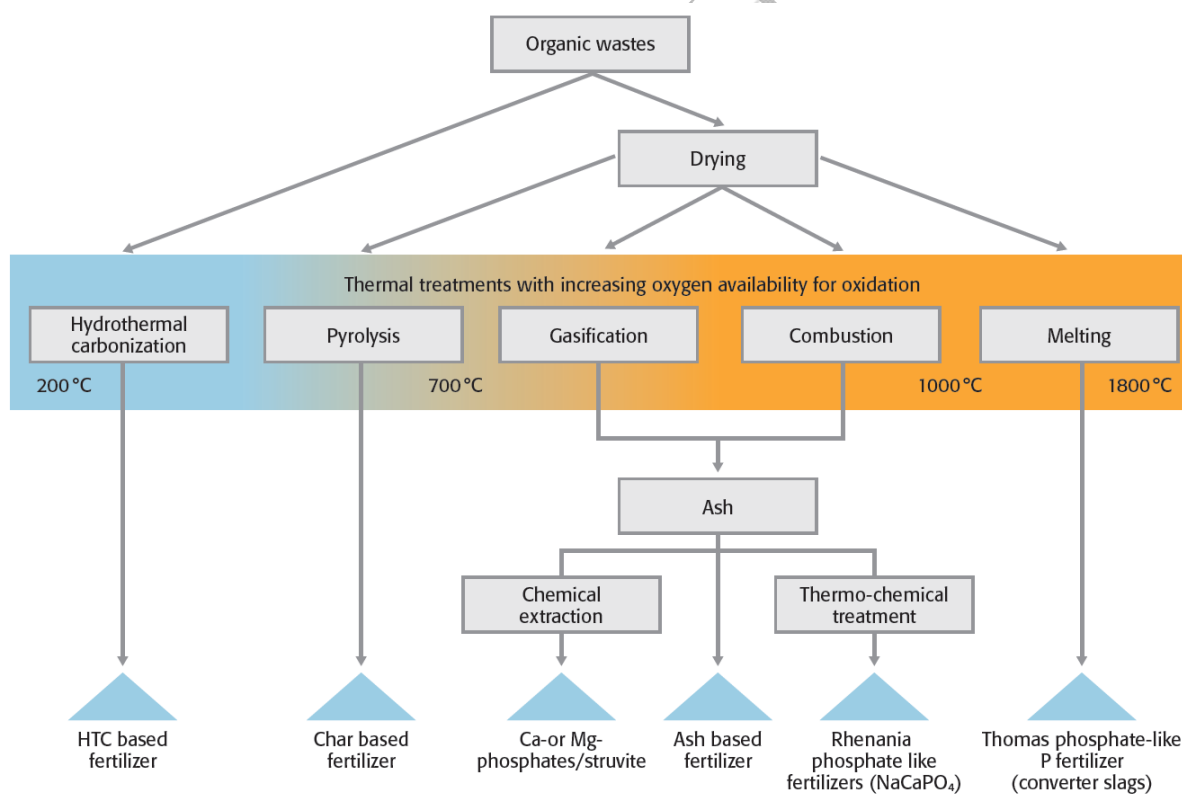
1345 The P-recovery process could also be a **two-step process**, where phosphates are recovered in
1346 an intermediate form (e.g. hydroxyapatite or iron-phosphate complexes; P forms that
1347 typically show a reduced plant P availability), after which the second phase of the
1348 STRUBIAS production process targets the mobilisation of the precipitated P into a form that
1349 is readily available for plant P uptake (Wilfert et al., 2015). Hence, a manufacturer could
1350 decide to target the production process towards a **derivate from the precipitated phosphate**
1351 **salt.**
1352

1353 In conclusion, it is proposed to modify the name of this CMC to "**precipitated phosphate**
1354 **salts & derivates**" instead of struvite.
1355

1356

1357 5.1.2 "Thermal oxidation materials & derivates" instead of "ash-based materials"

1358 The original project scope was limited to "ash-based products from mono or co-incineration
 1359 and combustion of biomass or resulting from industrial processes". It is proposed to delineate
 1360 the scope of the materials covered under this CMC, and more specifically to make a clear
 1361 distinction between the CMCs covered by the STRUBIAS materials "ash-based materials"
 1362 and "biochar". Both types of materials result from the **thermo-chemical conversion**
 1363 **processes, and no clear cut-off criteria have been defined to divide the end-materials**
 1364 **into hydrochar, biochar, or ash** (Moller, 2016) (Figure 1). The classification of the different
 1365 materials produced through thermochemical conversion is not always straightforward, and at
 1366 times, a combination of materials is collected. Moreover, "ash" can have very different
 1367 properties (e.g. organic carbon content depending on the degree of combustion) and be
 1368 formed through different pathways that have a distinct ability to remove organic
 1369 contaminants (Figure 1). Some biochars contain, for instance, a significant ash fraction.
 1370 Finally, the STRUBIAS sub-group indicated that ash-based materials might not be all-
 1371 encompassing as nutrient recovery can also take place in the form of "**converter slags**", a
 1372 material formed through a melting process in an oxygen-rich environment (Figure 1).
 1373 Therefore, focusing on the end materials of the production process might not be the best
 1374 approach to delimit the scope of the CMC.
 1375



1376
 1377 **Figure 1: Schematic overview of thermo-chemical processes that can be applied for nutrient and**
 1378 **organic matter recovery processes covered by the STRUBIAS project (adopted from Möller,**
 1379 **2016).**
 1380

1381 A way forward for the comprehensive inclusion of the different thermochemical materials is
 1382 to divide material categories based on the **oxygen profile applied in the thermochemical**

1383 **conversion process**, thus on the production conditions for the different materials. This is a
1384 straightforward approach as it enables to separate materials formed under oxygen-limiting
1385 conditions from materials under non-oxygen limiting combustion conditions. Complete
1386 oxidation in the combustion process would convert this carbon totally to CO₂. However, in
1387 technical plants a total conversion will never be accomplished and a small amount of
1388 products of incomplete combustion are found in all residue streams (Vehlow et al., 2006).
1389 Nonetheless, combustion under a non-oxygen limiting environment produces metals and
1390 slags of low organic C content, typically lower than 3%. As organic carbon and soot particles
1391 show a high adsorption potential for contaminants (Mätzing et al., 2001), the organic C
1392 content of the material collected from the thermochemical conversion plant is a highly
1393 relevant parameter from an environmental and human health perspective. Combustion under
1394 non-oxygen limiting conditions to low levels of organic C in the ashes is a well-demonstrated
1395 technique for the effective removal and thermal destruction of a broad range of organic
1396 contaminants that are inherently present in the targeted input materials for this CMC. As a
1397 matter of fact, **the thermal oxidation of waste materials is a widely applied method for**
1398 **the disposal or recovery of waste as outlined in the Best Available Techniques (BAT)**
1399 **Reference Document pursuant to Article 13 of Directive 2010/75/EU on industrial**
1400 **emissions (European Commission, 2017c)**. Basically, waste incineration is here referred to
1401 as the *oxidation* of the combustible materials contained in the waste. Waste is generally a
1402 highly heterogeneous material, consisting essentially of organic substances, minerals, metals
1403 and water. During incineration, flue-gases are created that will contain the majority of the
1404 available fuel energy as heat. The organic substances in the waste will burn when they have
1405 reached the necessary ignition temperature and come into contact with oxygen (European
1406 Commission, 2017c). The actual combustion process takes place in the gas phase in fractions
1407 of seconds and simultaneously releases energy. The objective of waste incineration is to treat
1408 waste so as to reduce its volume and hazard, whilst capturing in solid form (and thus
1409 concentrating, for instance metals) or destroying potentially harmful substances (European
1410 Commission, 2017c). Combustion processes can also provide a means to enable recovery of
1411 the energy, mineral and/or chemical content from waste. Also in Regulation (EC) No
1412 1069/2009 on animal by-products, the combustion in a non-oxygen limiting environment is
1413 referred to as an effective measure for the hygienisation of animal by-products. Hence, it is
1414 proposed to divide the end-materials from thermo-chemical conversion techniques based on
1415 the oxygen availability in the production process. **It is proposed to refer in the recovery**
1416 **rules for this CMC to a "thermal oxidation process in a plant under non-oxygen**
1417 **limiting conditions"**. This definition provides following advantages for this CMC:

- 1418 ○ **a demonstrated efficiency of thermal oxidation under non-oxygen limiting**
1419 **conditions to destroy a broad range of organic contaminants;**
- 1420 ○ **the explicit reference to this technique in the existing legislative EU**
1421 **frameworks for the treatment of wastes and animal by-products as a method**
1422 **for waste hygienisation;**
- 1423 ○ **a scope expansion to the inclusion of converter slags that are also produced as**
1424 **a result of a thermal oxidation process under non-oxygen limiting conditions.**

1425

1426 Some thermally oxidised materials that are collected from the combustion plant can **directly**
1427 **be used as a fertilising material on land** (e.g. poultry litter ashes). Materials that have
1428 undergone a **thermal oxidation process can also be subjected to further manufacturing**
1429 **steps** resulting in fertilising materials of a different chemical composition than the oxidised
1430 material. A relevant example is the production of triple superphosphate from the reaction of
1431 sewage sludge ashes with sulphuric acid or hydrochloric acid (see section 5.5.3.3). This may
1432 be required for the removal of inorganic contaminants (e.g. metals/metalloids) and/or the
1433 improvement of the availability of nutrients contained in the ashes and slags. As outlined in
1434 section 4.2.1, **the recovery rules should hence include provisions to enable a CMC status**
1435 **for both materials that have undergone a thermal oxidation as well as for "thermal**
1436 **oxidation material derivatives"**.

1437

1438 **Altogether, it is therefore proposed to change the name of this possible CMC from "ash-**
1439 **based materials" to "thermal oxidation materials & derivatives"**.

1440

1441 5.1.3 "Pyrolysis & gasification materials" instead of "biochar"

1442 This material group has been referred to in the beginning of the STRUBIAS project by the
1443 working title "**biochar**". The European Biochar Certificate applies the following definition
1444 for biochar (EBC, 2012):

1445 *"Biochar is a heterogeneous substance rich in aromatic carbon and minerals. It is*
1446 *produced by pyrolysis of sustainably obtained biomass under controlled conditions with*
1447 *clean technology and is used for any purpose that does not involve its rapid*
1448 *mineralisation to CO₂ and may eventually become a soil amendment"*.

1449

1450 In general, the **organic carbon content of pyrolysed chars fluctuates between 5% and**
1451 **95%** of the dry mass, depending amongst others on the feedstock and process temperature
1452 used. For instance the C content of pyrolysed beech wood is around 85% while that of
1453 poultry manure is around 25% (EBC, 2012) and that of bone is less than 10% (3R
1454 AgroCarbon, 2016). Therefore, the European Biochar Certificate refers to pyrolysed organic
1455 matter with a C content lower than 50% as **pyrogenic carbonaceous materials**, instead of
1456 biochar. From the information received from the STRUBIAS sub-group, it is clear that there
1457 is a considerable interest to use both **C-rich** (e.g. woody biomass) and **mineral-rich** (e.g.
1458 animal bone material, different types of manure) feedstocks as **input materials** for
1459 pyrolysis/gasification processes.

1460

1461 Moreover, the STRUBIAS sub-group also highlighted the possibility of including
1462 **hydrochar**, the material resulting from the wet pyrolysis or hydrothermal carbonisation of
1463 plant-based or animal-based input materials, under this CMC. This proposal has been
1464 investigated and it has been concluded that such materials could possibly be covered under
1465 the scope of this CMC, as long as the end-material meets the quality requirements to ensure
1466 environmental protection and to mitigate plant toxicity (e.g. minimum requirements on C
1467 stability).

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A single CMC should, however, cover both end-material types for which reason the name "**pyrolysis & gasification materials**" is proposed for any materials that are produced via production processes that cover the pyrolysis technology spectrum, including pyrolysis, gasification and wet pyrolysis techniques. This terminology offers the advantage that a clear reference is made to the production technology in the name of the CMC, similar to the other STRUBIAS CMCs. The materials covered under this CMC can be of a very different nature as the production process conditions may span from partial combustion to a fully reductive environment, resulting in materials with a low and high organic C content, respectively. Hence, this CMC name groups materials that have a similar potential hazardousness due to the incomplete oxidation of the feedstock materials, and does not refer to the nature of the resulting end material of the production process (similar to the other STRUBIAS CMCs).

DRAFT - WORK IN PROGRESS

1481 **5.2 Plant nutrient availability of STRUBIAS materials**

1482 A significant share of the STRUBIAS materials show a **high nutrient content** for which
1483 reason they might be used as ingredients for PFC 1 - Fertilisers. The **return of secondary**
1484 **nutrient resources to agricultural land is, however, not the same as efficiently recycling**
1485 **nutrients**. Phosphorus may be unavailable to crops when strongly bound to certain bi- and
1486 trivalent ions. A lack of consideration for the plant-availability of recycled P-sources (i) leads
1487 to the long-term accumulation of this critical nutrient in soils, which removes these nutrients
1488 from the global biogeochemical cycles, and (ii) may reduce farmers' confidence and create
1489 low market acceptance for innovative P-fertilisers derived from secondary raw materials.
1490 Based on these concerns, it may be advisable to control for the **plant availability of P in P-**
1491 **fertilisers**.

1492
1493 The nutrient value of fertilising products can be determined using either **bioassay tests or**
1494 **chemical methods** (Camps-Arbestain et al., 2017). The bioassay tests are based on the plant
1495 response to an amendment under controlled greenhouse conditions or in field trials. Chemical
1496 methods are based on specific chemical solutions - known as extractants (e.g. water, neutral
1497 ammonium citrate - NAC, formic acid or an aqueous solution of 2% citric acid) - that are
1498 used to extract P fractions from the fertiliser. Bioassay procedures are the most reliable for
1499 predicting nutrient availability, but these methods are more time-intensive and costly than
1500 chemical methods. In contrast, chemical methods are simpler to enforce as a criterion for
1501 plant P availability, and therefore constitute the commonly used measures in legal
1502 frameworks.

1503
1504 It is, however, **challenging to determine a single cut-off value that clearly and universally**
1505 **distinguishes between "effective" and "ineffective" fertilisers** because of following
1506 factors that impact upon the nutrient availability and release dynamics of nutrients present in
1507 fertilisers:

- 1508 ○ the varying nutrient use and uptake strategies of plant species and the temporal
1509 variation in nutrient demands for different plant species;
- 1510 ○ the different soil types and weather conditions;
- 1511 ○ the lack of extensive datasets that link results of chemical analysis to plant yield
1512 responses in laboratory and field settings. The need for agronomic trial work is very
1513 urgent and for each of the multiple extraction procedures further assessments are
1514 required before these can be completely validated;
- 1515 ○ the lack of consensus on the cut-off value for an "acceptable" relative fertiliser
1516 efficiency.

1517
1518 Based on the feedback on the questionnaire included in the STRUBIAS Interim Report, it
1519 was observed that the **techno-scientific literature that correlates plant P-availability,**
1520 **plant P-responses to fertilisation and fertiliser P-solubility for STRUBIAS materials in**
1521 **different extractants is very limited and scattered**. No single extractant or combination of
1522 extractants, seems to allow a clear distinction between "effective" and "ineffective" P
1523 fertilisers. This is not surprising, as also for the more traditional mineral P-fertilisers,

1524 different standards are applied to evaluate the plant P-availability of the wide spectrum of
1525 fertilising materials (e.g. neutral ammonium citrate for manufactured fertilisers, formic acid
1526 for soft phosphate rock). In this respect, it is relevant to note that P-fertilisers developed from
1527 secondary raw materials often have a different chemical composition than those that are
1528 currently on the market, and show low water solubility. Hence, setting exclusive criteria
1529 based on the available evidence **includes a tangible risk for excluding a market entrance**
1530 **for innovative P-fertilisers developed from secondary raw materials**, and thus
1531 undermining possibilities for innovative products that have been developed in line with the
1532 circular economy principles. Also, the STRUBIAS sub-group indicated the limitations of
1533 bioassay tests, from a practical and scientific point of view. Rather, it is preferred to promote
1534 an unlimited assortment of different types of P-fertilisers on the internal market so that
1535 farmers can select products based on their needs and interests. It is assumed that farmers
1536 active on a competitive fertiliser market will select the best products, in line with their
1537 specific settings and needs.

1538
1539 Several **STRUBIAS materials** fulfil specific roles to promote plant growth and increase
1540 agricultural yields, and often **stretch beyond the purpose of solely providing P to plants**.
1541 Examples include P-rich pyrolysis & gasification materials that could address the need for the
1542 recycling of organic matter in agroecosystems, or ashes that contribute to micronutrient plant
1543 nutrition. From this point of view, **it is a more straightforward option to enforce plant P-**
1544 **availability for specific CE products at PFC level**. The omission of requirements on plant
1545 P availability for STRUBIAS materials would be in line with the criteria for the other CMCs.
1546 Setting supplementary requirements for STRUBIAS CMCS may, in contrast, involve **a**
1547 **duplication of criteria at CMC and PFC level**, which is considered undesired by most
1548 members of the STRUBIAS sub-group.

1549
1550 For all these reasons, it is **proposed to set no criteria to regulate plant P availability for**
1551 **STRUBIAS materials if the nutrient value of fertilising products is regulated at PFC**
1552 **level** through product quality or labelling requirements, at least for the current category of
1553 inorganic P-fertilisers. In case no criteria on extractable P-content for inorganic P-fertilisers
1554 would be included at PFC level in the Revised Fertiliser Regulation, this issue should,
1555 however, be re-evaluated at CMC level for STRUBIAS materials.

1556

1557

1558 **5.3 Major issues highlighted by the STRUBIAS sub-group on the Interim Report on**
1559 **the draft proposals for recovery rules**

1560 5.3.1 Scope widening and a principal focus on "safety" criteria

1561 The STRUBIAS sub-group members highlighted the need to broaden the scope of the
1562 STRUBIAS CMC, expanding the eligible input materials and reduce limitations on process
1563 conditions, with the major objective to increase the recycling of nutrients, especially P.

1564

1565 These concerns have been addressed to the best possible extent in the pre-final STRUBIAS
1566 Report, as exemplified by following cases:

1567 ○ The **revision of process and material requirements to ensure that value-added**
1568 **materials that can contribute to nutrient recycling in a circular economy can**
1569 **enter the internal fertilising market.** As outlined in section 5.1, the scope for each
1570 of the STRUBIAS CMC has significantly been expanded by incorporation, for
1571 instance, of phosphate salts other than struvite, and pyrolysis & gasification materials
1572 as produced through hydrothermal carbonisation processes.

1573 ○ A detailed analysis has been performed, tracing P through the food and non-food
1574 chain. **This evaluation enabled to focus the selection on input materials that**
1575 **contain P that can be recycled, where technically and economically possible.** For
1576 "thermal oxidation materials & derivatives", almost all non-hazardous waste materials
1577 can, for instance, be used as input materials. At the same time, other eligible input
1578 materials that show potential for the recycling of other nutrients and organic matter
1579 have been added to the input material lists of "thermal oxidation materials &
1580 derivatives" and "pyrolysis & gasification materials", mostly in line with the proposals
1581 of the STRUBIAS sub-group (but see section 5.3.7).

1582 ○ The proposals for the recovery rules have been developed considering the principle
1583 of a **neutral stance towards existing and future technological developments.** The
1584 production process conditions have been designed with a large focus on the quality of
1585 the end-materials, rather than on the production process conditions. A relevant
1586 example is the use of the H/C_{org} parameter for pyrolysis & gasification materials as a
1587 parameter for C stability instead of imposing strict time-temperature profiles.

1588

1589 At the same time, it should be taken into consideration that under the current proposals
1590 STRUBIAS CMCs could be derived from waste-based materials, for which reason a different
1591 approach is required than for the CMCs already covered in the Commission's proposal for the
1592 Revised Fertiliser Regulation. It is often the case that waste materials are associated to a gate
1593 fee; the receiver of such wastes *receives* a financial retribution for acceptance of possible
1594 STRUBIAS input materials. In contrast, a manufacturer of fertilising materials that contain
1595 other CMCs *spends* financial resources to obtain or extract possible input materials. This is a
1596 very different context. The fundamental principles of environmentally sound waste
1597 management involve that provisions are required to **avoid that materials that do not meet**
1598 **the criteria outlined above could be used in EU fertilising products.** This is especially
1599 important as the **CE mark is associated with the free movement of goods** with only

1600 minimal legislative and administrative procedures associated. It should be ensured that no
1601 backdoors are being incorporated into the EU Fertiliser Regulation to circumvent the waste
1602 status of certain materials. A **relevant example** is the need for a criterion to restrict specific
1603 input materials (e.g. fossil fuels processed in plants other than incineration and biomass
1604 combustion plants) in thermal oxidation materials & derivatives.

1605
1606 Moreover, the recovery rules are **constrained by the existing EU legal framework on**
1607 **associated matters**, such as the Animal By-Products Regulation ((EC) No 1069/2009), the
1608 Waste Framework Directive ((EC) 2008/98/EC) and Directive (EU) 2018/851, or the
1609 REACH Regulation ((EC) No 1907/2006). **Relevant examples** are the exclusion of animal
1610 by-products of category 1 for STRUBIAS production processes (see section 5.3.5), or the
1611 compliance with the conditions for the incineration of waste as laid down in the Industrial
1612 Emissions Directive (2010/75/EU).

1613

1614 5.3.2 Avoid duplication of criteria on CMC and PFC level

1615 The fundamentals underlying the two sets of requirements (i.e. PFC and CMC level
1616 requirements) are given by the fact that **different component materials warrant different**
1617 **process requirements and control mechanisms adapted to their different potential**
1618 **hazardousness and variability**. Component materials for CE marked fertilising products
1619 should therefore be divided into different categories.

1620

1621 In the STRUBIAS Interim Report, there was **a focus on minimum nutrient requirements**
1622 **as a proxy for material purity**. This approach was proposed to ensure that STRUBIAS
1623 material quality and chemical composition are in line with the intended functions of the
1624 fertilising materials. The JRC has addressed this concern of the STRUBIAS sub-group by
1625 shifting the approach for criteria development away from minimum nutrient contents
1626 **towards the direct limitation of elements that are unwanted and could even be unsafe in**
1627 **STRUBIAS materials and the exclusion of certain input materials** (e.g. fossil fuels used
1628 at fossil fuel power plants for thermal oxidation materials & derivatives). These criteria are not
1629 expected to restrict the market for the targeted STRUBIAS materials. Nonetheless, a
1630 minimum P content for precipitated phosphate salts has been maintained in the second set of
1631 draft technical proposals as it is the most straightforward manner to delimit the scope of this
1632 CMC, and avoids compliance schemes that are more costly and complex (e.g. including XRD
1633 measurements to confirm the presence of *phosphate* minerals in the CMC precipitated
1634 *phosphate* salts & derivatives).

1635

1636 The proposals for criteria on the testing of **phosphorus plant availability** using chemical
1637 extractants have been removed since it is now clear that this aspect will most likely be
1638 regulated at PFC level for P-fertilisers (see section 5.2). This is a more apt manner to regulate
1639 this aspect because STRUBIAS materials can have very different intended functions as a
1640 fertilising material, and can thus be used in more than one PFC class. Moreover, the data put
1641 forward by the STRUBIAS sub-group indicated the challenge of relating concentrations of

1642 extractable P to plant P bio-availability due to the limited amount of techno-scientific data
1643 available for STRUBIAS materials.

1644

1645 Limit values for specific **metals and metalloids** have been retained in the criteria at CMC
1646 level, more specifically for thermal oxidation materials & derivatives. The metals and
1647 metalloids regulated at PFC level are restricted to a specific set of elements, more specifically
1648 As, Cd, hexavalent Cr, Hg, Ni, Pb, Cu and Zn. Nonetheless, the production processes of
1649 STRUBIAS materials are specific in the sense that they can concentrate non-volatile metals
1650 and metalloids in the solid residues during thermal conversion and due to the inclusion of
1651 waste-based materials and industrial by-products as eligible input materials. These
1652 observations imply that a **potential risk for the environment and human health exists due**
1653 **to the presence of some less common metals and metalloids in STRUBIAS materials.**
1654 Therefore, a detailed assessment is required as described in sections 5.5.5.1 and 5.6.5.1 for
1655 thermal oxidation materials & derivatives and pyrolysis & gasification materials, respectively.
1656 For the second set of proposals for the STRUBIAS recovery rules, the techno-scientific
1657 comments from the STRUBIAS sub-group on the methodology applied has been reviewed.
1658 Relevant and validated techno-scientific information (e.g. on solid-liquid partition
1659 coefficients for the different metals and metalloids, application rates, percolation fluxes, etc.)
1660 has been taken into account during the revised assessment, and the obtained results have been
1661 further corroborated against environmental and human toxicity studies. This has resulted in
1662 changes on the identity of the metals and metalloids include in the compliance schemes for
1663 the CMCs thermal oxidation materials & derivatives and pyrolysis & gasification materials as
1664 well as their proposed limit values.

1665

1666 5.3.3 The consideration of "intermediates" in fertiliser production processes

1667 As outlined in section 4.2.1, the structure of the Revised Fertiliser Regulation does not enable
1668 that chemical reactions or transformations take place between the different CMCs that are
1669 contained in the CE marked fertiliser. This implies that any chemical or thermochemical
1670 processing steps required to ensure that the materials under consideration **no longer pose a**
1671 **risk for human health or the environment** need to **occur before assessing the possible**
1672 **CMC status.** For instance unprocessed, **raw sewage sludge ashes can, by no means, be**
1673 **considered as a CMC** because further processing would be required before such materials
1674 could be placed on the market as a CE marked product. The recovery rules shall, therefore,
1675 encompass any manufacturing steps required to produce a material that can be used as such
1676 as a fertilising material, i.e. directly without any further processing other than normal
1677 industrial practice. Therefore, **the recovery rules shall describe process and product**
1678 **requirements until the end stage in a manufacturing process of a fertilising material is**
1679 **reached.** Concretely, this involves, for instance, that recovery rules shall include provisions
1680 for post-combustion manufacturing steps on raw sewage sludge ashes, and that product
1681 requirements apply on a triple superphosphate material that is (partially or entire) produced
1682 from incinerated sewage sludge.

1683 The STRUBIAS sub-group highlighted the need to explain better the possibility of "**two-**
1684 **step**" **manufacturing processes** to enable further manufacturing processes on intermediate

1685 materials (e.g. precipitated phosphate salts, ashes). The principle of two-step manufacturing
1686 processes is that a first manufacturing step can be applied to reduce concentrations of specific
1687 contaminants to acceptable levels (e.g. incineration or precipitation to produce materials with
1688 a low level of organic contaminants). In a second step, the obtained intermediate material can
1689 then be further processed using an extensive set of substances/mixtures to a chemically
1690 different material on condition that the risk for re-contamination is controlled. The second
1691 manufacturing step can, for instance, improve the plant availability of the nutrient contained
1692 in the product, or remove inorganic contaminants from the fertilising material.
1693 The second set of draft proposals for the recovery rules has taken these comments into
1694 consideration, and enables the manufacturing of "**derivates**" from precipitated phosphate
1695 salts and thermal oxidation materials (i.e. ashes and slags). Because the process limitations on
1696 the second step of the processes are minimal (e.g. no positive list of chemicals that can be
1697 used), a **large degree of freedom** is given to the manufacturers to apply processes of choice
1698 and to promote the development of innovative processes that start from intermediate
1699 materials. Examples of such processes are thermochemical manufacturing processes starting
1700 from raw ashes, or the chemical transformation of phosphates precipitates - other than Ca and
1701 Mg phosphates – into P fertilisers that are already available on the internal market (example
1702 of a possible future development as exemplified in Wilfert et al (2015)). Note that some
1703 provisions apply to such two-step manufacturing processes in order to avoid that inert
1704 materials are added with the exclusive intention of diluting the contaminants to their
1705 established limit values in this and other EU legislation (see section 5.3.4). This is in line
1706 with the requirements for CMC 1 (virgin materials), where also no limitations are set on the
1707 use of substances and mixtures to produce the CMC material.
1708

1709 5.3.4 The mixing of ashes

1710 **The technology used and the way in which the fertiliser manufacturing installation is**
1711 **designed, built, maintained, and operated impacts upon the emissions of contaminants**
1712 **to the soil originating from STRUBIAS materials that will be incorporated in the CE**
1713 **marked fertilisers.** For ashes, especially the metals and metalloids contained in the ashes are
1714 of main concern for contamination. In simple terms, some post-combustion manufacturing
1715 techniques effectively remove a large share of the contaminants, whereas others remove only
1716 a minor share. As some ashes - e.g. sewage sludge ashes - contain metals and metalloids (e.g.
1717 Pb, Ni, etc.) above the limit values set for inorganic fertilisers at PFC level, production
1718 processes that do not remove and discard metals typically reach the limit values through
1719 "dilution".
1720

1721 The **mixing of waste is common practice in the EU and is recognised as a treatment**
1722 **operation by Annex I and II to the Waste Framework Directive 2008/98/EC** (see
1723 footnotes to operations D13 / R12) (European Commission, 2012). Provision R12 of Annex
1724 II refers, for instance, to the exchange of waste for submission to any of the operations
1725 numbered R 1 to R 11. This provision "can include preliminary operations prior to recovery
1726 including pre-processing such as, inter alia, dismantling, sorting, crushing, compacting,
1727 pelletising, drying, shredding, conditioning, repackaging, separating, blending or mixing

1728 prior to submission to any of the operations numbered R1 to R11 [if no other R codes
1729 apply]". For STRUBIAS materials, especially code R5 is relevant by referring to the
1730 "recycling/reclamation of other inorganic materials". On the other hand, EU legislation also
1731 recognises that individual **waste streams should in principle be kept separate from other**
1732 **wastes and not mixed with the intention of reducing contamination levels and**
1733 **hazardous characteristics in order to meet limit values or to by-pass legal requirements.**
1734 This holds **especially true for hazardous waste** streams as Article 18(1) of the Waste
1735 Framework Directive states that "it shall be ensured that hazardous waste is not mixed, either
1736 with other categories of hazardous waste or with other waste, substances or materials. Mixing
1737 shall include the dilution of hazardous substances". Although Article 18(2) of the same
1738 Directive provides for a possible derogation from this rule, the conditions for such derogation
1739 are quite strict.

1740
1741 The STRUBIAS manufacturing technologies applied to process ashes can be equally applied
1742 to process phosphate rock into a P-fertiliser. Also for the primary raw material phosphate
1743 rock, the quality of the resulting P-fertiliser is highly dependent on the production process
1744 applied, with levels of specific metals (e.g. Cd) in phosphate rock derived P-fertilisers
1745 varying by more than one order of magnitude depending on the process applied (Ecophos,
1746 2018). Nonetheless, the most commonly applied process to convert phosphate rock, the
1747 acidulation process, does not remove metals to a significant extent, and the mixing of input
1748 materials of different quality and metal content is permitted for P-fertilisers derived from
1749 primary raw materials. Hence, demanding the removal of contaminants for P-fertiliser
1750 production processes derived from secondary raw materials may hinder the establishment of a
1751 **level playing field for the fertiliser sector**. In the recently developing market for the P
1752 recovery from secondary raw materials, it remains uncertain to what extent the most
1753 advanced techniques that remove metals from the ashes will become reasonably accessible
1754 under economically and technically viable conditions.

1755
1756 Sincere manufacturers of STRUBIAS materials will certainly **not apply mixing operations**
1757 **with the sole intention of contaminant dilution**; rather the mixing is a prerequisite to ensure
1758 the production of high-quality fertilising materials. The **proposed technical requirements**
1759 **for thermal oxidation materials & derivatives contained in the CE marked fertilising**
1760 **product include provisions to ensure that no long-term increase in the accumulation of**
1761 **metals and metalloids in soils occurs to levels of concern**. Hence, despite a higher metal
1762 return to land for processes that apply a mixing *relative* to processes that remove all
1763 contaminants from the ashes, **human health and environmental protection is de facto and**
1764 **implied through the maximum limits for metals in the revised Fertiliser Regulation**. The
1765 contaminants in the ashes originate largely from the uptake and recycling of metals in the
1766 agro-food system, and do not contribute to a further enrichment of the contaminants in the
1767 environment. Hence, recovery processes – even those relying on the principle of dilution –
1768 will not result in gross imports of new contaminants into the environment, in contrast to
1769 imports from phosphate-rock derived P-fertilisers that are associated to an inflow of metals
1770 from outside Europe. Nonetheless, the landfilling of ashes or their accretion in construction

1771 materials removes the metals from the biogeochemical cycles, at least on condition that it is
1772 assumed these routes are an everlasting sink.

1773

1774 Relative to business-as-usual practices for the handling of sludges in Europe, the route of
1775 producing P-fertilisers through the ash mixing process provides in general benefits through a
1776 reduced exploitation of the primary raw material phosphate rock, but the impacts on
1777 eutrophication, human health and global warming potential depend on the counterfactual use
1778 and handling scenario of the input material (i.e. landfilling versus land spreading of the
1779 sewage sludge; see section 8.8). This example indicates that **the impacts of the mixing of
1780 the ashes relative to current handling scenarios for biogenic wastes on environmental
1781 and human health aspects are not clear-cut and situation-dependent.**

1782

1783 In view of meeting the legislative requirements for waste materials, and more specifically to
1784 comply with Article 10 ["the necessary measures shall be undertaken to ensure that waste
1785 undergoes recovery operations"], Article 13 ["protection of human health and the
1786 environment"] and Article 18 ["it shall be ensured that hazardous waste is not mixed, either
1787 with other categories of hazardous waste or with other waste, substances or materials. Mixing
1788 shall include the dilution of hazardous substances"] of Directive 2008/98/EC, **following
1789 provisions** are proposed with respect to the handling and mixing of waste materials:

1790 ○ The **simple physical mixing of input materials classified as waste with other non-
1791 hazardous and hazardous wastes, substances or materials – i.e. without the
1792 occurrence of a chemical reaction – will not be permitted** as such practices might
1793 enable mixing with the sole intention of reducing contaminant values of waste.
1794 Therefore, it is proposed to refer in the legal requirements for the treatment of waste
1795 to the need to make use of "intermediates" rather than of "substances and mixtures".
1796 Pursuant to Regulation (EC) No 1907/2006, an **intermediate is defined as "a
1797 substance that is manufactured for and consumed in or used for chemical
1798 processing in order to be transformed into another substance"**. The use of this
1799 terminology will prevent that inert materials are added to fertilising materials with the
1800 sole intention of reducing contaminant levels. Therefore, the mixing of wastes with
1801 wastes or other materials should at all times occur with the intention to improve the
1802 quality of the resulting material and plant nutrient availability, to remove
1803 contaminants, or a combination of both. Operations aimed at lowering the
1804 contaminant concentration without lowering the contaminant to nutrient ratio in the
1805 original material should not be allowed.

1806 ○ Manufacturers that use **hazardous wastes** (e.g. sewage sludge ashes with certain
1807 species of Zn; Donatello et al., 2010) within their STRUBIAS production process
1808 **should demonstrate the removal or transformation of the respective hazardous
1809 substances to levels below the limit values as defined in Annex III of Directive
1810 2008/98/EC.**

1811

1812 5.3.5 Link to animal by-products Regulations and alternative processing methods in
1813 STRUBIAS production processes

1814 **Animal by-products are a possible input material for all STRUBIAS material groups**
1815 **and STRUBIAS production pathways** are already observed for precipitated phosphate
1816 salts, thermal oxidation materials & derivatives, and pyrolysis & gasification materials in
1817 Europe. For instance, K-struvites are precipitated from (pre-processed) manure slurries,
1818 poultry manure is incinerated, and animal bone material is pyrolysed.

1819
1820 Any input material of animal origin is subject to the scope of the controls of **Regulation (EC)**
1821 **No 1069/2009**. Products derived from animal by-products referred to in Article 32 of
1822 Regulation (EC) No 1069/2009 for which the end point in the manufacturing chain has not
1823 been determined should not be placed on the market as component materials contained in the
1824 CE fertilising product in accordance with the provisions of the revised Fertiliser Regulation.
1825 Therefore, any input materials of animal origin should be first subject to envisaged regulatory
1826 procedures to defining end points under the Animal By-products Regulation which include
1827 among others the EFSA opinion on the risks to public and animal health of the above-
1828 mentioned component materials (see below).

1829
1830 The possible end point for further use in the Revised EU Fertiliser Regulation will ultimately
1831 be laid down in the animal by-products Regulation, enabling that the Annexes of the Revised
1832 Fertiliser Regulations can refer to animal by-products or derived products for which an end
1833 point in the manufacturing chain has been determined in accordance with the third paragraph
1834 of Article 5(2) of Regulation (EC) 1069/2009. The proposals made in the STRUBIAS report
1835 will, however, make reference to specific materials and processing requirements.

1836
1837 The European Commission can thus lay down further modifications to the permitted use
1838 routes and technical requirements for the handling, treatment, transformation, processing and
1839 storage of animal by-products or derived products in the Animal by-products Regulation.
1840 This Regulation focusses on biological hazards that may be present in the materials. In
1841 addition to these requirements, supplementary requirements can be proposed to ensure
1842 environmental and human health protection (e.g. due to the presence of animal drug residues
1843 in manures) as well to promote the safe handling and storage of EU fertilising materials
1844 derived from animal by-products. At present, Article 32(1) of Regulation (EC) 1069/2009
1845 indicates that organic fertilisers and soil improvers may be placed on the market and used
1846 provided:

- 1847 (a) they are derived from category 2 or category 3 material;
- 1848 (b) they have been produced in accordance with the conditions for pressure sterilisation or
1849 with other conditions to prevent risks arising to public and animal health, in accordance
1850 with the requirements laid down pursuant to Article 15 and any measures which have
1851 been laid down in accordance with paragraph 3 of this Article;
- 1852 (c) they come from approved or registered establishments or plants, as applicable; and
- 1853 (d) in the case of meat-and-bone meal derived from Category 2 material and processed
1854 animal proteins intended to be used as or in organic fertilisers and soil improvers, they
1855 have been mixed with a component to exclude the subsequent use of the mixture for
1856 feeding purposes and marked when required by measures adopted under paragraph 3.

1857 In addition, digestion residues from transformation into biogas or compost may be placed on
1858 the market and used as organic fertilisers or soil improvers.

1859
1860 The STRUBIAS report can – based on robust techno-scientific evidence - **propose**
1861 **alternative conditions and technical requirements** for the handling, treatment,
1862 transformation, processing and storage of animal by-products or derived products and
1863 conditions for treatment of waste water based on techno-scientific evidence. In the latter case
1864 and if considered pertinent at a later stage by the Commission and the legislators, any
1865 alternative proposed method shall be assessed in line **with the procedure indicated in**
1866 **Article 20 of Regulation (EC) 1069/2009**. This involves, amongst others, an assessment by
1867 the European Food Safety Authority (EFSA) to evaluate risks associated with the food chain.
1868 EFSA collects and analyses existing research and data and provides scientific advice to
1869 support decision-making by risk managers responsible for making decisions or setting
1870 legislation about food safety.

1871
1872 Alternative methods should comply with the condition that sufficient evidence is available **to**
1873 **indicate that the alternative method provides a degree of protection that is at least**
1874 **equivalent, for the relevant category of animal by-products, to the processing methods**
1875 **that are currently laid down**. In this respect, following aspects are deliberated and ensuing
1876 measures are proposed for the use of animal by-products and derived materials in the
1877 STRUBIAS technical proposals:

- 1878 1) The JRC is not aware of any authorisation by the European Commission for the use of
1879 Category 1 animal by-product materials for the production of fertilising materials to be
1880 used in the food production system. Therefore, at present, **Category 1 animal by-**
1881 **product material is not further considered as input material for the present study**.
- 1882 2) The STRUBIAS sub-group and STRUBIAS interim reports have **indicated that a share**
1883 **of the STRUBIAS production pathways use animal by-products as input materials**
1884 **(i) that are already processed by the rendering industry in line with the processing**
1885 **methods (pressure sterilisation) or (ii) are digestion residues from transformation**
1886 **into biogas or compost. Both can under the current regulatory framework already**
1887 **be placed on the market as (organic) fertilisers**. Therefore, it is proposed that these
1888 processed materials can be **used, without further restrictions to control for biological**
1889 **hazards, as input materials for STRUBIAS production pathways**.
- 1890 3) There is also an interest from the STRUBIAS sub-group to rely on three different
1891 production processes that are currently not permitted as standard use methods in the
1892 Animal By-products Regulation provisions for international trade:
- 1893 i. Unprocessed manure as input material for precipitated phosphate salts;
 - 1894 ii. Unprocessed manure as input material for pyrolysis & gasification
1895 materials;
 - 1896 iii. Unprocessed animal by-products of Category 2 and 3, including manure,
1897 for thermal oxidation materials & derivates.

1898 Therefore, **alternative conditions and technical requirements** for the handling,
1899 treatment, transformation, processing and storage of the materials resulting from such
1900 materials are proposed as follows:

1901

1902 i. Unprocessed manure as input material for precipitated phosphate salts

1903 Manure, digestive tract content separated from the digestive tract, (raw) milk, milk-based
1904 products and colostrum classified as category 2 and category 3 materials pursuant to
1905 Regulation (EC) 1069/2009 does not require a specific treatment for hygienisation if the
1906 competent authority does not consider it a risk for the spreading of serious transmissible
1907 diseases; it can be applied to land in unprocessed form. However, **the placing on the market
1908 of processed manure, derived products from processed manure and guano from bats is
1909 subject to the requirements laid down in Annex XI (Chapter I, section 2) of Regulation
1910 (EU) 142/2011.** The standard processing method that such materials must undergo includes a
1911 heat treatment process of at least 70 °C for at least 60 minutes and they shall have been
1912 subjected to reduction in spore-forming bacteria and toxin formation, where they are
1913 identified as a relevant hazard. Nonetheless, the competent authority may authorise the use of
1914 other standardised process parameters than those referred to above, **provided that such
1915 parameters ensure the minimising of biological risks.** This involves, amongst others, the
1916 identification and analysis of possible hazards, a validation of the intended process by
1917 measuring the reduction of viability/infectivity of endogenous indicator organisms, including,
1918 for instance, *Enterococcus faecalis*, thermoresistant viruses such as parvovirus, parasites such
1919 as eggs of *Ascaris sp.*, *Escherichia coli*, *Enterococcaceae*, and *Salmonella*.

1920 Based on the assessment of the biological and other risks as outlined in section 5.4.5.2, it is
1921 proposed that manure, non-mineralised guano, and digestive tract content can be used as an
1922 eligible input material for production processes without prior processing on condition that
1923 precipitated phosphate salt has:

- 1924
- A maximum organic carbon content of 3% of the dry matter content¹⁸,
 - No presence of *Clostridium perfringens* in a concentration of more than 100
1926 CFU/g fresh mass and the absence of viable *Ascaris* eggs in a 25 g fresh mass
1927 sample of the precipitated phosphate salt.

1928 By way of derogation, the testing on *C. perfringens* and *Ascaris sp.* shall not
1929 be necessary for materials that have undergone following conditions:

- 1930
- Pressure sterilisation through the heating to a core temperature of more
1931 than 133°C for at least 20 minutes without interruption at an absolute
1932 pressure of at least 3 bars. The pressure must be produced by the
1933 evacuation of all air in the sterilisation chamber and the replacement of
1934 the air by steam (‘saturated steam’);
 - A processing step in a pasteurisation/hygenisation unit that reaches a
1935 temperature of 70 °C during the time of at least one hour.
- 1936
- 1937

¹⁸ As measured using vacuum drying at 40°C, CEN method under development.

1938 The rationale for proposing the conditions on maximum organic carbon content and
1939 supplementary microbial testing **relate predominantly to concerns associated to the**
1940 **release of antimicrobial residues with a high affinity for organic matter (e.g.**
1941 **tetracycline, sulphonamides) and the spreading of antibiotic-resistant bacteria (e.g.**
1942 **spore forming bacteria and other bacterial species).** The maximal limits for organic
1943 carbon, *C. perfringens* and *Ascaris* eggs can be met in the production process, even without
1944 supplementary processing steps. However, for materials resulting from manufacturing
1945 processes that include operations that ensure the effective elimination of biological pathogens
1946 (e.g. anaerobic digestion plus pasteurisation, thermal hydrolysis), exemptions are proposed
1947 for microbial testing. We refer to section 5.4.5.2 for a detailed discussion on the topic.

1948
1949 ii. Unprocessed manure as input material for pyrolysis & gasification
1950 materials

1951 Similar to precipitated phosphate salts, there is an interest from the STRUBIAS sub-group to
1952 use unprocessed manure as an input material to pyrolysis & gasification processes. Given the
1953 legal framework on the use of processed manure as outlined above for precipitated phosphate
1954 salts, an assessment has been performed of the impact of pyrolysis/gasification processes on
1955 biological and other hazards (see section 5.6.5). It was indicated that biological hazards are
1956 typically removed through the application of dry or wet heat under the time-temperature
1957 profiles applied in pyrolysis and gasification production processes. Pyrolysis/gasification
1958 processes are likely to significantly reduce or even remove the dominant antimicrobial
1959 substances that could be present in manures, such as tetracycline. Therefore, **it is proposed**
1960 **that manure, non-mineralised guano, and digestive tract content can be used as an**
1961 **eligible input material for pyrolysis production processes without prior processing.**

1962 As some pyrolysis and gasification processes are in agreement with the hygienisation steps to
1963 prevent risks as laid down pursuant to Article 15 and any measures which have been laid
1964 down in accordance with paragraph 3 of this Article of Regulation (EC) No 1069/2009 (e.g.
1965 hydrothermal carbonisation techniques apply a similar or even more stringent pressure
1966 sterilisation process than the processing method 1 described in Chapter III of Annex IV of
1967 Regulation (EU) 421/2011), it is proposed that pyrolysis & gasification derived from animal
1968 by-products of category 2 and 3 should undergo one of the following treatments at a stage
1969 prior to or during the pyrolysis & gasification material production process: (i) pressure
1970 sterilisation, (ii) Brookes' gasification process as described in point E, section 2, chapter IV,
1971 of Annex IV of Regulation (EU) No 142/2011

1972
1973 iii. Unprocessed animal by-products, including manure, for thermal oxidation
1974 materials & derivatives.

1975 The combustion at 850°C provides an equivalent or superior degree of protection to the
1976 processing methods set out in Chapter III of Annex IV for category 2 and 3 animal by-
1977 products. Above temperatures of 120°C, minimal thermal death times are required to
1978 inactivate biological pathogens that could be present in category 2 and 3 animal by-products,
1979 even under dry conditions. Moreover, the combustion at >850°C provides an effective
1980 manner to remove organic chemical pollutants that could be present in the animal by-

1981 products. **Therefore, it is proposed to place animal by-products of category 2 and 3 on**
1982 **the positive list of eligible input materials and to adhere to the operating conditions as**
1983 **laid down in Article 50 of the Industrial Emissions Directive for the processing of these**
1984 **materials, without the need for an additional hygienisation step prior to combustion.**
1985 The combustion conditions are in line with Regulation (EU) No 592/2014 that amends
1986 Regulation (EU) 142/2011, indicating the processing method for poultry litter through
1987 combustion in on-farm combustion plants. It is proposed that (1) these combustion conditions
1988 could apply as a processing method for all types of animal by-products of category 2 and 3,
1989 and (2) to all types of combustion plants, regardless of their maximum capacity and location
1990 on or off-farm, as long as they are compliant with the necessary hygiene standards as laid
1991 down in Regulation (EU) No 592/2014 and emission limit values depending on their capacity
1992 (e.g. Medium Combustion Plant (MCP) Directive, (EU) 2015/2193).

1994 5.3.6 Limits for bulk organic C for precipitated phosphate salts

1995 The proposal for the 3% limit value for organic C in precipitated phosphate salts & derivatives
1996 was supported by some STRUBIAS sub-group stakeholders, but questioned by others due to
1997 the lack of solid techno-scientific data to support the need for such a criterion on bulk carbon.
1998 In the second set of draft proposals, the limit value of 3% is maintained for precipitated
1999 phosphate salts & derivatives.

2000
2001 The main reason for maintaining the original proposal is the fact that the **knowledge base for**
2002 **environmental and safety aspects is dominantly built on precipitated phosphate salts of**
2003 **high purity** (section 5.4.5), and that **solid techno-scientific evidence indicates an inverse**
2004 **relationship between environmental and human health risks and material purity.** The
2005 organic C is not only an impurity, but also a vector for the adsorption of impurities, and thus
2006 an excellent proxy for the purity of the precipitated phosphate salt. The precipitation process
2007 lacks a robust treatment step to remove organic pollutants and the risks associated to the
2008 precipitated salts are thus positively correlated to the amount of impurities that are co-
2009 precipitated. Therefore, it is proposed to add organic C as a parameter, together with other
2010 particular organic and biological indicators (e.g. PAH, *Clostridium perfringens*, etc.), in the
2011 compliance scheme for this CMC.

2012
2013 The precipitation process involves the formation of a separable solid substance from a
2014 solution by converting the substance into an insoluble form through the addition of
2015 chemicals. Due to the nature of the process, the probability of incorporating dissolved
2016 impurities in the precipitated phosphate salt is relatively low as the precipitate is formed
2017 through the reaction of *dissociated, free* floating ions in solution that react with one another.
2018 For instance, Mg^{2+} and NH_4^+ react with PO_4^{3-} ions to create a struvite salt that can precipitate.
2019 Rather, the impurities become part of the precipitated phosphate salts because of the
2020 incomplete separation of the precipitate from the sludge or liquefied matrix that contains
2021 particulate or suspended impurities. Organic components have a large adsorption capacity for
2022 impurities owing to their large surface area and micro porous structure. Moreover, some
2023 organics are contaminants that make up a significant share of the organic carbon. Metals,

2024 specific pharmaceuticals (e.g. sulfonamides and tetracyclines) and biological pathogens are,
2025 for instance, dominantly present in the organic matrix of the sludge (Karvelas et al., 2003;
2026 Lou et al., 2018; Ye et al., 2018). Therefore, the organic carbon content in precipitated
2027 phosphate salts is positively correlated to the accumulation of impurities in the form of
2028 antibiotics (Ye et al., 2018), and other impurities have mainly been found in precipitated
2029 phosphate salts with an organic C content of >3% (STOWA, 2015). **The relationship**
2030 **between organic C content and the level of impurities is thus evident and demonstrated**
2031 **from a theoretical and experimental point of view.** The limit value of 3% is proposed
2032 because it is the upper limit for most of the precipitated phosphate salts that have been
2033 evaluated in the risk assessment for this CMC. The limit also imposes a reduction of one
2034 order of magnitude in organic C relative to unprocessed manure and sewage sludge.

2035
2036 The proposal of the 3% limit value enables in turn to propose a **minimal compliance scheme**
2037 for this CMC that effectively excludes the extensive and expensive testing for a broad range
2038 of organic contaminants (e.g. pharmaceutical compounds and personal care products,
2039 phthalates, surfactants, etc.), and strengthens **market confidence** in fertilising materials
2040 recovered from biogenic wastes in times of increased concerns about emerging organic
2041 contaminants in consumer products and the food chain. Hence, it is indicated that the
2042 inclusion of the proposed organic C limit of 3% can effectively contribute to a robust and
2043 stable legal framework. We further refer to section 5.4.5.1 for a detailed discussion on this
2044 topic.

2045

2046 5.3.7 Organic carbon content in ashes from biomass combustion plants

2047 The conditions for the incineration of waste as laid down in the **Industrial Emissions**
2048 **Directive 2010/75/EU** contain stringent temperature requirements of **850°C for more than 2**
2049 **seconds** or more than 1100°C for more than 0.2 seconds. Moreover, waste incineration plants
2050 shall be operated in such a way as to achieve a level of incineration **such that the total**
2051 **organic carbon content of slag and bottom ashes is less than 3%** or their loss on ignition
2052 is less than 5 % of the dry weight of the material. For materials other than waste within the
2053 meaning of Directive 2008/98/EC, such as plant-based materials, those strict conditions only
2054 apply to the largest combustion plants (>50 megawatt (MWth); Industrial Emissions
2055 Directive (IED)), but not to smaller plants (i.e. those covered under Regulation (EU)
2056 2015/1189 on ecodesign requirements for solid fuel boilers or under the Medium Combustion
2057 Plant (MCP) Directive).

2058

2059 Those Directives ensure the implementation of the obligations arising from the Gothenburg
2060 Protocol under the UNECE Convention on Long-Range Transboundary Air Pollution.
2061 Therefore, the primary focus of the abovementioned pieces of **legislation is on the emissions**
2062 **to the atmosphere, rather than on the characteristics of the solid material (i.e. soot, fly**
2063 **and bottom ashes, charred materials, etc.) remaining in the boiler or combustion plant.**
2064 As a matter of fact, the current fate of these materials after combustion involves its use in
2065 non-agricultural sectors (e.g. construction materials, or landfilling). For its use in a CE
2066 marked fertilising product that is not subject to further management controls and restrictions,

2067 a detailed assessment on the risks associated to human health and the environment should
2068 therefore be performed.

2069

2070 Certain materials, such as residues from agriculture and forestry, **are inherently low in**
2071 **organo-chemical pollutants for which reason stringent time temperature profiles are**
2072 **neither required to ensure the destruction of pollutants in the material, nor**
2073 **proportionate considering the limited risks for emissions of certain persistent organic**
2074 **pollutants.**

2075

2076 Most residue management regulations use the organic C as a key parameter indicating the
2077 degree of organic contaminant removal as organic carbon serves as a reactive surface for the
2078 adsorption of possible contaminants, such as volatile and persistent organic pollutants
2079 (Vehlow et al., 2006). Due to the incomplete combustion of organic matter and the possibility
2080 of using biomass of a high chlorine content, **organic pollutants**, such as for instance volatile
2081 organic carbon and polychlorinated biphenyls, can be formed and can remain in the
2082 combustion residue. In addition, information on the possible environmental risks related to
2083 the possible presence of **water-soluble and insoluble organic contaminants is lacking.**
2084 Biomass ashes can contain organic aromatic structures, condensed refractory biomass and
2085 char-like particles, and some biomass ashes thus show similarities to the materials obtained
2086 from pyrolysis and gasification processes.

2087

2088 The proposal is therefore:

2089 ○ The **strict time temperature profiles** with temperatures $>850^{\circ}\text{C}$ shall only apply to
2090 all eligible input materials, other than **certain plant-based materials.**

2091 ○ To limit the CMC “thermal oxidation materials & derivatives” to materials that are
2092 oxidised in such a way that the **total organic carbon content of the slags and**
2093 **bottom ashes is less than 3%, regardless of the input material applied.** This
2094 implies that partially oxidised materials shall not be allowed for this CMC and that
2095 also ashes from certain plant-based materials should meet this criterion. Possibly,
2096 such ashes of higher organic C shall be subject to further re-burning to levels below
2097 $<3\%$. Biomass that is combusted or gasified under (oxygen-limiting) conditions that
2098 results in the presence of **unburnt organic matter** (organic C content $> 3\%$) could
2099 possibly also make an entry in the CMC “**pyrolysis & gasification materials**”. The
2100 testing regime of the latter category is somewhat different than for “thermal oxidation
2101 materials & derivatives” because of the need for additional testing on specific
2102 contaminants (e.g. volatile organic carbon).

2103

2104 5.3.8 Sewage sludge as an input material for pyrolysis & gasification materials

2105 The proposal has been made by the STRUBIAS sub-group to include sewage sludge as an
2106 input material for pyrolysis & gasification materials.

2107

2108 Sewage sludge may contain a set of organic pollutants, including not only persistent organic
2109 pollutants (PAH, PCB, PCDD/F), but also a broad set of organic emergent pollutants such as

2110 phthalates (e.g. di (2-ethylhexyl) phthalate (DEHP)), surfactants present in cleaners and
2111 detergents (e.g. linear alkylbenzene sulphonates (LAS) and nonylphenols (NPE)), personal-
2112 care products, pharmaceuticals and endocrine-disrupting compounds (sulphonamides,
2113 galaxolide, etc.) and polymers used to bind solid particles in solid-liquid separation
2114 processes. Given the potential risks associated to these substances, **there are significant**
2115 **public and governmental concerns related to the recycling of sewage sludges in the**
2116 **European food chain. The spectrum of emerging contaminants in sewage sludge is**
2117 **extensive (Petrie et al., 2015), and much broader than for any of the eligible input**
2118 **materials for pyrolysis & gasification materials.** Whereas some of the above-mentioned
2119 contaminants can certainly be degraded under oxidative conditions at high temperatures, the
2120 necessary techno-scientific evidence is lacking that demonstrates their removal under
2121 oxygen-limiting and reducing conditions. It is known that stringent temperature/time
2122 pyrolysis profiles (>550°C, > 20 min) induce a weight loss in pyrolysis & gasification
2123 materials due to burning out of organic compounds (Deydier et al., 2005b; Koutcheiko et al.,
2124 2007; Ro et al., 2010; Marculescu and Stan, 2012), but **the knowledge base of studies that**
2125 **assessed the proportional removal of specific organic pollutants is limited and restricted**
2126 **to only few organic pollutants.** Limitations in the potential of dry and wet
2127 pyrolysis/gasification processes to remove organic pollutants have been observed for organic
2128 contaminants like nonylphenol, chlorinated aromatic fractions and specific veterinary
2129 antibiotics (Weiner et al., 2013; Ross et al., 2016; vom Eyser et al., 2016). Moreover, the
2130 mechanisms, nature and soil residence times of any decay products that could be formed
2131 remain unclear, and possibly metabolites can have differential toxicity from the parent
2132 compound (Weiner et al., 2013; Ross et al., 2016; vom Eyser et al., 2016). Whereas high
2133 temperatures can effectively transform contaminants in the gaseous phase, these could also
2134 potentially be re-adsorbed on the organic carbon and soot particles that show a high
2135 adsorption potential for contaminants (Mätzing et al., 2001). As indicated in the latest draft of
2136 the Best Available Techniques (BAT) reference document for waste incineration under the
2137 Industrial Emissions Directive (IED, 2010/75/EU) (European Commission, 2017c), **the**
2138 **pyrolysis of sewage sludge is a rather new method and not a widely proven technique**
2139 **for the treatment of waste materials.** Thus, there is no adequate and long-term experience
2140 that indicates the suitability of pyrolysis methods to ensure the effective removal of the broad
2141 spectrum of organic pollutants that could be present in waste materials like sewage sludge
2142 (European Commission, 2017c). For this reason, pyrolysis and gasification are only permitted
2143 thermal treatment methods on condition that the substances resulting from a pyrolysis,
2144 gasification or plasma process are subsequently incinerated, according to recitals 40 and 41,
2145 as well as Article 42 of the Industrial Emissions Directive.

2146
2147 Given that the solid residue quality is dependent on the process temperature (European
2148 Commission, 2017c), **the inclusion of sewage sludge on the positive input material list**
2149 **would also involve a complex compliance scheme for this CMC, stringent**
2150 **time/temperature profile conditions to ensure a breakdown of bulk organic composites,**
2151 **or a combination of both.** Because of the heterogeneous nature of organic compounds, the
2152 compliance cost would considerably increase (e.g. GC-MS measurements). Moreover, it may
2153 be challenging for the STRUBIAS sub-group to reach agreement on the identity of the

2154 organic compounds that should be included in the compliance scheme as well as on safe limit
2155 values for many of these emerging organic compounds.

2156

2157 Research findings from the last decade indicate that pyrolysis & gasification materials
2158 derived from sewage sludge will not meet the limit values for toxic metals (especially Cd,
2159 Cu, Pb, Ni, Zn) at PFC level (He et al., 2010; Hossain et al., 2010; Gascó et al., 2012;
2160 Méndez et al., 2012; Van Wesenbeeck et al., 2014; Lu et al., 2016). Heavy metals are
2161 predominantly recovered in the solid matrix (char) during the pyrolysis/gasification process,
2162 and thus hardly any metal removal takes place during the pyrolysis/gasification process
2163 (Tomasi Morgano et al., 2018). Rather, toxic metals become more concentrated in pyrolysis
2164 & gasification materials, and no post-pyrolysis/gasification processes are described to remove
2165 the inorganic contaminants. Whereas this is an often reported argument to exclude sewage
2166 sludge as an input material, the JRC believes that cost-effective compliance schemes on the
2167 output material could effectively control for toxic metals/metalloids. Nonetheless, **it is**
2168 **unlikely that pyrolysis & gasification materials derived from sewage sludge can make**
2169 **up an important share of the pyrolysis & gasification materials on the internal market,**
2170 unless the limit values for toxic metals are respected through the mixing with other
2171 component materials. The limited market viability of pyrolysis & gasification materials
2172 derived from sewage sludge might be further undermined by the fact that the plant bio-
2173 availability of phosphorus in such materials remains largely unknown. The plant nutrient
2174 availability in pyrolysis & gasification materials is controlled by the coordinated cations
2175 present (Al, Fe, Ca, Mg) (Ippolito et al., 2015). As some sewage sludges are enriched in Al
2176 and Fe, relative to other nutrient-rich input materials such as manure, a reduction in the plant
2177 nutrient availability can be expected for sewage sludge-derived pyrolysis & gasification
2178 materials relative to their manure-derived counterparts. Therefore, the uncertainty associated
2179 to the plant availability of the nutrients present in sewage sludge-derived pyrolysis &
2180 gasification materials is a concern, especially as the STRUBIAS sub-group indicated a lack
2181 of satisfactory chemical testing methods to evaluate plant nutrient and P availability in
2182 STRUBIAS materials.

2183

2184 In conclusion, there are two fundamental problems that have led the JRC to take its present
2185 position of not proposing sewage sludge on the positive input material list for pyrolysis &
2186 gasification materials in this second draft report. First, **the necessary science of the impacts**
2187 **on human health and the environment is not in place for organic contaminants, nor is**
2188 **the presumption of non-adverse impacts confirmed by techno-scientific evidence**
2189 **collected by the STRUBIAS sub-group for sewage sludge-derived pyrolysis &**
2190 **gasification materials.** Second, in view of the limited market potential for sewage sludge
2191 derived pyrolysis & gasification materials, **the risk to undermine consumer confidence in**
2192 **pyrolysis & gasification materials in general and to increase complexity in the**
2193 **compliance scheme for the CMC group is so large that it presently distorts the**
2194 **evaluation of any other factors involved in the assessment.** The possible benefit of adding
2195 sewage sludge on the input material list is simply too low to counterbalance any eventual loss
2196 in consumer confidence for pyrolysis & gasification materials, and by extension, fertilising
2197 materials derived from waste. This proposal is in line with the non-acceptance of

2198 contaminated input materials, including sewage sludge, for pyrolysis & gasification materials
2199 according to voluntary standardisation schemes (EBC, 2012) and national legal frameworks
2200 (Meyer et al., 2017). Moreover, it should be noted that, in view of the very local nature of
2201 certain product markets, EU Member States can still rely on the principle of optional
2202 harmonisation to make available non-harmonised fertilisers on the market in accordance with
2203 national law. Finally, the proposals in this document provide two other avenues for the safe
2204 recovery of valuable fertilising elements from sewage sludge, via precipitation of phosphate
2205 salts or thermal oxidation.

DRAFT - WORK IN PROGRESS

2206 **5.4 Precipitated phosphate salts & derivates**

2207 5.4.1 Scope delimitation and possible uses

2208 The **recovery and recycling of phosphate through precipitation processes aims at**
2209 **reducing the dependence on phosphate rock as a critical raw material**, the ultimate
2210 primary raw material of all the P cycling through the food and non-food system. Precipitated
2211 phosphate salts may contain also other plant nutrients (Ca, N, Mg, etc.), but their recycling is
2212 of a lesser concern as these elements are not present on the list of critical raw materials. The
2213 scope of the CMC is outlined in section 5.1.1.

2214
2215 The current **legal framework for precipitated phosphate salts or struvite-like recovered**
2216 **materials varies across the different EU Member States** (Dikov et al., 2014; De Clercq et
2217 al., 2015; ESPP, 2017). Precipitated phosphate salts can be legally used as a **fertiliser** in the
2218 Netherlands, Belgium, Germany, France, Denmark and the UK. As a general rule, the
2219 material needs to comply with maximum limit values for inorganic contaminants (As, Cd, Cr,
2220 Cu, Hg, Pb, Ni, Zn), biological pathogens and minimum nutrient contents in most Member
2221 States, while some countries also have maximum limit values for organic contaminants
2222 (PAH, PCDD/F, HCH, aldrin, dieldrin, endrin, isodrin, DDT+DDD+DDE and mineral oil)
2223 based on the dry matter or the nutrient content of the fertiliser. The legislation in the
2224 Netherlands explicitly refers to sewage sludge as an input material for precipitated
2225 phosphates, but makes no mention of the recovery of phosphate salts from other input
2226 materials. Additionally, a cross-border mutual recognition initiative for struvite between the
2227 Netherlands, Flanders (Belgium) and France is under development (North Sea Resources
2228 Roundabout). **No voluntary standards for struvite have been agreed so far.**

2229
2230 The proposed framework of the Revised Fertiliser Regulation enables that CMCs can be used
2231 in a PFC category of choice. Nonetheless, precipitated phosphate salts & derivates are likely
2232 to be contained in CE fertilising products of **Product function Category I – Fertilisers,**
2233 **thanks to their high P content.**

2234

2235 5.4.2 Input materials and reactants

2236 5.4.2.1 Targeted input materials

2237 Nutrient recovery as phosphate salts is restricted to liquids and slurries and the separated
2238 fractions of those materials (e.g. the liquid digestate fraction after anaerobic digestion). As a
2239 matter of fact, piloting and operational facilities that manufacture precipitated phosphate salts
2240 are mainly installed at **municipal waste water treatment plants** and, to a smaller extent, at
2241 sites from the **agri-food processing industry (mostly potato and dairy)**. A small amount of
2242 operational and piloting plants recover nutrients as phosphate salts from energy crop plants,
2243 and **chemical industry waste streams** (pharmaceutical industry). At small-scale (laboratory)
2244 installations, P-recovery from **bio-waste digestates** and **other food processing industries**
2245 (e.g. rendering industry) have been documented. These material streams comprise the overall
2246 share of the P that is dissipated in liquid or slurrified state in the EU (see section 14).

2247

2248 Also animal by-products of category 2 and 3 can be used for the production of precipitated
2249 phosphate salts, as follows:

2250 • The precipitation of pure Ca and Mg-phosphates from complex matrices like **manure**
2251 is challenging, although recent progress has been made (Huang et al., 2015).
2252 Therefore, the implementation of nutrient recovery processes from **manure and**
2253 **livestock stable slurries** is limited, with the recovery of K-struvite from veal calf
2254 manure being the only process that is operational (Stichting Mestverwerking
2255 Gelderland; Ehlert et al, 2016a). Nonetheless, a substantial interest and potential
2256 exists to recover P from manure and livestock stable slurries through P-precipitation
2257 (e.g. BioEcoSim phosphate salt precipitation process). Additionally, there is an
2258 interest within the STRUBIAS sub-group to manufacture precipitated phosphate salts
2259 from fish excreta and sludges. As outlined in section 5.3.5, **the placing on the**
2260 **market of processed manure, derived products from processed manure and**
2261 **guano from bats is subject to the requirements laid down in Annex XI (Chapter**
2262 **I, section 2) of Regulation (EU) 142/2011.** These requirements indicate that manure
2263 should undergo a hygienisation treatment or, alternatively, that the processed manure
2264 material should demonstrate compliance with a set of microbial standards (e.g.
2265 *Ascaris* eggs, spore-forming bacteria, viruses, etc.), if authorised by the competent
2266 authority. STRUBIAS production processes are at times not compliant with the
2267 standard processing methods ("a heat treatment process of at least 70 °C for at least 60
2268 minutes and they shall have been subjected to reduction in spore-forming bacteria and
2269 toxin formation"). Nonetheless, some STRUBIAS production pathways may even
2270 provide an equal level of environmental protection as the standard processing method
2271 (STOWA, 2016). Therefore, it is proposed that unprocessed manure can be used as an
2272 input material for the production of precipitated phosphate salts on condition that the
2273 end-material that will be incorporated in a CE marked fertilising product is *either*
2274 compliant with a set of microbiological requirements *or* has been subject to specific
2275 standard processing methods (see section 5.3.5 and section 5.4.5). If accepted by the
2276 Commission, such a proposal could possibly avoid the default implementation of
2277 energy and cost-intensive hygienisation steps in the production process, and provide
2278 an equal or higher level of environmental protection than the current requirements laid
2279 down in the implementing Regulation (EU) 142/2011.

2280 • Other animal by-products of category 2 and 3 can in theory also be used for the
2281 production of precipitated phosphate salts (e.g. residues from gelatin production
2282 processes, digestates of rest materials from heat-processed animal by-products in the
2283 rendering industry, etc.). These types of materials are typically **residues from the**
2284 **rendering industry and have thus already undergone a treatment process in line**
2285 **with the requirements laid down in the Animal By-products Regulation** (e.g.
2286 pressure sterilisation). Therefore, these materials have already "reached the end point
2287 in the manufacturing chain" according to Regulation (EC) 1069/2009, and can under
2288 the existing legal framework already be used for production of organic fertilisers and
2289 soil improvers.

2290 Considering the proposed different testing requirements and compliance schemes in the
2291 second set of draft proposals for STRUBIAS materials, it is proposed to separate manure,

2292 non-mineralised guano, and digestive tract content from the other animal by-products on the
2293 list of input materials.

2294

2295 Following materials from the food processing industry show a significant potential for P-
2296 recovery in the form of precipitated phosphate salts:

2297 ○ **Waste from potato processing facilities is suitable for phosphate recovery**
2298 **since the wastewater contains large amounts of phosphate.** During preparation
2299 of the prebaked frozen product, potatoes are treated with sodium acid
2300 pyrophosphate ($\text{Na}_2\text{H}_2\text{P}_2\text{O}_7$) after the blanching treatment. Sodium acid
2301 pyrophosphate is needed to complex iron (Fe^{2+}). In this way sodium acid
2302 pyrophosphate prevents that iron in the potato reacts with chlorogenic acid during
2303 the heating processes (Rossell, 2001). The oxidation of the Fe^{2+} -chlorogenic acid
2304 complex by oxygen from the air would otherwise result into a grayish-colored
2305 substance that causes after-cooking gray discoloration (Rossell, 2001). The
2306 blanching treatment also causes leaching of phosphate from the potatoes, but no
2307 known contaminants are formed during the reaction.

2308 ○ Many processing plants produce sludge from the extraction processes of the crop
2309 part of interest. **Sugar mills** produce wastewater, emissions and **solid waste from**
2310 **plant matter and sludges** (Hess et al., 2014). The technique applied for sugar
2311 extraction from plant tissues has an impact on the volumes of water used
2312 (consumed and polluted) to produce sugar (Bio Intelligence Service -
2313 Umweltbundesamt - AEA, 2010). Considering the high nutrient contents of the
2314 beet, the molasses and waste waters generated during the sugar beet processing
2315 are also rich in N and P (Gendebien et al., 2001; Buckwell and Nadeu, 2016).
2316 Gendebien et al. (2001) indicated, for instance, effluent P concentrations of > 100
2317 $\text{mg PO}_4^{3-}\text{-P L}^{-1}$. During the further processing and the fermentation of molasses in
2318 the **brewery industry**, vinasses and wastewater may be generated from the
2319 cleaning of chemical and biochemical reactors (for mashing, boiling, distillation,
2320 fermentation and maturation) and solid-liquid separations (separation and
2321 clarification).

2322 ○ **Dairy wastewaters** contain milk solids, detergents, sanitisers, milk wastes, and
2323 cleaning waters from intermediate clean-up operations at the different processing
2324 steps (storage, pasteurisation, homogenisation, separation/clarification, etc.).

2325

2326 By using and producing plant and edible food materials as starting materials, also certain
2327 **food processing industry** waste streams and wastewaters are intrinsically of low risk as long
2328 as the origin and additives of the waste water components and the processing steps that may
2329 lead to contamination of the stream are controlled. After all, Commission Regulation (EU)
2330 No 1130/2011 includes a list of authorised additives approved for use in food additives,
2331 enzymes and flavourings, and substances of concern are thus effectively prohibited by law.
2332 Nonetheless, a significant proportion of the wastewaters are originating from the washing of

2333 installations. Typical **cleaning agents** used in the food-processing industry sector are
2334 (European commission, 2006a):

- 2335 • alkalis, e.g. sodium and potassium hydroxide, metasilicate, sodium carbonate;
- 2336 • acids, e.g. nitric acid, phosphoric acid, citric acid, gluconic acid;
- 2337 • pre-prepared cleaning agents containing chelating agents such as EDTA, NTA,
- 2338 phosphates, polyphosphates, phosphonates or surface-active agents;
- 2339 • oxidising and non-oxidising biocides.

2340 **The use of chelating agents and biocides may hamper nutrient recovery as the**
2341 **contaminants may be transferred to the recovered material.** The use of detergents in the
2342 EU is controlled through Regulation (EC) No 648/2004 that only enables the use of
2343 biodegradable detergents. Moreover, recent research indicated that common cleaners and
2344 surfactants, such as linear alkyl benzenesulfonates are not co-precipitated to a significant
2345 extent in phosphate salts (Egle et al., 2016). Specific **disinfection products**, such as chlorine,
2346 can form disinfection by-products which can be carcinogenic and highly ecotoxic in their
2347 nature, and no information is available on their behavior during precipitation processes.

2348
2349 It is proposed to enable the use of wastewaters from food processing industries, **unless**
2350 **previous processing steps involved contact with:**

- 2351 ○ detergents other than those permitted pursuant Regulation (EC) No 648/2004,
- 2352 ○ oxidising and non-oxidising biocides,
- 2353 ○ animal by-products or derived products falling within the scope of Regulation
- 2354 (EC) No 1069/2009 for which no end point in the manufacturing chain has
- 2355 been determined in accordance with the third paragraph of Article 5(2) of that
- 2356 Regulation;

2357 Moreover, it is proposed to include semi-solid **waste materials from the agro-food**
2358 **processing industry** (e.g. molasses, vinasses, etc.) as input materials. On the proposed input
2359 material list, such materials are included as **bio-wastes** within the meaning of Directive
2360 2008/98/EC and Directive EU 2018/851 (i.e. "biodegradable garden and park waste, food and
2361 kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail
2362 premises and comparable waste from food processing plants").

2363
2364 Large amounts of **wastewater** are produced by the **energy production industry, pulp and**
2365 **paper industry, chemical industry and pharmaceutical industry** (Moloney et al., 2014;
2366 Eurostat, 2016). The wood pulp and paper industry is the non-food sector that dominantly
2367 contributes to P-losses (van Dijk et al., 2016), but the P is present in a highly diluted form
2368 (0.2 – 0.4 mg L⁻¹). Phosphorus losses from other non-food sectors, more specifically
2369 **chemical waste streams**, are low and diluted, for which reason P-precipitation is technically
2370 challenging (van Dijk et al., 2016). Moreover, specific chemical waste streams **may contain**
2371 **contaminants that are present in large quantities** (e.g. pharmaceutical compounds). Also,
2372 the STRUBIAS sub-group did not identify specific chemical industry waste streams used for
2373 P-recovery through precipitation processes. However, the behaviour during the precipitation
2374 process is unknown for contaminants encountered in treated pulp and paper sludges (e.g.
2375 absorbable organic halides (AOX) and chlorinated organic compounds; Pokhrel and

2376 Viraraghavan, 2004). For these reasons, **it is proposed to exclude waste from such**
2377 **materials as input material.**

2378

2379 5.4.2.2 *Reactants*

2380 The precipitation process is based on the addition of **chemical reactants, phosphate counter**
2381 **ions, and pH regulators** (chemicals, CO₂) in a reactor (Quintana et al., 2004; Le Corre et al.,
2382 2009; Rahman et al., 2014). Different reactor types and configurations exist (see section
2383 15.1), some of them having a **seed bed** (sand, struvite, but also poorly soluble Mg-
2384 compounds (MgO), stainless steel mesh, pumice stone and borosilicate glass may be used;
2385 Kataki et al., 2016). The use of Mg-containing industrial by-products has been indicated to
2386 reduce operational costs (Quintana et al., 2004). However, as outlined in section 4.2.2, the
2387 STRUBIAS recovery rules will adopt the provisions of the use of industrial by-products as
2388 laid down in the general framework of the Revised Fertiliser Regulation as developed by the
2389 Commission.

2390

2391 5.4.2.3 *Proposals for input materials and reactants*

2392 Based on the information presented in paragraphs 5.4.2.1 and 5.4.2.2, following proposal is
2393 put forward for input materials and reactants for the manufacturing of precipitated phosphate
2394 salts:

2395 A CE marked fertilising product may contain precipitated phosphate salts exclusively
2396 obtained through precipitation of one or more of the following input materials:

- 2397 a) wastewaters and sludges from municipal wastewater treatment plants;
2398 b) manure, non-mineralised guano, and digestive tract content pursuant to
2399 Regulation (EC) No 1069/2009;
2400 c) animal by-products and derived materials from Category 2 or Category 3
2401 material of Regulation (EC) No 1069/2009, other than manure, non-mineralised
2402 guano, and digestive tract content, provided that:
2403 ○ they have been hygienised in accordance with the conditions for
2404 pressure sterilisation or with other conditions to prevent risks arising to
2405 public and animal health, in accordance with the requirements laid down
2406 pursuant to Article 15 of Regulation (EC) No 1069/2009, or
2407 ○ they are digestion residues from transformation into biogas as set out in
2408 Annex V of (EU) No 142/2011;
2409 d) wastewaters from food processing industries, unless the food processing steps
2410 involved contact with any of the following:
2411 ○ detergents other than those permitted pursuant Regulation (EC) No
2412 648/2004,
2413 ○ oxidising and non-oxidising biocides, or
2414 ○ animal by-products of category 1 or derived products falling within the
2415 scope of Regulation (EC) No 1069/2009;
2416 e) bio-waste within the meaning of Directive (EU) 2018/851 amending Directive
2417 2008/98/EC resulting from separate bio-waste collection at source, other than
2418 those materials included in point c);

- 2419 f) living or dead organisms or parts thereof, which are unprocessed or processed
2420 only by manual, mechanical or gravitational means, by dissolution in water, by
2421 flotation, by extraction with water, by steam distillation or by heating solely to
2422 remove water, or which are extracted from air by any means, except
2423 o materials originating from mixed municipal waste,
2424 o sewage sludge, industrial sludge or dredging sludge,
2425 o animal by-products or derived products falling within the scope
2426 Regulation (EC) No 1069/2009, and
2427 o materials separately mentioned in points a) - e); or
2428 g) chemical substances and fluidised bed substrates, other than:
2429 o those listed under a) - f),
2430 o waste within the meaning of Directive 2008/98/EC,
2431 o non-biodegradable polymers, and
2432 o animal by-products or derived products falling within the scope of
2433 Regulation (EC) No 1069/2009.

2434 In addition, a CE marked fertilising product may contain precipitated phosphate salts
2435 obtained through precipitation of any material listed in points (a)-(g), or combination
2436 thereof, processed by manual, mechanical or gravitational means, by solid-liquid
2437 fractionation using biodegradable polymers, by dissolution in water, by flotation, by
2438 extraction with water, by steam distillation or by heating solely to remove water, by
2439 thermal hydrolysis, by anaerobic digestion or by composting as long as the
2440 temperature of such processes is not raised above 275°C.

2441
2442 *[Note: The exclusion of a material from a lettered item does not prevent it from being an*
2443 *eligible component material by virtue of another lettered item]*
2444

2445 5.4.3 Production process conditions

2446 It is proposed that phosphate salts can be recovered at plants that are specifically designed for
2447 the **purpose** of producing **fertilising materials** or be the by-product resulting from a process
2448 aimed at **producing different primary outputs** (e.g. energy and treated water) as long as
2449 end-material quality conditions are fulfilled. For this reason, operational facilities can be a
2450 **stand-alone** installation or be **integrated** into another system.

2451 2452 5.4.3.1 Pre-processing

2453 Phosphate salts are precipitated from PO_4^{3-} ions present in liquids and slurries, but pre-
2454 treatments exist that bring P in solution (e.g. anaerobic digestion). **Solid-liquid separation**
2455 techniques are then applied to remove interfering ions, colloidal and suspended particles from
2456 a phosphate-containing liquid solution. Also, the concentration of P-rich precipitates together
2457 with the other colloidal and suspended particles during P-recovery processes are facilitated
2458 through solid-liquid separation processes.

2459
2460 In case phosphate is recovered from liquid and slurry fractions, pre-treatments are applied to
2461 increase the content of orthophosphate ions (PO_4^{3-}) present in the liquid. **A pre-treatment is**
2462 **often a pre-requisite to increase the P-recovery efficiency and is directly applied on**
2463 **input materials**. Based on the scientific literature (Alonso Camargo-Valero et al., 2015;

2464 Bamelis et al., 2015; Camargo-Valero et al., 2015) and the information received from the
2465 STRUBIAS sub-group, applied pre-treatments include **acidification and liming, thermal**
2466 **hydrolysis (at temperatures of 150°C-180°C), pressure** modifications, the circulation of
2467 wastewater in **enhanced biological phosphorus removal (EBPR) tanks, and anaerobic**
2468 **digestion**. These techniques are applied in existing municipal waste water treatment plants or
2469 at operational piloting P-recovery facilities.

2470

2471 **Flocculants, pH regulators, chemical and biological stabilisers and detergents and**
2472 **flocculants** are commonly used to increase the efficiency of removal of waste fractions from
2473 food processing facilities.

2474

2475 **Solid-liquid separation** techniques (e.g. centrifuge, sieve belt, filter press, screw press,
2476 rotation liquid sieve, vibration screen, sedimentation tank, dissolved air flotation, lamella
2477 separator, filtration by means of straw bed, ultrafiltration using semi-permeable membranes,
2478 and reverse osmosis), possibly after the application of polymers, are generally applied at
2479 some stage during pre-processing stages of the input material preceding the precipitation of
2480 phosphate salts. **Organic or inorganic coagulants** are sometimes used to achieve a good
2481 separation between solid and liquid phases (Hjorth et al., 2010; Schoumans et al., 2010).
2482 Usually coagulants, flocculants and polymers are poly-electrolytes, aluminium and iron
2483 sulfates and chlorides, calcium oxides and hydroxides, polyacrylamide or also magnesium
2484 oxide and magnesium hydroxides. The above-mentioned techniques are all based on
2485 **mechanical separation**, possibly complemented by the addition of chemical substances,
2486 **mild temperature treatment** and membrane technologies. No limitations on the use of such
2487 techniques are proposed as long as the polymers applied have no adverse effects on animal or
2488 plant health, or on the environment (see requirements proposed for CMC 9 and 10 in the
2489 proposal for the Revised Fertiliser Regulation).

2490

2491 As phosphate salt precipitation can take place on materials obtained after applying the above-
2492 mentioned techniques, it is proposed to make a reference to chemicals that can be used (g)
2493 and pre-treatments in the paragraph related to the input materials as follows (see also section
2494 5.4.2):

2495

2496 g) chemical substances and fluidised bed substrates, other than:

2497

2498 ○ those listed under a) - f);

2499

2499 ○ waste within the meaning of Directive 2008/98/EC;

2500

2500 ○ non-biodegradable polymers; and

2501

2501 ○ animal by-products or derived products falling within the scope of
2502 Regulation (EC) No 1069/2009.

2502

2503 In addition, a CE marked fertilising product may contain precipitated phosphate salts
2504 obtained through precipitation of any material listed in points (a)-(g), or combination
2505 thereof, processed by manual, mechanical or gravitational means, by solid-liquid
2506 fractionation using biodegradable polymers, by dissolution in water, by flotation, by
2506 extraction with water, by steam distillation or by heating solely to remove water, by

2507 thermal hydrolysis, by anaerobic digestion or by composting as long as the
2508 temperature of such processes is not raised above 275°C.

2509
2510 The limit of **275 °C** is proposed based on the upper temperature limit for thermal treatments
2511 investigated and applied i.e. the thermal hydrolysis processes (Barber, 2016). There is no risk
2512 for the *de novo* formation of persistent organic compounds such as PAH, PCDD/Fs or PCBs
2513 within the proposed temperature range (Vehlow et al., 2006; Van Caneghem et al., 2010).

2514

2515 5.4.3.2 Core process

2516 According to the conditions on production process provisions, a wide range of materials
2517 could theoretically be precipitated, some of which falling clearly beyond the scope of this
2518 CMC. Examples of materials that could be produced include for instance precipitates other
2519 than those rich in phosphates (e.g. calcium sulfate, silver nitrate, etc.), or sludge-like
2520 insoluble precipitates formed in chemical waste water treatment plants by the application of
2521 chemicals like (FeCl₃, Fe₂(SO₄)₃), alum (Al(SO₄)₃) or lime (Ca(OH)₂). Obviously, these
2522 materials are not within the scope of this CMC. These materials have a low P content (e.g. 1-
2523 5% P for sewage sludge; Janssen and Koopman, 2005; Herzel et al., 2016). **Hence, setting a
2524 criterion on the minimum P₂O₅ content will delimit the scope of the CMC category, in
2525 line with the objective of providing an avenue for the recovery of P-rich materials that
2526 can directly be used as fertilisers on land or as intermediates for fertiliser material
2527 production processes.** The JRC is aware that a criterion for minimum P-content has been
2528 proposed at PFC level (PFC 1 – Fertilisers), but at the same time, it is believed that P-content
2529 is the preferred manner to ensure that materials fit within the scope of this CMC. Alternative
2530 approaches based on the measurement of the mineral composition (e.g. X-ray diffraction
2531 (XRD), mineral liberation analyses (MLA) using Scanning Electron Microscope (SEM) -
2532 Mineral Energy Dispersive Spectra (MEDS), etc.) are less straightforward and will lead to
2533 higher compliance costs (2000 – 4000 Euro per sample). Measuring the P₂O₅ content will not
2534 lead to additional compliance costs as this parameter will be measured as part of the
2535 conformity assessment procedures for PFC 1 – Fertilisers.

2536 The targeted precipitated phosphate salts typically have a P₂O₅ content of more than 25%
2537 (Table 2). Nonetheless, the P₂O₅ content could be lower for specific phosphate salts,
2538 especially for hydrated salts. Sodium phosphate dibasic 12-hydrate (Na₂HPO₄.12H₂O) was
2539 identified as the phosphate salt with the lowest P₂O₅ content (20%). Since a limited amount
2540 of impurities might be co-precipitated together with the pure crystals without major
2541 environmental and human health risks, a minimum P₂O₅ content that corresponds to 80% of
2542 that mineral is proposed as a criterion to delimit the scope of this CMC:

2543
2544 **The precipitated phosphate salt shall have a minimum P₂O₅ content of 16% of the dry
2545 matter content¹⁹,**
2546

¹⁹ As measured using vacuum drying at 40°C.

2547 Current end-materials of operational plants typically have a P₂O₅ content > 20% (see section
 2548 16.1.1), indicating that this criterion should be not a restricting element in the compliance
 2549 scheme. **Together with the criterion on maximum organic C content (<3%, see section**
 2550 **5.4.5.1), these requirements will clearly differentiate precipitated phosphate salts from**
 2551 **materials that fall beyond the scope of this CMC.** Based on the reported values from
 2552 operational plants, the 20% threshold value for the P₂O₅ content of precipitated phosphate
 2553 salts is an achievable target for industrial P-recovery processes (section 16.1.1).

2554 There are other processes (e.g. *flocculation* of suspended P present in sludges, *adsorption* of
 2555 P on calcium silicate hydrates) that could lead to the production of P compounds. Examples
 2556 of adsorption processes on calcium silicate hydrates are described in Petzet and Cornel
 2557 (2012) and Kuwahara and Yamashita (2017). Because the nature of such processes is
 2558 different from *precipitation* (as outlined in section 5.1.1), the non-selective inclusion of
 2559 compounds other than phosphates occurs, leading to the production of materials that are
 2560 lower in P-content, and possibly higher in contaminants. Assessing such materials and
 2561 production processes other than precipitation processes falls beyond the scope of the CMC
 2562 precipitated phosphate salts & derivates.

2563

2564 **Table 2: Elemental composition of different types of precipitated phosphate salts in pure form**
 2565 **as dried at a temperature of 40°C until constant weight.**

EC / List number	name	molecular formula	P (%)	P ₂ O ₅ (%)	Mg (%)	N (%)	Ca (%)	H ₂ O (crystal bonded) †
232-075-2	ammonium magnesium orthophosphate (hydrate)	NH ₄ MgPO ₄ ·6H ₂ O	12.6	28.9	9.9	5.7	-	44
n.a.	dittmarite	NH ₄ MgPO ₄ ·2H ₂ O	17.9	41.0	14.0	8.1	-	20.8
231-823-5	magnesium hydrogen phosphate	MgHPO ₄	25.8	59.1	20.2	-	-	-
231-826-1	calcium hydrogenorthophosphate (anhydrous)	CaHPO ₄	22.8	52.2	-	-	29.5	-
231-826-1	calcium hydrogenorthophosphate (dihydrate)	CaHPO ₄ ·2H ₂ O	18.0	41.2	-	-	23.3	20.9
235-330-6	pentacalcium hydroxide tris(orthophosphate)	Ca ₅ (PO ₄) ₃ (OH)	18.5	42.4	-	-	39.9	-

2566 †: subject to available measurement standards for the determination of crystal-bonded water

2567

2568 The chemicals, pH regulators and seed beds required for the precipitation process are
 2569 discussed and identified together with the proposals for the list of eligible input materials and
 2570 reactants in section 5.4.2.2.

2571

2572 5.4.3.3 Post-precipitation manufacturing steps

2573 Nutrients in most recovered Ca and Mg phosphate salts show a high plant availability
 2574 (section 5.4.4) and the material has no adverse effects on the environment and human health
 2575 during the handling and use phase as a fertiliser (see section 5.4.5). Therefore, precipitated
 2576 phosphate salts that meet the proposed criteria of this project **can be used directly as a**
 2577 **fertiliser** or as an ingredient in the tested physical fertiliser blends. As indicated during the

2578 STRUBIAS Kick-off Meeting and by Six et al. (2014), there is considerable interest of the
2579 fertiliser blending and mineral fertilising industry to use precipitated phosphate salts as **an**
2580 **intermediate raw material in their production processes:**

- 2581 ○ Given that the P in most pure precipitated phosphate salts is already in plant-available
2582 form, there is no need for acidulation and further chemical reactions of the
2583 precipitated phosphate salts. Hence the materials may be ready for use in **physical**
2584 **fertiliser blends**, for instance together with acidulated phosphate rocks of CMC 1
2585 (*Virgin material substances and mixtures*) (Six et al., 2014). Nonetheless, the
2586 different components should meet certain criteria, with respect to purity and
2587 granulometry (Formisani, 2003). Certain combinations of molecules should be
2588 avoided due to possibly occurring chemical reactions in the granulator that cause
2589 nutrient loss or reduce the water solubility of specific elements in the blend. A
2590 potentially limiting factor for the further direct use of precipitated phosphate salts
2591 could also be the moisture content of the (hydrated) precipitated phosphate salts and
2592 the chemical compatibility with other selected fertilising compounds in physical
2593 blends.
- 2594 ○ Some precipitates may not be suitable as fertilising material due to their lower plant
2595 P-availability, but may be appropriate **intermediates for chemical manufacturing**
2596 **processes of water- or acid-soluble P-fertilisers**. This especially holds true for P-
2597 recovery processes leading to the production of end materials such as hydroxyapatite
2598 (Kabbe, 2017), a phosphate salt of lower plant P-availability, especially at alkaline pH
2599 (Arai and Sparks, 2007). Moreover, forthcoming P-recovery processes could also rely
2600 on similar two phase processes, i.e. through the precipitation of other materials of low
2601 plant P-availability (e.g. Fe-phosphates) that can be used as an intermediate in a P-
2602 fertiliser production process (Wilfert et al., 2015).

2603
2604 Hence, it is desirable to enable the further chemical processing of precipitated phosphate salts
2605 in the recovery rules to permit the production of fertilising materials of choice. Given the
2606 framework of the proposed revised Fertiliser Regulation, such chemical processing steps
2607 should be covered under this CMC and thus be included in the recovery rules (see section
2608 4.2.1 and section 5.3.3).

2609
2610 As outlined in section 5.3.3, "**two-step**" manufacturing processes enable the further
2611 processing of intermediate materials. The principle of the two-step manufacturing processes
2612 for this CMC is that the precipitation process isolates a material that can be considered as
2613 "safe" due to the low values of organic contaminants, biological pathogens, and inorganic
2614 contaminants. The safety of this material is assured by a combination of process requirements
2615 and parameter testing on the precipitate (e.g. biological pathogens, maximal organic C
2616 contents, etc.). Therefore, subsequent chemical manufacturing steps can be applied to
2617 produce a fertilising material of a preferred chemical composition, as long as no new "risk
2618 materials" are introduced. Risk materials are, in this context, defined as materials which can
2619 introduce biological contamination or other non-intentional organic contaminants. Hence, it is
2620 proposed to enable only virgin materials (and possibly *safe* industrial by-products as

2621 permitted within the framework of the proposed revised Fertiliser Regulation, see section
2622 4.2.2) for such post-precipitation manufacturing steps, and **to exclude waste materials,**
2623 **materials which have ceased to be waste, waste animal by-products** (similar to the
2624 provisions for CMC 1). Because the process limitations on the second step of the processes
2625 are minimal, a high degree of **sovereignty is allowed for manufacturers to apply processes**
2626 **of choice** and to promote the development of innovative processes that start from
2627 intermediate materials. The proposed provisions cover all wet chemical processes that
2628 involve the removal of P along with other elements from the precipitate by elution, after
2629 which the dissolved elements are recovered by solidification, precipitation, ion exchange or
2630 membrane technologies. **The end-material from the whole manufacturing process**
2631 **("precipitated phosphate salts & derivates that will be incorporated in the CE marked**
2632 **fertilising product") will then be subject to further testing on dry matter content and Al**
2633 **and Fe contents** (see section 5.4.4).

2634

2635 **Therefore, it is proposed to include following point in the CMC recovery rules:**

2636

2637 A CE marked fertilising product may contain derivates from precipitated phosphate
2638 salts compliant with paragraphs 1 to 3 [input materials, production process conditions
2639 and material quality criteria of the precipitate, respectively] as produced through a
2640 chemical manufacturing step that reacts the precipitate with intermediates within the
2641 meaning of Regulation (EC) No 1907/2006 listed under point g) of paragraph 1.

2642

2643

2644 *5.4.3.4 Finishing steps*

2645 **No specific requirements for "finishing" techniques that relate to the agglomeration or**
2646 **washing of materials have to be included at CMC level.** Post-processes (e.g. modification
2647 of size or shape by mechanical treatment, washing with water) are normal industrial practice
2648 and any materials required are included on the input material list.

2649 Hence, precipitated phosphate salts & derivates may undergo further post-processing steps
2650 with the intention to:

2651 ○ Improve the purity of the material and to remove any physical and organic
2652 impurities by **washing** with substances that do not change the chemical structure
2653 of the crystalline phases of the precipitate;

2654 ○ **Agglomerate** the product as pellets or granules using a variety of equipment
2655 including rotating pans and drums, fluidised beds and other specialised equipment.
2656 It should be noted that granulation processes might cause the heating of the
2657 precipitated phosphate salts, which could alter the chemical composition of the
2658 product due to dehydration;

2659

2660 5.4.4 Agronomic value

2661 The objective for materials from the CMC precipitated phosphate salts & derivatives is to
2662 supply plants with soluble phosphates as a macronutrient. **Recovered Ca- and Mg-**
2663 **phosphate salts show generally good plant P-availability, with plant responses to**
2664 **fertilisation being similar to mined and synthetic P-fertilisers currently on the market**
2665 **(see section 6.2.2).**
2666

2667 Some members of the STRUBIAS sub-group also formulated requests to include recovered
2668 Fe-phosphates in this category, thus as CMC materials that can be incorporated into the CE
2669 marked fertilising product (e.g. KREPRO process). **Aluminium and iron phosphates are,**
2670 **however, not registered as fertilisers pursuant to Regulation EC No 1907/2006**
2671 **(REACH).** The material properties of the ferric phosphates (24-29% Fe) obtained through
2672 the KREPRO process that were proposed as end-materials to be included in this CMC
2673 showed high organic C contents (6% - 29%), low to moderate P contents (6.6% – 30.6%,
2674 expressed as P₂O₅), and molar Fe/P ratios in the range of 1.3 - 5.1. As only limited testing has
2675 been performed on these materials, their agronomic value remains uncertain due to concerns
2676 on the plant availability of Fe-complexed phosphates (Lindsay and De Ment, 1961; Ghosh et
2677 al., 1996; Wilfert et al., 2015). Kahiluoto et al. (2015) indicated good plant availability for
2678 sludges with moderate molar Fe/P ratios of 1.6, but not for materials with higher molar Fe/P
2679 ratios of 9.8. Moreover, if the P in Fe- and Al-phosphates were plant available, there is a
2680 substantial risk that the soluble aluminium or iron forms will induce plant toxicity as the
2681 liberation of P from such complexes will involve a breakup of the chemical bonds, and thus
2682 the liberation of free Al and/or Fe in the soil solution. Both Fe and Al can be toxic if supplied
2683 in excessive concentrations to plants (Connolly and Guerinot, 2002). **Hence, the direct use**
2684 **of Al- and Fe-phosphates as CMC materials is not desirable as (1) the agronomic value**
2685 **of such materials of a P source remains unknown, thus leading to a tangible risk for the**
2686 **accretion of P in the soil, and (2) liberated phosphate counter-ions in the form of Al or**
2687 **Fe could cause potentially toxic plant effects.** Therefore, following criterion is proposed:
2688

2689 **Precipitated phosphate salts & derivatives contained into the CE marked fertilising**
2690 **product shall have a maximum of 10% of the sum of elemental Al and elemental Fe of**
2691 **the dry matter content²⁰;**
2692

2693 The proposed cut-off value allows Fe and Al to be present in relatively low amounts in the
2694 precipitated phosphate salts. This is important as eligible input materials, such as sewage
2695 sludge, are often rich in Al or Fe, some of which will be transferred as impurities to the
2696 precipitate. Typical values for Al and Fe in precipitated phosphate salts are in the range of 0 -
2697 4% and 0 - 2% for Al and Fe, respectively (González-Ponce et al., 2009; Gell et al., 2011;
2698 Antonini et al., 2012; Uysal et al., 2014; Vogel et al., 2015; Siciliano, 2016). Assuming a
2699 minimum P₂O₅ content of 20% and a maximum Fe content of 10% in the precipitated
2700 phosphate salt, the molar Fe/P ratio in the material would be ~0.65, a value at which plant P
2701 availability would not be compromised (Kahiluoto et al., 2015). The proposal on maximal
2702 Al/Fe contents are also in line with the technical report of Ehlert et al. (2016a) that evaluated

²⁰ As measured using vacuum drying at 40°C, CEN method under development.

2703 the possible inclusion of "recovered phosphates" in the Dutch fertiliser legislation, and
2704 recommended to constrain the category to Ca and Mg phosphates.

2705

2706 In line with Wilfert et al. (2015), there may be a *potential* for P-recovery from sludges
2707 containing Al-P and Fe-P complexes as *input materials or intermediates* for the production of
2708 precipitated phosphate salt fertilisers. This is the reason why they have been included further
2709 in this document as eligible input materials (section 5.4.2) and no criterion for the maximum
2710 Fe and Al content of the intermediate precipitate (section 5.4.3.2) has been proposed.
2711 Proposed limits on Fe and Al only apply to the finished precipitated phosphate salts &
2712 derivate materials contained into the CE marked fertilising product. Altogether, **it is possible**
2713 **to use Al/Fe-rich compounds as an input material to produce an end-material**
2714 **pertaining to this CMC. Moreover, a two-step precipitation process can be applied,**
2715 **where Fe is used to precipitate phosphate into Fe-phosphates (with a P₂O₅ content of**
2716 **>20% and an organic C content of <3%) as long as this precursor is later transformed**
2717 **into a material that meets the proposed requirement on maximum Al + Fe content (as**
2718 **described in section 5.4.3.3).**

2719

2720 5.4.5 Environmental and human health safety aspects

2721 Certain input materials that are targeted for nutrient recovery through P-precipitation have
2722 high contents of inorganic and organic pollutants (Boxall, 2012), that may potentially be
2723 transferred to the precipitated phosphate salt. Some of these pollutants can be monitored by
2724 chemical analysis (e.g. polyaromatic hydrocarbons (PAHs), metals like Cd and Hg, etc.) in
2725 the resulting materials. However, in recent years concerns have been raised on a broad variety
2726 of compounds including natural toxins, human pharmaceuticals, phthalates, veterinary
2727 medicines, pesticides and derivatives, nanomaterials, personal care products, paints and
2728 coatings, etc. (Boxall, 2012). Especially these organic contaminants are of concern as
2729 analytical methods to trace these - by nature heterogeneous - compounds are complex and
2730 costly. Moreover, risk assessments on these pollutants are often lacking, which makes it
2731 challenging to derive limit values.

2732

2733 It is important to recognise that precipitated phosphate salts **are a new type of industrial**
2734 **material, and compared to better-known materials, relatively few samples have been**
2735 **tested for contaminants, especially of organic origin.** As already outlined in section 5.4.2,
2736 most laboratory, piloting and operating P-precipitation plants from which information on
2737 environmental and human health safety aspects is available are reliant on municipal waste
2738 waters as inputs (both for struvite and calcium phosphates). Nevertheless, also data for
2739 different food processing industries and manure and livestock stable slurries are available
2740 (section 16.1.2). **Data on contaminants, especially organics, are mainly available for**
2741 **precipitated phosphate salts of high purity with a low C content** (especially for struvites,
2742 but also for dicalcium phosphates – confidential data) and limited information is available for
2743 precipitated phosphate salts that show relatively higher levels of organic C.

2744

2745

2746 5.4.5.1 Organic chemical contaminants

2747 Identification of specific contaminants

2748 Given that no thermal destruction phase is present during the production of precipitated
2749 phosphate salts, it is **relevant to assess the environmental and human health impacts**
2750 **from the presence of specific organic contaminants in phosphate salts.** Possible pre-
2751 processing techniques such as anaerobic digestion and wet-digestion, pasteurisation, and
2752 thermal hydrolysis (section 5.4.3.1) might cause a substantial reduction in the risk for organic
2753 contaminants (Lukehurst et al., 2010), but are not always applied in the production process
2754 and do not secure the removal of the wide variety of organic pollutants that can be found in
2755 some input materials. Therefore, a hazard exists for the absorption and inclusion of organic
2756 contaminants in the end-material of the recovery process.

2757
2758 It is pertinent to evaluate hazards according to the **probability of occurrence** in the
2759 framework of a risk assessment. In this context, relevant frameworks for comparison are the
2760 direct land application of sewage sludge, manures, and digestates from manure slurries and
2761 bio-waste on land (Langenkamp and Part, 2001; Smith, 2009; WCA environment, 2014;
2762 Petrie et al., 2015; Ehlert et al., 2016b). Such comparisons are useful as the precipitation
2763 process **is a separation technique, rather than a transformation process.** Therefore, only
2764 contaminants present in the input materials can be transferred to the precipitate. In contrast to
2765 thermal oxidation materials & derivatives and pyrolysis & gasification materials, there is no *de*
2766 *novo* formation of contaminants in this separation process.

2767
2768 **Although emerging pollutants require supplementary screening (see below), risk**
2769 **assessments for sewage sludge, manures and designated bio-wastes from food and feed**
2770 **industry and residues from agriculture and landscape management indicate that**
2771 **organic contaminants are not expected to pose major health problems to the human**
2772 **population when those are directly re-applied on agricultural land** (Langenkamp and
2773 Part, 2001; Smith, 2009; WCA environment, 2014; Ehlert et al., 2016b). This view is based
2774 on a technical evaluation of the situation, which acknowledges the concentration of organic
2775 contaminants in sewage sludge in relation to their behaviour and fate in the soil. It was
2776 concluded that the biodegradation and behaviour of organic compounds in the soil together
2777 with the low levels of crop uptake minimize the potential impacts of most organic pollutants
2778 on human health (Langenkamp and Part, 2001; Smith, 2009).

2779
2780 Nevertheless, the **risk assessments also indicated that certain substances present in input**
2781 **materials** like sewage sludges, manures, digestates and (industrial) waste waters **require**
2782 **further investigation** (UMK-AG, 2000; Langenkamp and Part, 2001; Smith, 2009; WCA
2783 environment, 2014; Ehlert et al., 2016b): (i) phthalates, (ii) surfactants present in cleaners and
2784 detergents, (iii) PAH, PCDD/Fs and PCBs, (iv) plant protection products and biocides, and
2785 (v) antibiotic and other drug residues, personal-care products, and endocrine-disrupting
2786 compounds. Therefore, it is relevant to evaluate to what extent the abovementioned
2787 substances can be transferred to the precipitated phosphate salts:

- 2788 ○ From the database compiled by Egle et al. (2016) and the confidential information
2789 received from the STRUBIAS sub-group, it could be observed **that phthalates,**
2790 **surfactants and cleaning substances** (as measured by nonylphenole and
2791 nonylphenole ethoxylates with 1 or 2 ethoxy groups (NPE) and linear
2792 alkylbenzene sulphonates (LAS)) are generally present in low quantities in
2793 phosphate salts that are recovered from municipal waste waters, and several orders
2794 of magnitude below the limit values for these compounds established in different
2795 EU Member States and the provisions of Directive 86/278/EEC (Langenkamp and
2796 Part, 2001).
- 2797 ○ Data on **PAH, PCDD/Fs and PCBs** in precipitated phosphate salts are very
2798 limited. Kraus and Seis (2015) found very low quantities of these persistent
2799 organic pollutants in three struvites. PCBs and PCDD/F contents in precipitated
2800 phosphate salts were also well below levels of concern according to other studies
2801 (Uysal et al., 2010; confidential information provided by the STRUBIAS sub-
2802 group; Kraus and Seis, 2015; Egle et al., 2016). Confidential data provided by the
2803 STRUBIAS subgroup indicated a PAH content of 2.5 mg kg⁻¹ fresh matter for
2804 struvite recovered from digested sludge. Given that the current dataset is limited
2805 to 7 samples, **it is proposed to monitor and limit PAHs in precipitated**
2806 **phosphate salts when those are derived from sewage, an input material that is**
2807 **possibly rich in PAHs.**
- 2808 ○ Limited information is available for **plant protection products and biocides.**
2809 This issue is especially relevant when digestates from plant-based and animal
2810 products are used as input materials for P-recovery. However, the use of known
2811 potentially unsafe plant protection products (e.g. aldrin, dieldrin, HCHs, HCBs,
2812 DDT/DDD/DDE) has been largely phased out, for which reason the risk is
2813 inherently low. In their study on the safety of designated bio-wastes from food and
2814 feed industry and residues from agriculture and landscape management, Ehlert et
2815 al. (2016b) indicated that data on organic micropollutants in crop digestates are
2816 largely missing, but that such compounds are not mainly restricting the use of
2817 digestates on land as there is no major risk for the environment and human health.
- 2818 ○ The use of **pharmaceutical products and personal care products** has caused
2819 concerns about the presence of pharmaceutical compounds in precipitated
2820 phosphate salts derived from municipal waste waters, and more specifically
2821 separately collected urine, and stable manure and livestock slurries (Ronteltap et
2822 al., 2007; Ye et al., 2017). Residual antibiotics can affect the soil and aquatic
2823 microbiome, resulting in differential inhibition of certain microorganisms and in
2824 perturbations in community composition. The increasing use of antibiotics in
2825 medicine, veterinary medicine, and agricultural production systems has coincided
2826 with increasing development of high levels of antibiotic resistance and novel
2827 antibiotic resistances (Popowska et al., 2012).
2828 **Antibiotics have been widely applied in the livestock industry** both as
2829 prophylaxis (or therapy) and as growth stimulators. Veterinary antibiotics in

2830 manures have raised significant concern; these residues have a great capacity to
2831 disturb the natural ecological balance and trigger an increase of resistant bacteria
2832 in the environment (Tong et al., 2009). Moreover, the uptake of antibiotics by
2833 children and pregnant women should be constrained, and some compounds have
2834 been reported to cause an array of animal and human diseases including
2835 nephrotoxicity, hepatotoxicity, and hypersensitivity reactions, hypouricemia,
2836 hypokalemia, proximal and distal renal tubular acidosis. The most common
2837 antibiotics in swine wastewater are tetracyclines, sulfonamides, and
2838 fluoroquinolones (Li et al., 2013). Residual concentrations of tetracyclines from
2839 fresh animal wastes have been reported to range from 11 to 880 ng g⁻¹ (Daghir
2840 and Drogui, 2013). Ye et al. (2018) indicated that 21-98% of the tetracyclines and
2841 0-68% of the fluoroquinolones present in a separated liquid pig manure fraction
2842 could be retained in struvite, leading to tetracycline concentrations in the granules
2843 that range from 0.2 to 2.0 µg g⁻¹. It was indicated that the tetracycline entrapment
2844 in the precipitated phosphate salt was linearly correlated to the total organic
2845 carbon content in the salt (R² = 0.72, n = 15) because tetracyclines have a high
2846 affinity for organic matter through cation bridging and cation exchange (Luo et
2847 al., 2011). Hence, during solid-liquid separation, the overall share of the
2848 tetracyclines present in the unprocessed manure will adsorb to the solid manure
2849 fractions that are rich in organic C (Wallace et al., 2018). Therefore, the maximal
2850 total retention of the antibiotics in precipitated phosphate salts will be reduced as,
2851 by definition, precipitation is a process that forms solid materials from dissolved
2852 substances present in the liquid fraction. Nonetheless, in order to avoid the
2853 entrapment of tetracyclines adhered to soil organic matter, it is recommendable to
2854 limit the organic C content in the precipitate (see below, section 'total organic
2855 carbon'). This holds particularly true as common pre-treatments and hygienisation
2856 steps as mesophilic anaerobic digestion only result in a limited removal of these
2857 veterinary antibiotics (Massé et al., 2014; Montes et al., 2015; Liu et al., 2018;
2858 Wallace et al., 2018).

2859 Rontentap et al. (2007) reported that common **pharmaceutical compounds**
2860 **present in sewage and municipal waste waters** (e.g., propranolol, ibuprofen,
2861 diclofenac and carbamazepine) transfer into the precipitated materials in only very
2862 small quantities i.e., at rates ranging from 0.01% (diclofenac) to 2.6%
2863 (propranolol) in the precipitated phosphate salt versus their amounts in urine.
2864 Escher et al. (2006) found that less than 1 to 4% of the spiked hormones and
2865 pharmaceutical compounds in the urine feedstock were present in struvite. This
2866 was a better removal performance than what could be achieved via alternative
2867 approaches such as bioreactor treatment, nanofiltration, ozonation or UV.
2868 Similarly, Ye et al. (2017) reported that 0.3% - 0.5% of the tetrazines from spiked
2869 solutions were found in struvites. Kemacheevakul et al. (2012) also found traces
2870 of some pharmaceutical products (tetracycline, erythromycin and norfloxacin,
2871 other spiked compounds were not traced back in the end-material) that were
2872 supplied as spikes to artificial urines, but also here the accumulation was
2873 negligible. In the study of STOWA (2015), metoprolol was found in detectable

2874 concentrations in one out of the four struvites (only in an unwashed sample with
2875 an organic C content of 3.7%), but not in the remaining samples that were lower in
2876 organic C. Butkovskyi (2016) investigated the transfer of pharmaceutical
2877 compounds (diclofenac, naproxen, ibuprofen, metformin, and paracetamol),
2878 biocides (triclosan, benzalkonium chloride, 2,4 dichlorophenol), fragrance
2879 (galaxolide or HHCB), and parabens in struvites. It was indicated that only 2,4
2880 dichlorophenol was found in minimal concentrations ($0.5 \mu\text{g g}^{-1}$) in the
2881 precipitated phosphate salt. The STRUBIAS sub-group also provided analyses of
2882 a wide range of pharmaceutical compounds for struvites from digested sludges; it
2883 was found that the concentration of two compounds (carbamazepine and
2884 carvedilol) was minimally elevated above detection limits, but that the
2885 precipitation processes reduced the concentrations of all other compounds
2886 investigated to below detectable levels. **It is concluded that pharmaceutical
2887 compounds can possibly accumulate in precipitated phosphate salts, but that
2888 the concentrations measured in relatively pure precipitated phosphate salts
2889 are low. Therefore, no major risk in terms of safety of recovered struvite
2890 from eligible input materials has been identified for material handling, the
2891 environment or the food chain.** This conclusion is in agreement with the risk
2892 assessment performed by de Boer et al. (2018) who indicated that the risk to
2893 human health from eating crops that were fertilised with struvites of high purity is
2894 insignificant. The average person would have to eat approximately 750 kg of dry
2895 food per day to reach the acceptable daily intake limit, defined as the amount of a
2896 specific foodstuff that can be ingested (orally) on a daily basis over a lifetime
2897 without an appreciable health risk. It is noted that the overall share of the studies
2898 that assessed the risk originating from pharmaceutical compounds present in
2899 sewage have used precipitated phosphate salts of a relatively high purity and low
2900 organic carbon content, mostly originating from already operating struvite
2901 reactors.

2902

2903 In general, data **indicate that precipitated phosphate salts are generally safe with respect**
2904 **to organic contaminants.** The safe use of precipitated phosphate salts has also been
2905 indicated in a **bioassay** that assessed ecotoxicity on plants and aquatic organisms after the
2906 application of recovered struvite (ADEME - Naskeo Rittmo Timab, 2016). Theoretical and
2907 experimental evidence indicates that the **organic C level of the phosphate salts could be a**
2908 **critical factor to control the possible transfer of pollutants** from the input material to the
2909 fertilising products.

2910

2911 Total organic carbon

2912 The section above indicated that no unacceptable risks are present for particular organic
2913 pollutants in precipitated phosphate salts. However, **it should be noted that this assessment**
2914 **was almost entirely based on precipitated phosphate salts of a high purity,** as indicated
2915 by XRD measurements, nutrient contents (P, Mg, N; and their ratios), or organic carbon

2916 contents. Therefore, **the conclusion of reduced risks associated to organic chemical**
2917 **contaminants is only demonstrated for high-quality precipitated phosphate salts, and no**
2918 **conclusions can be drawn for materials of a lower quality.**
2919

2920 In line with the suggestions from STOWA (2015) and based on the precautionary principle, **it**
2921 **is therefore recommended to target the quality of precipitated phosphate salts towards**
2922 **materials of a higher purity.** Materials of higher purity show a reduced probability of
2923 entrapping organic chemical contaminants, as well as other pollutants.
2924

2925 Different proxies can be used to characterise the purity of precipitated phosphate salts, with
2926 nutrient contents (P, N, Mg, and their relative ratios) and crystallographic measurements
2927 (XRD and other) being the most common. Nonetheless, these proxies are less suitable for
2928 defining purity because (1) the different precipitated phosphate salts that are encompassed in
2929 this CMC (e.g. struvite, K-struvite, dittmarite, dicalciumphosphate, anhydrous calcium
2930 hydrogenorthophosphate, etc.) vary widely in their nutrient content and elemental ratios, and
2931 (2) crystallographic measurements carry a high cost. **Therefore, it is proposed to use**
2932 **organic carbon as a proxy that is inversely related to material purity.** The organic carbon
2933 content of the precipitated phosphate salt is a basic indication of the level of organic
2934 contamination and purity. The salts can contain both natural and synthetic organic matter.
2935 Examples of natural organic matter include undecomposed organic matter and bacteria,
2936 whereas synthetic organic matter includes, but is not limited to contaminants like pesticides,
2937 antibiotics and detergents. **Some functional groups in dissolved organic matter (e.g.,**
2938 **carboxyl, hydroxyl, carbonyl) facilitate electrostatic association with contaminants and**
2939 **enhance the migration by cotransport** (Polubesova et al., 2006). Organic matter originating
2940 from possibly contaminated input materials like sewage sludge and manure slurries can be
2941 the vehicle for the transportation of a variety of organic pollutants and biological pathogens
2942 in precipitated phosphate salts. Organic matter might thus not only contain contaminants that
2943 were present in the input material, it is often a vector for the selective adsorption of synthetic
2944 contaminants that were present in the liquefied matrix from which the precipitated phosphate
2945 salt was precipitated. It has been indicated that the organic C content is inversely related to
2946 some specific pharmaceutical compounds such as tetracycline (Lou et al., 2018; Ye et al.,
2947 2018), a major organic chemical contaminant of interest.
2948

2949 Manure and sewage sludge shows an organic C content of around 30%, and a P content of 1-
2950 3%, expressed on a dry matter basis. In order to achieve an improvement in contaminant
2951 levels of one order of magnitude for compounds that are adsorbed to organic matter, **it is**
2952 **proposed to limit the organic C content in precipitated phosphate salts of 3% of the dry**
2953 **matter content.** The STOWA study indicated that PAHs (PAH₁₀: 9.5 mg kg⁻¹ dry matter),
2954 pharmaceutical compounds (metoprolol, 0.4 mg kg⁻¹) as well as spore-forming bacteria
2955 (spores of sulphite-reducing clostridia: 4.5 – 860 colony forming units g⁻¹ struvite) were, for
2956 instance, present in “struvites” with an organic C content of 3.7% derived from digested
2957 sludge, but not in struvites with an organic C content below 1%. The proposed maximum
2958 organic C level of 3% for precipitated phosphate salts should thus further result in a major

2959 reduction of the risk for organic contaminants relative to the most contaminated input
2960 material of the eligible input material list.

2961

2962 Based on the documented values for organic C, it is believed that the 3% organic C limit is an
2963 achievable target for precipitated phosphate salts that are derived from manure and municipal
2964 waste waters. When materials have an organic C content >3%, these organic compounds are
2965 often present as larger recognisable organic fractions (e.g. twigs, seeds; see STOWA, 2015)
2966 that can be easily removed via a material washing procedure (STOWA, 2015). Hence, **the**
2967 **overall share of the operational P-recovery facilities meet the proposed limit value of**
2968 **3% for organic C and techniques are available to achieve the proposed limits.**

2969

2970 In addition, the limit value of 3% for organic carbon should provide the following benefits:

2971

2972 • **Minimal compliance costs and administrative burdens for operators** in the
2973 context of the conformity assessment procedures in the proposal for the Revised
2974 Fertiliser Regulation. The **analytical procedures to trace and quantify individual**
2975 **organic contaminants are complicated and expensive**, with **costs** typically largely
2976 exceeding those for the determination of inorganic metals and metalloids
2977 (Langenkamp and Part, 2001). Although the relationship between organic C content
2978 and the abundance of contaminants is based on a limited dataset, specific
2979 contaminants have only been found in levels of concern for precipitated phosphate
2980 salts with an organic C content > 3%. Setting a limit value of 3% for organic C could
2981 enable a testing regime with a minimum of parameters, thus avoiding costly
2982 measurements of inorganic and organic compounds (metals and metalloids that are
2983 not regulated at PFC level, pharmaceutical compounds and personal care products,
2984 pesticides, plant protection chemicals and their decay products, agronomic efficacy
2985 parameters, PCDD/F, PCB, etc.). Setting a higher maximum limit for organic C
2986 would, conversely, be associated with complex and costly conformity assessment
2987 procedures as well as with further research and time delays required to derive safe
2988 limit values and to establish measurement standards for the broad range of
2989 contaminants;

2989

2990 • **Market confidence and acceptance** is a critical aspect for fertilisers derived from
2991 secondary raw materials. The overall share of the literature information that shows the
2992 agronomic efficacy and the product safety for precipitated phosphate salts is based on
2993 materials of high quality and low organic matter content. Moreover, the public, the
2994 media and governments are increasingly concerned about the presence of a broad
2995 spectrum of emerging organic pollutants of biogenic origin in consumer products and
2996 the food chain (Petrie et al., 2015). For many of such compounds, solid risk
2997 assessments are lacking to assess the validity of these concerns in precipitated
2998 phosphate salts. Setting a limit on organic C may further help support the proposed
2999 inclusion of fertilisers derived from secondary materials as CMCs in the Revised
3000 Fertiliser Regulation and their uptake by farmers and the broader public.

3001

3002

3003 5.4.5.2 Biological pathogens

3004 Examples of pathogens that could be present in eligible input materials, especially manure
3005 and municipal waste waters, include **bacteria** (e.g. *Salmonella*, *Legionella*, *Shigella*,
3006 *Clostridium*, *Vibrio cholera*, *Campylobacter*, *E. coli*), **viruses** (e.g. Hepatitis A and E virus,
3007 norovirus, rotavirus, enterovirus, reovirus, astrovirus, calicivirus), **protozoa** (e.g.
3008 *Cryptosporidium*, *Giardia*, *Entamoeba*, *Toxoplasma gondii*) and **worm eggs** (e.g. *Ascaris*,
3009 *Toxocara*) that can cause a broad array of animal and human diseases. During the production
3010 process of precipitated phosphate salts, some pathogens are killed during drying or
3011 precipitation at moderately high pH, but not all. **Especially for anaerobic spore-forming**
3012 **bacteria and parasitic nematodes, the elimination could be incomplete resulting in their**
3013 **accumulating in the precipitated phosphate salts** (Decrey et al., 2011; STOWA, 2015;
3014 Ehlert et al., 2016a). To a minor extent, also viruses could be transferred to the precipitated
3015 phosphate salt, but become rapidly deactivated as the precipitated phosphate salt is dried
3016 (Decrey et al., 2011). Therefore, the presence of viruses is not expected to be an issue of
3017 concern, on condition that the end material is dried after its production. Also the presence of
3018 organic toxins in precipitated phosphate salts should be far below levels of concern for
3019 human and environmental health protection (Gell et al., 2011).

3020 The adequate removal of biological pathogens is **of importance to control for antimicrobial**
3021 **resistance in the agro-food chain**. Antibiotic resistance can disseminate readily among
3022 microbial populations through horizontal gene transfer facilitated by the mobile genetic
3023 elements in antibiotic resistant bacteria, which can compromise the efficacy of antibiotics in
3024 animal and human medicine. In addition to the release of antibiotic residues in the
3025 environment (discussed in section 5.4.5.1), antimicrobial resistance is also affected directly
3026 by the development of **antibiotic resistant bacteria** in intestines of animals and humans,
3027 which end up in the excreta and eventually in the environment through the application of
3028 materials derived from biogenic wastes (Looft et al., 2012). Amongst others, *Clostridium* spp.
3029 might be resistant to multiple antimicrobial agents, and thus contribute to antimicrobial
3030 resistance in the food chain (Frieri et al., 2017). The application of low quality struvite
3031 derived from pig manure (no hygienisation steps applied, with an unknown presence of
3032 biological pathogens present in the struvite) has been shown to increase both the abundance
3033 and diversity of antibiotic resistant bacteria in soil and phyllosphere (Chen et al., 2017).

3034
3035 The presence of biological pathogens is also dependent on the **pre-processing techniques**
3036 **that are applied for the hygienisation of the eligible input materials** (Wallace et al.,
3037 2018). Contrasting evidence exists on the capability of mesophilic anaerobic digestion (36 or
3038 42°C) (Bagge et al., 2005; Xu et al., 2015) to remove pathogens, but methods that apply
3039 (thermophilic) anaerobic digestion after pasteurisation pretreatment and pressure sterilisation
3040 techniques result in a significant decrease or effective removal of spore-forming bacteria and
3041 *Ascaris* eggs (Sahlstrom et al., 2008; Bagge et al., 2010; Fröschle et al., 2015). Nonetheless,
3042 many different production routes for precipitated phosphate salts do not apply such
3043 hygienisation step.

3044

3045 Hence, for reasons of environmental and human protection, it is important to restrict the
3046 presence of biological pathogens in precipitated phosphate salts, and to provide as such
3047 substantial improvements relative to the landspreading of unprocessed manure and sewage
3048 sludge for sustainable agriculture, routes that are well-known for their contribution to
3049 pathogen spreading and antimicrobial resistance (Udikovic-Kolic et al., 2014; Chen et al.,
3050 2016; Singer et al., 2016). The requirements for the hygienisation of animal derived materials
3051 are laid down in the **Animal By-product Regulation (EC) 1069/2009**. The placing on the
3052 market of **processed manure, derived products from processed manure and guano from**
3053 **bats is subject to the requirements laid down in Annex XI (Chapter I, section 2) of**
3054 **Regulation (EU) 142/2011**. The standard processing method that such materials must
3055 undergo includes a heat treatment process of at least 70 °C for at least 60 minutes and they
3056 shall have been subjected to reduction in spore-forming bacteria and toxin formation, where
3057 they are identified as a relevant hazard. Nonetheless, the competent authority may authorise
3058 the use of other standardised process parameters than those referred to above, provided that
3059 such parameters ensure the minimising of biological risks. This involves, amongst others, the
3060 identification and analysis of possible hazards, a validation of the intended process by
3061 measuring the reduction of viability/infectivity of endogenous indicator organisms, including,
3062 for instance, *Enterococcus faecalis*, thermoresistant viruses such as parvovirus, parasites such
3063 as eggs of *Ascaris* sp., *Escherichia coli*, *Enterococcaceae*, and *Salmonella*. National
3064 legislation on biological pathogens in fertilising materials varies across EU Member States,
3065 with **some EU countries having strict limits on pathogens (e.g. France) and others**
3066 **having a more generic description on the need to restrict human health effects related to**
3067 **fertiliser management practices (e.g. the Netherlands).**

3068
3069 An approach is proposed for the microbial testing of precipitated phosphate salts that is
3070 dependent on the input material applied. **Standard microbial testing is proposed to involve**
3071 ***Salmonella* spp. and *Escherichia coli* or *Enterococcaceae*, but including additional**
3072 **requirements on spore-forming bacteria (*Clostridium perfringens* as an indicator**
3073 **organism) and *Ascaris* eggs when manure or municipal wastewater are used as input**
3074 **material for the production process.** Moreover, it is proposed that microbial testing is not
3075 required when certain pre-treatments (conditions for anaerobic digestion as specific in
3076 in Annex V of Regulation (EU) No 142/2011, pressure sterilisation, thermal hydrolysis,
3077 etc.) are applied that result in a hygienisation of the precipitated phosphate salt. The
3078 limit values for the different biological pathogens are proposed to be in line with the values as
3079 laid down in the French legislation (Norme NFU 44-095), as follows:

3080
3081 **Regardless of the input material applied, the precipitated phosphate salt shall meet all**
3082 **of the following requirements:**

- 3083 a) ... [not related to biological pathogens];
- 3084 b) ... [not related to biological pathogens];
- 3085 c) ... [not related to biological pathogens];
- 3086 d) No presence of *Salmonella* spp. in a 25 g sample; and
- 3087 e) No presence of *Escherichia coli* or *Enterococcaceae* in a concentration of more
3088 than 1000 CFU/g fresh mass.

3089
3090 Precipitated phosphate salts derived from materials listed under point (a) and (b)
3091 [i.e. municipal wastewaters and manure] shall meet the following requirements:
3092 f) ... [not related to biological pathogens];
3093 g) No presence of *Clostridium perfringens* in a concentration of more than 100
3094 CFU/g fresh mass; and
3095 h) No presence of viable *Ascaris* sp. eggs in a 25 g fresh mass.
3096

3097 By way of derogation from point d), e), g) and h), testing shall not be necessary for
3098 materials that have undergone following conditions:

- 3099 i. Pressure sterilisation through the heating to a core temperature of more than
3100 133°C for at least 20 minutes without interruption at a pressure (absolute)
3101 of at least 3 bars. The pressure must be produced by the evacuation of all
3102 air in the sterilisation chamber and the replacement of the air by steam
3103 ('saturated steam'); or
3104 ii. Processing in a pasteurisation/hygiene unit that reaches a temperature of
3105 70 °C during a time of at least one hour.
3106

3107 5.4.5.3 Metals and metalloids

3108 Metals and metalloids (semimetals) have been associated with contamination and potential
3109 toxicity or ecotoxicity. The group includes essential microelements that are required for the
3110 complete life cycle of an organism, but the establishment of **safe environmental levels** must
3111 consider the intake-response relations for both deficiency and toxicity. The degree of toxicity
3112 of metals and semimetals varies greatly from element to element and from organism to
3113 organism and depends on its concentration in soil, plant, tissue, ground water, etc.
3114

3115 Data on inorganic metals and metalloids (As, Cd, Cu, Cr (VI), Hg, Ni, Pb, and Zn) are
3116 mainly available for struvites and Ca-phosphates obtained from municipal waste waters, but
3117 information was also collected for manure, separately collected urine, and livestock stable
3118 slurries and particular food processing industries (potato industry and dairy industry) (section
3119 16.1.2). Nevertheless, municipal wastewaters are the input material that is most enriched in
3120 inorganic metals and metalloids (Eriksson, 2001). Materials from certain food-processing
3121 industries (Gendebien et al., 2001), (digestates) of vegetable waste from agriculture and
3122 forestry (Valeur, 2011; Al Seadi and Lukehurst, 2012; Ehlert et al., 2016b) contain
3123 significantly lower amounts of inorganic metals and metalloids.
3124

3125 As indicated in section 16.1.2, **precipitated phosphate salts show low levels of inorganic**
3126 **metals and metalloids**, both for P-salts that have been derived from municipal waste waters
3127 (precipitated from sludge liquor and digested sludge), manure, and other eligible input
3128 materials. Also for Ca phosphates of low organic C content, confidential information
3129 underscores that inorganic metals and metalloids in precipitated phosphate salts are not a
3130 major issue of concern. This is in conformity with the mechanism of precipitation that
3131 involves the formation of a separable solid substance from a *solution* by converting the
3132 substance into an insoluble form through the addition of chemicals. Metals are mostly

3133 associated with organic matter in sludges (Karvelas et al., 2003), for which reason the
3134 proposed maximum limit of 3% for organic C may help to limit the metal content in the
3135 precipitates.

3136
3137 Given that the metal/metalloid levels are **generally 1-2 orders of magnitude lower than the**
3138 **limits for inorganic contaminants at PFC level** for inorganic macronutrient fertilisers in the
3139 proposal for the Revised Fertiliser Regulation (Cd: 60-40-20 mg kg⁻¹ P₂O₅; Cr (VI): 2 mg kg⁻¹;
3140 Ni: 120 mg kg⁻¹; Pb: 150 mg kg⁻¹; As: 60 mg kg⁻¹), it is proposed to add **no specific limits**
3141 **for inorganic metals and metalloids, independent of the input material applied.**
3142 Moreover, Zn and Cu are not an issue of concern as the reported concentrations are generally
3143 low. Cd contents (on average <1.8 mg Cd kg⁻¹ P₂O₅, with a maximum documented value of
3144 3.7 mg Cd kg⁻¹ P₂O₅) are about 1 to 2 orders of magnitude lower than those encountered in
3145 phosphate rock (20 to more than 200 mg per kg P₂O₅; Oosterhuis et al., 2000) and 1 order of
3146 magnitude lower than those of mined and synthetic P-fertilisers (Kratz et al., 2016).

3147

3148 5.4.5.4 Emissions

3149 **Emissions from the application of fertiliser are generally attributed to four different**
3150 **mechanisms during material handling and application** (Midwest Research Institute,
3151 1998): (1) reactions between the soil and the applied fertiliser generating increased gaseous
3152 air emissions including NO_x, N₂O, NH₃, and SO₂; (2) soil disturbance generating particulate
3153 matter emissions where soil particles and other materials in the soil become airborne, (3)
3154 volatilization of the fertiliser immediately above and behind the application vehicle
3155 generating gaseous emissions (e.g. NH₃), and (4) particulate matter emissions from the
3156 fertiliser itself during handling or application.

3157

3158 The elements that underlie the mechanisms 1, 2 and 3 are complex and depend on a number
3159 of material properties, soil and climatic properties via complex relationships that have not
3160 been characterised quantitatively. Similar to mined and synthetic fertilisers, the best form of
3161 emission control identified for precipitated phosphate fertilisers to date **is through**
3162 **appropriate "nutrient management"** (Midwest Research Institute, 1998). Here, nutrient
3163 management is defined as the form, placement, and timing of the fertiliser application relative
3164 to the crops' need for fertiliser. Therefore, **it is proposed to support the general labelling**
3165 **requirements for all PFC materials in the proposal for the Revised Fertiliser**
3166 **Regulation**, including instructions for intended use, intended application rate, timing and
3167 frequency, recommended storage conditions, and any other relevant information on measures
3168 recommended to manage risks.

3169

3170 The fourth mechanism may generate **airborne dusts and particulate matter emissions**,
3171 which could penetrate into the pulmonary alveolar region of the lungs. Moreover, particulate
3172 emissions could arise during specific handling operations during fertiliser production
3173 processes (e.g. blending). Airborne dusts are of particular concern because they are well
3174 known to be associated with classical widespread occupational lung diseases such as

3175 pneumoconioses, especially at higher levels of exposure. Industrial handling and application
3176 of precipitated phosphate salts could thus represent potential physical hazards with regards to
3177 health hazards related to the inhalation of dusts, as well as environmental pollution. The
3178 European standard EN 15051 describes the measurement of the dustiness of a powder by
3179 using a rotating drum or continuous drop method. Nonetheless, the dustiness of a powder
3180 product, defined as the propensity of a material to generate airborne dust during its handling
3181 (Lidén, 2006), not only depends on the **intrinsic physical properties of the material but**
3182 **also on the handling scenario.**

3183
3184 The European Regulation (EC) No. 1272/2008 on classification, labelling and packaging
3185 (CLP) of substances and mixtures aligns the European Union system of classification,
3186 labelling and packaging of substances and mixtures to the UN Globally Harmonized System
3187 of Classification and Labelling of Chemicals, GHS. The CLP regulation requires
3188 manufacturers, importers, and downstream users to classify substances or mixtures according
3189 to the harmonized classification criteria for physical, health, or environmental hazards. CLP
3190 Articles 5, 6, and 8.6 clearly point out that available and new information on substances and
3191 mixtures shall relate to the form or physical state(s) in which the substance or mixture is
3192 placed on the market and in which it can reasonably be expected to be used. Furthermore,
3193 CLP Title V required that by 1 December 2010, substances that met the criteria for
3194 classification as hazardous according to the CLP Regulation or substances subject to
3195 registration under REACH (Regulation (EC) No 1907/2006 concerning the Registration,
3196 Evaluation, Authorisation and Restriction of Chemicals) must have been notified to the
3197 classification and labelling inventory of the European Chemicals Agency. Safety data sheets
3198 are effective and well-accepted tools to communicate safety information of products in the
3199 supply chain (Pensis et al., 2014). In addition, the ECHA Guidance to the CLP Regulation
3200 published on 13 July 2009 mentions that “for human health, different forms (e.g. particle
3201 sizes, coating) or physical states may result in different hazardous properties of a substance or
3202 mixture in use” and therefore they may be classified differently. Hence, **correct**
3203 **classification and labelling allows downstream users to assess the risk associated with**
3204 **airborne dust during the handling and application of the heterogeneous materials**
3205 **within the CMC precipitated phosphate salts, and to take the necessary measures to**
3206 **prevent any potential adverse impacts in case a risk has been identified.**

3207
3208 Directive **2010/75/EU** of the European Parliament and the Council on industrial emissions
3209 (the **Industrial Emissions Directive or IED**) is the main EU instrument regulating pollutant
3210 emissions from industrial installations. This directive effectively controls for gaseous and
3211 particulate matter emissions to the environment during production processes of fertilising
3212 materials. Moreover, also the **Directive 2008/50/EC** of the European Parliament and of the
3213 Council of 21 May 2008 on ambient air quality and cleaner air for Europe establishes air
3214 quality objectives, including those for fine particulate matter.

3215
3216 It is concluded that the review of the literature and comments from the STRUBIAS sub-group
3217 provided no information on specific control measures required for precipitated phosphate
3218 salts to control for emissions. **It is indicated that the provisions in the proposal for the**

3219 **Revised Fertiliser Regulation on labelling and existing EU legislation are sufficiently**
3220 **effective to control for any adverse impacts associated to emissions during the**
3221 **production, handling and application of precipitated phosphate salts.**
3222

3223 5.4.5.5 Occupational health

3224 **Council directive 89/391/EEC on the introduction of measures to encourage**
3225 **improvements in the safety and health of workers at work seeks to adequately protect**
3226 **workers and encourages improvements in occupational health and safety in all sectors**
3227 **of activity, both public and private.** The Directive also promotes workers' rights to make
3228 proposals relating to health and safety, to appeal to the competent authority and to stop work
3229 in the event of serious danger. No further legal requirements are therefore proposed.
3230

3231 5.4.6 Physico-chemical properties

3232 5.4.6.1 Physical impurities

3233 It has been demonstrated that washed struvites may contain physical impurities including
3234 gravels and organic matter such as seeds, twigs, etc. (STOWA, 2015).
3235



3236 **Figure 2: Isolated impurities from (low-quality) struvite precipitate samples (adopted from**
3237 **STOWA, 2015).**
3238
3239

3240 Given that these impurities are often vectors for the adsorption of contaminants (STOWA,
3241 2015), it is proposed to **limit visually detectable physical impurities (e.g. recognisable**
3242 **organic materials, stones, glass, and metals) greater than 2 mm to < 0.5%.**
3243

3244 5.4.6.2 Dry matter content

3245 **It is proposed to set a threshold of 90% for dry matter content** in order to prevent the
3246 biological re-contamination of precipitated phosphate salts during the storage and transport of
3247 the material prior to application on land. Precipitated phosphate salts may include hydrated
3248 salts, for which reason common analytical methods for the determination of the dry matter
3249 content could cause a chemical alteration of the product (e.g. struvite loses 51% of its weight
3250 when dried at 105°C). Therefore, it is proposed to determine dry matter content using
3251 alternative methods that do not remove the crystallisation water from the end-material.

3252 Specific methods that apply lower drying temperatures are currently under development and
3253 could be used for all materials covered under this CMC (e.g. ISO/AWI 19745, Determination
3254 of Crude (Free) water content of Ammoniated Phosphate products -- DAP, MAP -- by
3255 gravimetric vacuum oven at 50 °C; CEN method under development - vacuum drying at
3256 40°C).

3257

3258 5.4.6.3 pH

3259 Precipitated phosphate salts typically have a neutral to slightly basic pH. Hence, pH shocks
3260 for the soil microorganisms and fauna are not expected, and no specific requirements are
3261 proposed for pH.

3262

3263 5.4.6.4 Granulometry

3264 Agglomeration is used as a means of improving product characteristics and enhancing
3265 processing conditions. In addition to these benefits, agglomeration also solves a number of
3266 problems associated with material particle sizes:

- 3267 ○ Significant dust reduction/elimination and mitigation of product loss;
- 3268 ○ Improved handling and transportation;
- 3269 ○ Improved application and use;
- 3270 ○ Increased water infiltration as there is no risk for the blocking of soil pores.

3271 It is noted that the particle form (granule, pellet, powder, or prill) of the product shall be
3272 indicated on the **label** of solid inorganic macronutrient fertilisers (see labelling requirements
3273 in the proposal for the Revised Fertiliser Regulation). According to the STRUBIAS
3274 subgroup, it is not considered relevant to set a criterion on granulometry or particle size
3275 distribution, and hence it is proposed to leave this aspect open to the market.

3276

3277

3278 5.4.7 Handling and storage

3279 The storage of hydrated precipitated phosphate salts struvite and hydrated dicalcium
3280 phosphates under high temperatures can cause the gradual loss of ammonia and water
3281 molecules, ultimately transforming the precipitated phosphate salt into different mineral
3282 phases (e.g. amorphous magnesium hydrogen phosphate). The storage of precipitated
3283 phosphate salts under dry conditions promotes the inactivation or removal of bacterial and
3284 viral pathogens, and prevents possible re-contamination (Bischel et al., 2015). **It is proposed**
3285 **that physical contacts between input and output materials shall be avoided in the**
3286 **production plant, and that finished precipitated phosphate salts shall be stored in dry**
3287 **conditions.**

3288

3289 5.5 Thermal oxidation materials & derivates

3290 5.5.1 Scope delimitation and possible uses

3291 This CMC comprises materials that have **undergone a thermal oxidation in a non-oxygen**
3292 **limiting environment**, as well as derivates that are (partially) manufactured from those
3293 materials (see section 5.1.2). Hence, the CMC includes both **ashes and slags** as collected
3294 from the combustion reactor, as well as materials with a different chemical composition
3295 derived from those ("**derivates**"; e.g. triple superphosphate derived from sewage sludge
3296 ashes). It is referred to section 5.3.3 for a detailed explanation on the technical provisions of
3297 dealing with such "precursors" or "intermediates" in the framework of the Revised Fertiliser
3298 Regulation and this CMC.

3299
3300 Thermal oxidation materials & derivates may have a variety of applications as fertilising
3301 products in agriculture and forestry (Insam and Knapp, 2011; Vassilev et al., 2013a).
3302 Primarily, they can be used as ingredients in products that have an intended use as a fertiliser
3303 or a liming material as follows:

- 3304 • Ashes and slags resulting from the combustion or melting of solid biomass can
3305 contain valuable plant macronutrients such as K, P, S, Ca and Mg, with most of them
3306 in relatively soluble forms (Vesterinen, 2003; Obernberger and Supancic, 2009;
3307 Haraldsen et al., 2011; Insam and Knapp, 2011; Brod et al., 2012) (see section
3308 5.5.4.1). Ca, Mg, and K contents are usually present in the form of oxides,
3309 hydroxides, carbonates and silicates, associated to basic properties; therefore, some
3310 ashes can serve as liming agent (Demeyer et al., 2001; Saarsalmi et al., 2010;
3311 Ohecova et al., 2014). Phosphorus occurs as phosphates of Ca, K, Fe, and Al (Tan
3312 and Lagerkvist, 2011), and certain thermal oxidation materials (e.g. poultry litter ash)
3313 can have P-contents that are equivalent to those of straight macronutrient P-fertilisers.
3314 Hence, thermal oxidation materials & derivates may serve **as a component material**
3315 **for the production of solid macronutrient inorganic fertilisers and organo-**
3316 **mineral fertilisers.**
- 3317
3318 • When ash gets in contact with soil water, the pH of the soil solution increases as the
3319 oxides and hydroxides in the ash dissolve and hydroxide ions are formed. Thus, the
3320 ash has **a liming effect** when added to the soil as an amendment and can be used to
3321 neutralise acidity. The chemical constituents that determine the liming effect are
3322 essentially the same as for lime. However, ash is a more complex chemical mixture
3323 and the liming effect is lower than for lime products when expressed per unit weight
3324 (Karlton et al., 2008). The ash that comes directly from the thermal oxidation process
3325 is not chemically stable in the presence of moisture and CO₂ from the atmosphere.
3326 The oxides in the ash react with water and CO₂ and form hydroxides and carbonates.
3327 During this process the ash increases in weight (Karlton et al., 2008). As outlined by
3328 the STRUBIAS sub-group, there is a clear need to label the liming equivalence of
3329 ashes as also negative effects on productivity may arise when the liming effect on soil
3330 pH is larger the normal acidification of agricultural soils. **Therefore, it is proposed**

3331 that the neutralizing value shall be labelled to PFC products when the neutralising
3332 value > 15 (equivalent CaO) or 9 (equivalent HO-).
3333

- 3334 • Any fertilising product that has minimum macronutrient content should be marketed
3335 as a macronutrient fertiliser in the proposal of the Revised Fertiliser Regulation,
3336 independent of the quantity of micronutrients present in the fertiliser. Considering the
3337 content of macronutrients (N, P, K, Mg, Ca, S, Na; as defined in the Revised Fertiliser
3338 Regulation) in thermal oxidation materials & derivates (section 16.2.1), a possible
3339 entry in the current proposal for the Revised Fertiliser Regulation **for thermal**
3340 **oxidation materials & derivates as micronutrient fertilisers is unlikely.**
3341
- 3342 • Some studies have indicated the potential of ashes, often coal ashes with a low
3343 content of plant available nutrients, to improve physical properties of the soil,
3344 including bulk density, porosity, water holding capacity and/or to cause a shift in soil
3345 texture classes (Jala and Goyal, 2006; Basu et al., 2009; Pandey and Singh, 2010;
3346 Blissett and Rowson, 2012; Yao et al., 2015). Therefore, ashes are sometimes
3347 promoted as an inorganic soil improver. Nevertheless, beneficial increases in physical
3348 soil properties are only observed in applications of large ash quantities (often 5-20%
3349 or more weight percent of the receiving soil; application rates of 70-500 tonnes ha⁻¹)
3350 (Chang et al., 1977; Buck et al., 1990; Khan et al., 1996; Prabakar et al., 2004). Such
3351 application rates are associated to a huge environmental footprint for transport, and a
3352 substantial dilution of nutrients in the receiving soil when nutrient-poor ashes are
3353 applied. Moreover, laboratory incubation studies found that addition of fly ash to
3354 sandy soils has a variable impact upon soil biota, with some studies documenting a
3355 severe inhibition of microbial respiration, enzyme activity and soil nitrogen cycling
3356 processes such as nitrification and N mineralisation (Jala and Goyal, 2006). The
3357 STRUBIAS sub-group indicated that **no market and demand exists for the use of**
3358 **thermal oxidation materials, such as coal ash, that exclusively target soil**
3359 **improving functions in the Revised Fertiliser Regulation.** Rather, any soil
3360 improving function of thermal oxidation materials is perceived as a potential **side-**
3361 **benefit** for those ashes acting as a macronutrient fertiliser or a liming agent.
3362 Therefore, the recovery rules shall include the necessary provisions to ensure that the
3363 revised Fertiliser Regulation shall not be used to enable a CE status for waste
3364 materials and by-products that have no added value for agriculture (e.g. ashes from
3365 fossil fuel combustion) (see section 5.5.2 on input materials).
3366

3367 Note that the section above on possible uses is only informative to set a possible window of
3368 opportunities for thermal oxidation materials & derivates in view of their possible intended
3369 uses and associated application rates. The proposed framework of the revised Fertiliser
3370 Regulation enables, however, that, in principle, all CMCs can be used in all PFC categories.
3371

3372 For thermal oxidation materials & derivates, **national legislation** related to the material
3373 properties and their use exists in different EU Member States. Moreover, national End-of-
3374 Waste protocols have been described for certain thermal oxidation materials (e.g. UK poultry

3375 litter ash quality protocol). These initiatives mostly focus on inorganic metals and metalloids
3376 (e.g. Cd, Hg, etc.) and persistent organic pollutants (e.g. PAH, PCDD/Fs, etc.), for which
3377 reason a clear reference to these initiatives will be made in the respective sections of this
3378 document.
3379

3380 5.5.2 Input materials and reactants

3381 5.5.2.1 Targeted input materials

3382 a) Waste incineration at 850 °C for > 2 seconds is generally considered as an effective
3383 technique to remove biological pathogens and volatile pollutants from non-hazardous
3384 waste streams, for which reason in principle a wide-ranging list of waste input materials
3385 is acceptable. Therefore, the proposal is to include **waste and (industrial) by-products**
3386 within the meaning of Directive 2008/98/EC, with following input materials being
3387 **excluded**:

3388 i. *Waste and by-products classified as hazardous* according to Annex III to
3389 Directive 2008/98/EC (Waste Framework Directive). This exclusion is
3390 justified as (1) all non-hazardous substances of the European List of Waste
3391 cover the most relevant input materials that can be used for nutrient recovery
3392 in a techno-economic feasible manner, and (2) some residues from hazardous
3393 waste could still be associated to risks in ashes and slags.

3394 ii. *Mixed municipal waste*. The residual ash fraction after incineration of this type
3395 of waste should normally have a total organic C content of <3%, but can
3396 potentially contain high concentrations of hazardous residues originating from
3397 the input waste (Zhang et al., 2004). Occurrences of hazardous chemicals such
3398 as herbicides, dioxins and furanes and their decay compounds in leachate
3399 from ashes disposed at municipal waste landfills have been reported (Priester
3400 et al., 1996; Römcke et al., 2009). Moreover, the nutrient content of mixed
3401 municipal solid waste is relatively low (section 16.2.1).
3402

3403 In addition to the waste materials, following input materials are also proposed for inclusion:

3404 ○ **living or dead organisms or parts thereof**, which are unprocessed or processed only by
3405 manual, mechanical or gravitational means, by dissolution in water, by flotation, by
3406 extraction with water, by steam distillation or by heating solely to remove water, or which
3407 are extracted from air by any means, except:

- 3408 ○ materials originating from mixed municipal waste,
- 3409 ○ sewage sludge, industrial sludge or dredging sludge,
- 3410 ○ animal by-products or derived products falling within the scope Regulation
3411 (EC) No 1069/2009 for which no end point in the manufacturing chain has
3412 been determined in accordance with the third paragraph of Article 5(2) of that
3413 Regulation,
- 3414 ○ materials separately listed under other points;

- 3415 ○ **Animal by-products of category 2 and 3** pursuant to the Regulation (EC) No 1069/2009
3416 (Animal By-Products Regulation). It is noted that the JRC is not aware of any
3417 authorisation by the European Commission for the use of Category 1 animal by-product
3418 materials for the production of fertilising materials to be used in the food production
3419 system. The main reason is to control for animal health, in particular the possible
3420 transmission of prion diseases (Paisley and Hostrup-Pedersen, 2005a; Saunders et al.,
3421 2008). Prion diseases, or transmissible spongiform encephalopathies, are fatal
3422 neurodegenerative diseases impacting a number of mammalian species, including cattle
3423 (bovine spongiform encephalopathy, BSE or ‘mad cow’ disease), sheep and goats
3424 (scrapie), deer, elk and moose (chronic wasting disease) and humans (Creutzfeldt-Jakob
3425 disease, and others). Scrapie and chronic wasting disease are of particular environmental
3426 concern as they are horizontally transmissible and remain infectious after years in the
3427 environment. It is likely that the environment serves as a stable reservoir of infectious
3428 chronic wasting disease and scrapie prions (Saunders et al., 2008). Johnson and
3429 colleagues have shown that prions bound to soil minerals are more infectious than
3430 unbound prions (Johnson et al., 2007). In addition, the disposal of mortalities during BSE
3431 outbreaks, both in the past and potential future disposal events, serves as another
3432 environmental source of prions with the potential to infect humans. Therefore, the
3433 possible presence of prions, the main contaminant of interest that discerns category 1
3434 from category 2 and 3 animal by-products, poses a significant environmental concern
3435 (Saunders et al., 2008). Prions present in category 1 material are associated to the highest
3436 risk from a human and animal health perspective for thermal oxidation materials &
3437 derivatives; this type of contaminants shows the highest resistance against thermal
3438 degradation and adsorbs in an irreversible manner to soil particles (Saunders et al., 2008).
3439 **The prion infectivity risks for animals are about two orders of magnitude higher**
3440 **than the infectivity risk for humans through the fertiliser-soil-food exposure**
3441 **pathway** (Paisley and Hostrup-Pedersen, 2005b), implying that possible measures to
3442 control for animal health will effectively control for human health issues. Other possible
3443 contaminants that may exclusively be present in category 1 materials, but not in category
3444 2 and 3 animal by-products, including those listed in Group B(3) of Annex I to Directive
3445 96/23/EC will be effectively removed during the combustion process (e.g. mycotoxins
3446 (De Saeger et al., 2016), PCBs (see section 5.5.5.2.);
- 3447 ○ **bio-waste** within the meaning of Directive (EU) 2018/851 amending Directive
3448 2008/98/EC resulting from separate bio-waste collection at source;
- 3449 ○ **Residues from the composting, anaerobic digestion, pyrolysis or gasification of living**
3450 **and dead organisms, bio-waste, and animal by-products** as listed above;
- 3451 ○ **Auxiliary fuels** (natural gas, liquefied petroleum gas, natural gas condensate, process
3452 gases and components thereof, crude oil, coal, coke as well as their derived materials),
3453 when used in incineration, co-incineration or biomass combustion plants to process input
3454 materials listed above;
- 3455 ○ **Substances which occur in nature to be used in production processes of the iron and**
3456 **steel industry**, including non-hazardous by-products generated by this industry;

3457

3458 Moreover, the **addition of combustion additives and reactive agents that are required for**
3459 **thermo-chemical conversion processes** that aim at the production of higher-quality ashes
3460 and slags is **permitted as outlined in section 5.5.3.2 and 5.5.3.3.**

3461

3462 The proposed list of eligible input materials takes into consideration following elements
3463 indicated by the STRUBIAS sub-group:

3464 ○ Incineration is a well-demonstrated technique to remove many organic and organo-
3465 chemical pollutants from waste-based materials. Therefore, the **CMC "thermal**
3466 **oxidation materials & derivates" offers unique possibilities for the production of**
3467 **fertilising materials from a broad range of biogenic and industrial waste**
3468 **streams;**

3469 ○ **All major streams that contain dissipated P should preferentially be included** as
3470 eligible input material for this CMC as most of these streams are also C-rich and can
3471 be combusted;

3472 ○ Also, the technical proposals should include ashes that contain plant resources, other
3473 than P (e.g. Ca, Mg, micronutrients, etc.). Often these materials are derived from
3474 biomass and specific industries (e.g. pulp and paper industry);

3475 ○ Nonetheless, there is a need **to exclude certain input materials** that might introduce
3476 a risk for the presence of additional contaminants in the ashes and slags, and that
3477 **could lead to more complex compliance schemes** (e.g. mixed municipal waste
3478 fractions separated through mechanical, physicochemical, biological and/or manual
3479 treatment, hazardous chemical wastes, etc.);

3480 ○ **Fossil fuels are sometimes used in small quantities** (e.g. during start-up, after
3481 maintenance, as combustion additives, as a reducing agent, etc.) **in waste (co-)**
3482 **incineration plants and biomass combustion plants.** At the same, the basis of
3483 support to use the EU fertiliser regulation as a route to provide a CE status to
3484 **residues from fossil-fuel based thermal plants is lacking**, even if minimum
3485 quantities of biomass or sewage sludges are used as an input material. Therefore, a
3486 reference is made to the auxiliary nature of the fossil fuels, and to the type of plants
3487 where fossil fuels can be used (i.e. incineration, co-incineration or biomass
3488 combustion plants).

3489 ○ **Steel and iron slags** are produced through a thermal oxidation process, for which
3490 reason industrial by-products from the sector could be classified as thermal oxidation
3491 materials & derivates. Moreover, there are ongoing developments from the sector to
3492 further increase the quality of such slags for their valorisation in agriculture (e.g.
3493 adding P-rich input materials such as sewage sludge or animal bones in the reactors).

3494

3495 5.5.2.2 *Reactants*

3496 Reactants are added in the production process of thermal oxidation materials & derivates with
3497 the objective i) to facilitate the operational conditions of the combustion process in the case
3498 of **fuel additives**, (ii) to increase the **quality** of the resulting fertilising materials in
3499 **thermochemical processes, and (iii) as part of post-combustion manufacturing processes.**

3500 Fuel additives

3501 Some biomass fuels have high K contents, which react with other ash forming elements (i.e.
 3502 Cl, Si, P and S) and lead to different ash related operational problems (Wang et al., 2012a).
 3503 Biomass ash sintering causes different negative effects in the combustion plants: (a)
 3504 formation of ash agglomerates that obstruct the air-biomass contact, which may cause an
 3505 inhibition of the fluidisation in the fluidised bed equipment; (b) formation of sintered ash
 3506 deposits on the heat exchangers resulting in a reduced heat exchange capacity, difficulty in
 3507 cleaning the deposited ash and, occasionally, mechanical failure in the heat exchangers. The
 3508 ash related operational problems thus reduce the efficiency of the combustion systems, cause
 3509 extra costs for boiler cleaning and maintenance, and hinder further utilisation of biomass
 3510 materials as combustion fuels. Ash related operational problems are especially severe during
 3511 combustion of biomass fuels derived from the agricultural sector, contaminated waste
 3512 materials and residues from bio-refinery and food processing plants. Utilisation of natural and
 3513 chemical additives to abate these problems has been studied and tested for several decades.
 3514 **Various additives can mitigate ash related issues via the following mechanisms:** 1)
 3515 capturing problematic ash species via chemical adsorption and reactions, 2) physical
 3516 adsorption and removal of troublesome ash species from combustion facilities, 3) increasing
 3517 the biomass ash melting temperature by enhancing inert elements/compounds in ash residues,
 3518 and 4) limiting biomass ash sintering by diluting and pulverising effects from the additives.

3519 Additives are grouped according to the contained reactive compounds, including Al-silicate
 3520 based additives, sulphur based additives, calcium based additives, and phosphorus based
 3521 additives. Additives with strong chemical adsorption and reaction capacities can minimize K
 3522 related ash sintering, deposition and slagging during biomass combustion processes. As
 3523 observed from Table 3, **most additives are natural materials and minerals** that are on the
 3524 list of proposed permitted input materials (see 5.5.2). Also, chemicals such as ammonium
 3525 sulphate, aluminium sulphate, iron sulphate, ammonium phosphate, phosphoric acid and
 3526 DCP, are listed (Table 3).

3527

3528 **Table 3: List of common additives used during the combustion process (adopted from Wang et**
 3529 **al., 2012a).**

Suspected effects	Additives	Main components
Chemical adsorption and interaction	kaolin, halloysite,	$Al_2Si_2O_5(OH)_4$, $Al_4(OH)_8/Si_4O_{10} \cdot 10H_2O$
	cat litter, emathlite, clay minerals, clay sludge	Mixture of aluminum silicates (i.e. $Al_2Si_4O_{10}$, $Al_2Si_4O_{10}$), silica and alumina
	illite	one explain $KAl_2Si_2AlO_{10}(OH)_2$
	detergent zeolites	$Na_x[(AlO_2)_x(SiO_2)_y] \cdot zH_2O$
	ammonia sulfate, aluminum sulfate, iron sulfate,	$(NH_4)_2SO_4$, $Al_2(SO_4)_3$, $Fe_2(SO_4)_3$
	ammonia phosphate, phosphoric acid	$(NH_4)_3PO_4$, H_3PO_4
	DCP	$Ca(H_2PO_4)_2 \cdot H_2O$
	limestone, lime, marble sludge	$CaCO_3$, CaO
	sewage sludge, paper sludge, peat ash, coal fly ash	$Al_4Si_4O_2$
	dolomite, bauxite, quartz, titanium oxide	$CaMg(CO_3)_2$, SiO_2 , Al_2O_3 , TiO_2
Physical adsorption	kaolin, zeolite, halloysite	$Al_2O_2(SiO_2)_2 \cdot (H_2O)_2$, $Al_2Si_2O_5(OH)_4$,
	clay minerals	aluminum silicates with different Al/Si ratios (i.e. $Al_2Si_4O_{10}$, $Al_2Si_4O_{10}$)
	clay sludge, sewage sludge, paper sludge	Mixture of aluminum silicates (i.e. $Al_2Si_4O_{10}$, $Al_2Si_4O_{10}$), detergent zeolites
	lime, limestone, dolomite, calcined dolomite	$CaCO_3$, CaO , $CaMg(CO_3)_2$, $CaO \cdot MgO$
	bauxite, gibbsite	Al_2O_3 , $Al(OH)_3$
Dilution effect and inert elements enrichment	bauxite, lime, limestone,	Al_2O_3 , $CaCO_3$, CaO
	silicon oxide, marble sludge,	SiO_2 , $CaCO_3$
Restraining and powdering effects	lime, limestone	$CaCO_3$, CaO

3530

3531

3532 Reactants for thermochemical P-recovery processes to produce better quality fertilising
3533 materials

3534 Some **thermochemical P-recovery approaches** rely on the addition of reactants to improve
3535 the quality of the resulting ashes and slags or the transformation of P-compounds into the
3536 gaseous phase. It is referred to section 15.2.2 for a detailed description of such production
3537 processes in planning, pilot or operational phase (RecoPhos, AshDec, Mephrec, EuPhoRe,
3538 etc.). These processes commonly use **alkaline and/or earth alkali salts, coke and**
3539 **chlorination agents** to reduce and volatilise compounds of interest for their posterior
3540 removal (e.g. metals in AshDec process) or isolation (e.g. elemental P in thermo-reductive
3541 RecoPhos process). Considering the emerging nature of P-recovery production through
3542 thermal processes and the evolving legal framework for fertilisers in the EU, it is not unlikely
3543 that more processes will develop in the near future. Therefore, the STRUBIAS sub-group
3544 indicated that the list of reactants should not be exhaustive and should remain as unrestricted
3545 as possible. This is in line with the provisions for CMC 1 ("Virgin material substances and
3546 mixtures") in the proposal for the revised Fertiliser Regulation, where also minimal
3547 provisions on use of virgin materials as intermediates in production processes have been
3548 defined.

3549

3550 Chemical reactants for post-combustion manufacturing processes

3551 As outlined in section 5.3.3, "**two-step**" manufacturing processes enable the further
3552 processing of intermediate materials, such as incineration ashes. The principle of the two-step
3553 manufacturing processes for this CMC is that the thermal oxidation process removes specific
3554 contaminants (e.g. organic contaminants, biological pathogens, etc.), after which a
3555 subsequent chemical manufacturing step can be applied to produce a fertilising material of a
3556 preferred chemical composition and of low metal content. In the proposals for the technical
3557 requirements, the thermal oxidation process should meet the conditions for waste incineration
3558 and will be tested for specific organic contaminants (e.g. PAH, see section 5.5.5.2). Ashes
3559 that meet these requirements will thus have low levels of organic contaminants.

3560 Therefore, it is **proposed that such materials can be further processed with (chemical)**
3561 **intermediates to shape a high-quality material that can be incorporated into a CE**
3562 **marked fertiliser**. Specifically, it is proposed that the obtained intermediate material can be
3563 further processed using an extensive set of substances/mixtures, as long no new "risk
3564 materials" are introduced in the process. Risk materials are in this context defined as
3565 materials which can introduce biological contamination or other non-intentional organic or
3566 inorganic contaminants. Hence, it is proposed to enable only virgin materials (and possibly
3567 *safe* industrial by-products as permitted within the framework of the revised Fertiliser
3568 Regulation, see section 4.2.2) for such post-incineration manufacturing steps, and **to exclude**
3569 **waste materials, materials which have ceased to be waste, and animal by-products**
3570 (similar to the provisions for CMC 1). Because the process limitations on the second step of
3571 the processes are minimal, a high degree of **sovereignty is allowed for manufacturers to**
3572 **apply processes of choice** and to promote the development of innovative processes that start
3573 from intermediate materials. The proposed provisions cover all wet chemical processes that
3574 involve the removal of P along with other elements from the ashes by elution, after which the

3575 dissolved elements are recovered by solidification, precipitation, ion exchange or membrane
3576 technologies. The elution process predominantly involves the use of strong acidic solvents,
3577 though on occasion, alkaline substances have been used or a combination of the two. The list
3578 of solvents includes, amongst others, sulphuric acid (H₂SO₄), hydrochloric acid (HCl), nitric
3579 acid (HNO₃), phosphoric acid (H₃PO₄), oxalic acid (H₂C₂O₄), and sodium hydroxide
3580 (NaOH). Also the addition of other substances, such as steam (used for instance in the
3581 EcoPhos process), will be permitted in the post-combustion manufacturing process. Finally,
3582 intermediates used to produce chemical fertiliser blends (e.g. NPK) will be permitted. **The**
3583 **end-material from the whole manufacturing process ("thermal oxidation materials &**
3584 **derivates that will be incorporated in the CE marked fertilising product") will then be**
3585 **subject to further testing for inorganic contaminants** (see section 5.5.5.1).
3586

3587 5.5.2.3 *Proposals for input materials and reactants*

3588 Based on the information presented in the paragraphs 5.5.2.1 and 5.5.2.2, following proposal
3589 is put forward:

3590 A CE marked fertilising product may contain thermal oxidation materials exclusively
3591 obtained through thermochemical conversion under non-oxygen-limiting conditions
3592 from one or more of the following input materials:

- 3593 a) living or dead organisms or parts thereof, which are unprocessed or processed only
3594 by manual, mechanical or gravitational means, by dissolution in water, by
3595 flotation, by extraction with water, by steam distillation or by heating solely to
3596 remove water, or which are extracted from air by any means, except:
- 3597 ○ materials originating from mixed municipal waste,
 - 3598 ○ sewage sludge, industrial sludge or dredging sludge,
 - 3599 ○ animal by-products or derived products falling within the scope
3600 Regulation (EC) No 1069/2009, and
 - 3601 ○ materials separately listed under points c) – g);
- 3602 b) animal by-products or derived products of category 2 and 3 falling within the
3603 scope of Regulation (EC) No 1069/2009;
- 3604 c) bio-waste within the meaning of Directive (EU) 2018/851 amending Directive
3605 2008/98/EC resulting from separate bio-waste collection at source;
- 3606 d) residues from composting, anaerobic digestion, pyrolysis or gasification as a pre-
3607 treatment technique of the input materials listed under point (a) - (c);
- 3608 e) waste and by-products within the meaning of Directive 2008/98/EC with the
3609 exception of:
- 3610 ○ materials which display one or more of the hazardous properties listed in
3611 Annex III of Directive 2008/98/EC,
 - 3612 ○ materials originating from mixed municipal waste,
 - 3613 ○ bio-waste within the meaning of Directive (EU) 2018/851 amending
3614 Directive 2008/98/EC resulting from separate bio-waste collection at
3615 source, and
 - 3616 ○ animal by-products of category 1 or derived products falling within the
3617 scope of Regulation (EC) No 1069/2009;

- 3618 f) auxiliary fuels (natural gas, liquefied petroleum gas, natural gas condensate,
3619 process gases and components thereof, crude oil, coal, coke as well as their derived
3620 materials), when used in incineration, co-incineration or biomass combustion
3621 plants to process input materials listed under points (a) - (e);
3622 g) substances which occur in nature to be used in production processes of the iron and
3623 steel industry, including non-hazardous by-products generated by this industry; or
3624 h) chemical substances, with the exception of:
3625 o those listed under points a) - g),
3626 o wastes within the meaning of Directive 2008/98/EC,
3627 o animal by-products or derived products falling within the scope of
3628 Regulation (EC) No 1069/2009, and
3629 o non-biodegradable polymers.
3630

3631 *[Note: The exclusion of a material from a lettered item does not prevent it from being an*
3632 *eligible component material by virtue of another lettered item]*
3633

3634

3635 5.5.3 Production process conditions

3636 Thermal oxidation materials can be obtained from combustion plants that are specifically
3637 designed for the **purpose** of producing fertilising materials or they can be a production
3638 residue resulting from a process aimed at **disposing waste** or **producing a different primary**
3639 **product** (e.g. steel). The thermal oxidation plant can be a **stand-alone** installation or be
3640 **integrated** into another system.

3641

3642 5.5.3.1 Pre-processing

3643 Input materials with high **moisture content** are typically subject to mechanical treatments
3644 such as thickening, dewatering or drying. Occasionally, treatments combining an increase in
3645 dry matter content of the input material and energy recovery (e.g. anaerobic digestion,
3646 hydrothermal carbonisation) may be applied. Hot gases exiting the furnace could also pass
3647 through an energy recovery system at the thermal oxidation plant whereby the energy can be
3648 (partly) recovered in the form of heat or electricity. The heat can be used for maintaining the
3649 combustion temperatures or for the pre-drying of the input material prior to combustion.
3650

3651 **No limitations** are proposed on any possible pre-processing steps as long as the input
3652 material list is respected. This implies that the input materials, and a combination thereof,
3653 may be physically mixed, screened, sized and chemically reacted. Also, any materials
3654 obtained from material transformation processes such as digestion, composting, pyrolysis,
3655 hydrothermal carbonisation, etc. will be permitted as long as the final thermal oxidation
3656 materials & derivatives meet the product quality requirements and the minimum conditions for
3657 the core process.
3658

3659 5.5.3.2 Core process

3660 Combustion conditions and carbon contents in ashes and slags

3661 The **chemical composition and contaminant levels** present in thermal oxidation materials
3662 are not only largely influenced by the characteristics of the biomass input materials, but also
3663 by the **operating conditions** during thermal oxidation, including the type of furnace (grate
3664 firing versus fluidised bed combustion), the combustion temperature and the residence time
3665 of ashes (Steenari et al., 1999; Obernberger and Supancic, 2009; Tan and Lagerkvist, 2011;
3666 Pöykö et al., 2014).

3667
3668 For large combustion plants (>50 megawatt (MWth)) and waste incineration plants in
3669 Europe, the **combustion conditions are determined in the Industrial Emissions Directive**
3670 (2010/75/EC, IED). The IED prescribes that waste combustion plants shall be designed,
3671 equipped, built and operated in such a way that the gas resulting from the incineration of
3672 waste is raised, after the last injection of combustion air, in a controlled and homogeneous
3673 fashion and even under the most unfavourable conditions, to a temperature of at least 850° C
3674 for at least two seconds (or 1100°C for 0.2 seconds), and that the total organic carbon content
3675 of slag and *bottom* ashes is less than 3% or their loss on ignition is less than 5% of the dry
3676 weight of the material. The legislation for medium combustion plants (between 1 and 50
3677 MWth; Directive (EU) 2015/2193) and for smaller appliances (heaters and boilers <1 MWth)
3678 covered by Regulation (EU) 2015/1189 (on ecodesign requirements for solid fuel boilers) do
3679 not specify the combustion time-temperature conditions or the quality of the resulting ashes
3680 and slags; they focus on the emissions into the air. **Regulation (EU) No 592/2014** amending
3681 Regulation (EU) No 142/2011 as regards the use of **animal by-products and derived**
3682 **products** as a fuel in combustion plants adheres to the specifications as indicated in the
3683 Industrial Emissions Directive as described above.

3684
3685 At the **Kick-off Meeting of the STRUBIAS sub-group, there was large support among**
3686 **the participants to refer to the criteria for the thermochemical conversion of thermal**
3687 **oxidation materials & derivatives from the Industrial Emissions Directive and the Animal**
3688 **by-products Regulation.**

3689
3690 **Organic carbon** is a foremost parameter to determine the ash and slag quality (Vehlow et al.,
3691 2006). A complete oxidation in the combustion process would convert this carbon totally to
3692 CO₂. However, in real world conditions a total conversion will never be accomplished and a
3693 small amount of products of incomplete combustion are found in all residue streams. In the
3694 gas phase this is first of all CO. Other organic compounds are typically present as traces only.
3695 In the solid residues the carbon speciation ranges from PAH through soot or types of
3696 activated carbon to almost graphitic carbon (Ferrari et al., 2002). Most residue management
3697 regulations use the organic C as a key parameter indicating the degree of organic contaminant
3698 removal. Organic C serves as a reactive surface for the adsorption of possible contaminants,
3699 such as persistent organic pollutants (Vehlow et al., 2006). Modern incinerators show a
3700 tendency towards improved burnout and thus to lower organic C concentrations in all residue
3701 streams. An evaluation of available data indicates that such plants easily reach a > 99%

3702 conversion of carbon and its compounds in the waste to CO₂ (European Commission, 2006c;
3703 Vehlow et al., 2006). **No specific limit value is proposed for the loss on ignition (LOI)** as
3704 the combination of organic C, temperature, time and other product quality parameters (e.g.
3705 electrical conductivity, maximum levels for polyaromatic hydrocarbons, etc.) should be
3706 sufficient to delimit the scope of thermal oxidation materials & derivatives. The organic C
3707 content is measured by default on many fertilising materials and forms part of testing
3708 parameters for different PFC classes. Therefore, measuring the loss on ignition might be
3709 redundant and would only lead to a further increase in compliance testing requirements for
3710 thermal oxidation materials & derivatives.

3711
3712 **The IED and Regulation (EU) No 592/2014** on poultry litter only focus on the **carbon**
3713 **content of the bottom ashes**. The burnout of the particulate matter in the flue gas and fly
3714 ashes is typically higher than that of the bottom ashes, and hence the former two materials
3715 usually show a lower organic C content than bottom ashes (Vehlow et al., 2006). Therefore,
3716 the C content is only measured on the bottom ash and slags. Even though some thermal
3717 oxidation materials & derivatives are produced from *fly* ashes (e.g. sewage sludge fly ashes
3718 from fluidised bed systems), it is proposed that operators of incineration and biomass
3719 combustion plants shall perform testing on the bottom ash and slags residue fraction because
3720 (1) it is specified as such in the above-mentioned Regulations for the incineration of waste
3721 and animal by-products, (2) biomass plant operators typically discard the fly ash fraction due
3722 to its high content of metals and other contaminants, and (3) the bottom ashes typically show
3723 a higher C content.

3724
3725 It is proposed not to impose strict time-temperature profiles (**>850°C for more than 2**
3726 **seconds or 1100°C for 0.2 seconds**) for **certain plant-based materials** in the technical
3727 requirements (i.e. those listed under point a) of the input material listed). Those materials **are**
3728 **inherently low in pollutants for which reason stringent time temperature profiles are**
3729 **neither required to ensure the destruction of pollutants in the material, nor**
3730 **proportionate considering the limited risks for emissions of certain persistent organic**
3731 **pollutants**. It is, however, proposed that the end-quality of the resulting ashes should meet
3732 the material quality requirements, including the organic carbon limits in the bottom ashes and
3733 slags. The incomplete combustion of uncontaminated biomass may lead to high levels of
3734 unburnt carbon in the ashes (Demirbas, 2005; James et al., 2012). In general, concentrations
3735 of CO, toxic volatile organic compounds such as acrolein, formaldehyde, and benzene,
3736 gaseous and particulate PAHs, and other organic species are enriched in emissions from
3737 incomplete biomass combustion (Rohr et al., 2015) and trace metals tend to accumulate in the
3738 organic ash fraction (Kabata-Pendias, 2011). High carbon contents in ash can also reduce ash
3739 stabilisation, increase the risk of spontaneous ignition after application, and significantly
3740 increase the ash volume. A complete combustion of the fuel also ensures low levels of
3741 persistent organic pollutants, such as PCBs and PCDD/Fs (see section 5.5.5.2). Finally, a
3742 high content of unburnt organic matter presents challenges for post-processing treatments
3743 such as pelletisation, briquetting and hardening as it decreases the binding properties of the
3744 ashes (James et al., 2012; Löfvren, 2012). In line with the product definition of ashes as
3745 mostly inorganic compounds, it is **proposed to limit organic C in the bottom ashes also to**

3746 **3% (dry matter basis)**. Alternatively, biomass that is not completely oxidised in a thermal
3747 conversion process under oxygen-limiting conditions can be classified as a pyrolysis &
3748 gasification material (see also section 5.3.7).
3749

3750 Additives and reactive agents

3751 It is referred to section 5.5.2.2 for a description on the reactants and additives used in thermal
3752 oxidation processes and specific P-recovery processes that aim at the production of better
3753 quality fertilising materials in an integrated, modified thermochemical process (e.g.
3754 RecoPhos, AshDec, Mephrec, EuPhoRe, etc.).

3755

3756 5.5.3.3 *Post-combustion manufacturing steps*

3757 Raw ashes as obtained after thermal oxidation may undergo further manufacturing steps with
3758 the intention to **reduce levels of metals or metalloids to acceptable, safe levels** and/or to
3759 **increase the plant availability of the phosphorus present in the ashes**. Therefore, raw
3760 ashes can be further processed as part of a "**two-step manufacturing process**", as outlined in
3761 section 5.3.3 and section 5.5.2.2. Such processes are typically of a chemical nature (e.g.
3762 Ecophos, Recophos, acidulation, etc.).

3763

3764 The reactants that can be applied in such processes principally include **virgin materials and**
3765 **other materials that can be used for the production of fertilisers derived from primary**
3766 **raw materials**, similar to those comprised under CMC 1 in the proposal for the revised
3767 Fertiliser Regulation (see section 5.5.2.2 for details; substances excluding biomass, animal
3768 by-products, wastes and their transformation products, fossil fuels, and raw materials for the
3769 steel and iron industry, and non-biodegradable polymers).

3770

3771 It is proposed to refer to these materials as "intermediates", rather than to "substances and
3772 mixtures". Pursuant to Regulation (EC) No 1907/2006, **an intermediate is defined as "a**
3773 **substance that is manufactured for and consumed in or used for chemical processing in**
3774 **order to be transformed into another substance"**. The use of this terminology will prevent
3775 that inert materials are added to in the manufacturing of CE fertilising products with the sole
3776 intention of reducing contaminant levels of the final CE product. Therefore, the mixing of
3777 wastes with wastes or other materials should at all times occur with the intention to improve
3778 the quality of the resulting material and plant nutrient availability, to remove contaminants, or
3779 a combination of both. Operations aimed at lowering the contaminant concentration without
3780 lowering the contaminant to nutrient ratio in the original material should not be allowed. No
3781 further restrictions on the use of intermediates are proposed. Nonetheless, in order to comply
3782 with the legal requirements laid down in Directive 2008/98/EC, it is proposed that
3783 manufacturers that use **hazardous wastes** (e.g. sewage sludge ashes with certain species of
3784 Zn; Donatello et al., 2010) within their STRUBIAS production process **should demonstrate**
3785 **the removal or transformation of the respective hazardous substances to levels below**
3786 **the limit values as defined in the proposal for the revised Fertiliser Regulation and**
3787 **other EU policy documents on the classification of waste** (see Commission notice on

3788 technical guidance on the classification of waste - 2018/C 124/01). Although no best
3789 available techniques have been defined for STRUBIAS production processes, it is believed
3790 that – at present – such provisions might lead to the development of chemical and
3791 thermochemical techniques that enable the simultaneous compliance with the requirements
3792 laid down in Article 10 ["the necessary measures shall be undertaken to ensure that waste
3793 undergoes recovery operations"], and Article 13 ["protection of human health and the
3794 environment"] of Directive 2008/98/EC.

3795

3796 Some stakeholders have argued that by setting no further restrictions on the use of
3797 intermediates, manufacturers are given the possibility to dilute contaminants present in ashes
3798 (e.g. metals in sewage sludge) to below the limit values for contaminants established at CMC
3799 and PFC level, **resulting in increased emissions of contaminants present in the input**
3800 **materials to the soil relative to techniques that effectively remove the contaminants by**
3801 **diverting them into a separate waste stream.** Under the current nutrient recovery
3802 proposals, such practices could indeed take place and following arguments were raised to
3803 support this approach:

- 3804 • Constraining the mixing of secondary raw materials in the revised Fertiliser
3805 Regulation **would hamper creating a level playing field for fertiliser**
3806 **manufacturers.** After all, the mixing of input materials of different quality is allowed
3807 for fertiliser manufacturers that use phosphate rock as input/source materials.
- 3808 • The mixing of non-hazardous waste with other substances and mixtures is not
3809 prohibited in the existing EU legislation on waste.
- 3810 • The mixing of input materials with intermediates is not exclusively performed for the
3811 dilution of waste, but also to (1) transform the P in the ashes into a more bio-available
3812 form and thus **decrease the ratio of contaminants to bio-available P in the end-**
3813 **material,** and (2) to produce a chemical fertiliser blend (e.g. NPK fertiliser of the
3814 highest quality). For some micronutrients (e.g. Zn), the **addition of intermediates is**
3815 **in fact a good practice** as removing micronutrients from the ashes would require
3816 afterwards the addition of those elements to provide a balanced plant nutrition,
3817 involving their production from primary raw materials and associated environmental
3818 impacts;
- 3819 • **Life cycle assessments** (section 8) indicated that **producing P-fertilisers through**
3820 **the mixing process provides benefits through the reduced need to extract the**
3821 **primary raw material phosphate rock, but that impacts on human health and the**
3822 **environment depend on the counterfactual use and handling scenario of the**
3823 **waste material that contained the sludges.**

3824

3825 For further discussion on this aspect, it is also referred to section 5.3.4.

3826

3827 For all these reasons, the following proposal is put forward for the implementation of post-
3828 combustion manufacturing processes:

3829

3830 A CE marked fertilising product may contain derivatives from thermal oxidation
3831 materials that have been produced from the input materials listed in paragraph 1
3832 and compliant with paragraph 4 and that have been manufactured according to a
3833 thermal oxidation process compliant with paragraphs 2 and 3. The post-
3834 combustion manufacturing process shall be of following nature:
3835 a) chemical manufacturing: processes that chemically react thermal oxidation
3836 materials with intermediates within the meaning of Regulation (EC) No 1907/2006
3837 listed under point h) of paragraph 1; or
3838 b) thermochemical manufacturing: processes that thermochemically react
3839 thermal oxidation materials with intermediates within the meaning of Regulation
3840 (EC) No 1907/2006 listed in paragraph 1. Thermochemical process conditions
3841 shall be compliant with paragraph 2 and 3, and the thermal oxidation material
3842 derivative shall meet conditions listed in paragraph 4.
3843 Thermal oxidation materials that display one or more of the hazardous properties
3844 listed in Annex III of Directive 2008/98/EC shall not be mixed, either with waste,
3845 substances or materials with the intention of reducing hazardous substances to
3846 levels below the limit values for the hazardous property as defined in that
3847 Directive. Using a mass balance approach, manufacturers that use thermal
3848 oxidation materials with hazardous properties must demonstrate the removal or
3849 transformation of the contaminants to levels below the limit values as defined in
3850 Annex III of Directive 2008/98/EC.

3851

3852 5.5.3.4 *Finishing steps*

3853 **No specific requirements for "finishing" techniques that relate to the agglomeration or**
3854 **washing of materials have to be included at CMC level.** Post-processes (e.g. modification
3855 of size or shape by mechanical treatment, washing with water) are normal industrial practice
3856 and any materials/processes required are included on the input material list. Hence, thermal
3857 oxidation materials & derivatives may undergo further post-processing steps with the intention
3858 to increase the chemical stability of the ashes or to agglomerate ashes as pellets or granules
3859 (Vesterinen, 2003).

3860

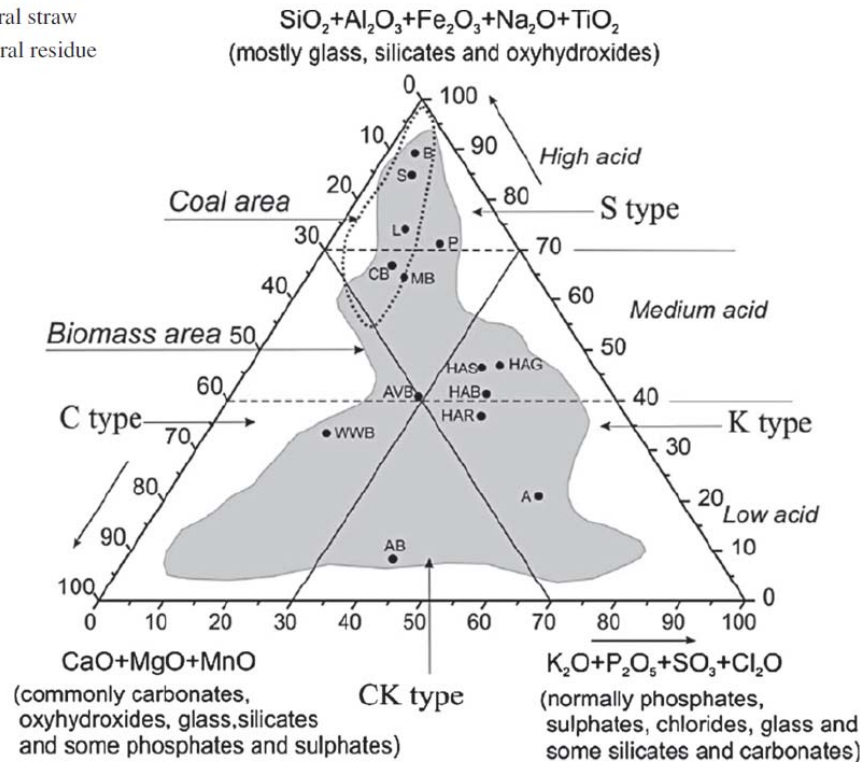
3861 5.5.4 Agronomic value

3862 5.5.4.1 *Nutrient contents and element ratios*

3863 Based on the characterisation of ash properties in relation to their potential utilisation
3864 (Vassilev et al., 2010; Vassilev et al., 2013a; Vassilev et al., 2013b), ashes are classified
3865 according to their **elemental composition** (Figure 3).

3866

- WWB - Wood and woody biomass
- HAB - Herbaceous and agricultural biomass
- HAG - Herbaceous and agricultural grass
- HAS - Herbaceous and agricultural straw
- HAR - Herbaceous and agricultural residue
- AB - Animal biomass
- MB - Mixture of biomass
- CB - Contaminated biomass
- AVB - All varieties of biomass
- P - Peat
- L - Lignite
- S - Sub-bituminous coal
- B - Bituminous coal
- A - Algae



3867

3868 **Figure 3: The classification system of ashes from fossil fuels and biomass based on the**
 3869 **composition of their major elements (adopted from Vassilev et al., 2013b)**

3870

3871 Most raw ashes ("**K type**", right hand side of the triangle) are relatively **rich in one or more**
 3872 **of the essential plant macronutrients P, K, and S**. Ashes that will be applied with the
 3873 intention to **increase soil pH** (liming materials) are characterised as "**C type** ashes", and
 3874 show high Ca and Mg contents. The high nutrient contents of ashes derived from the eligible
 3875 input materials is confirmed in section 16.2.1, and most of these ashes will classify as C type,
 3876 K type or CK type. The macronutrients K, Ca, Mg, and S are relatively easily leached from
 3877 ashes, especially in the plant rhizosphere where plants may create a relatively acid micro-
 3878 environment through the release of root exudates (Freire et al., 2015). Phosphate (PO_4^{3-}),
 3879 however, may be unavailable to plants when strongly bound to particular bi- and trivalent
 3880 ions. The plant available P-content for thermal oxidation materials & derivatives that are
 3881 intended to be used as P-fertilisers will be regulated at PFC level.

3882

3883 "**S type**" ashes are dominated by **glass, silicates, and oxyhydroxides** (mainly of the elements
 3884 Si, Al, and Fe), but fail to have a significant amount of carbonates, phosphates or sulphates,
 3885 for which reason these ashes are **unsuitable as liming materials or macronutrient**
 3886 **fertilisers**. These ashes cover a relatively small zone at the top of the triangle, and are mostly
 3887 produced from lignite, sub-bituminous coal and bituminous coal. As indicated by the
 3888 STRUBIAS sub-group, there is no basis of support to include these materials as thermal
 3889 oxidation materials & derivatives in the Revised Fertiliser Regulation. Therefore, the use of

3890 fossil fuels as input materials is limited to their role as auxiliary fuels in incineration, co-
3891 incineration, and biomass combustion plants as indicated in section 5.5.2. Hence, fossil fuel
3892 ashes as formed at fossil fuel power stations cannot be considered as thermal oxidation
3893 materials. The direct consequence of this restriction of input materials is that **no further**
3894 **criteria are required to exclude such "S type" ashes, dominated by glass, silicates, and**
3895 **oxyhydroxides.**

3896
3897 Also thermal oxidation material derivatives that are produced through post-combustion
3898 manufacturing steps show a high content of plant available nutrients. All these materials have
3899 a P₂O₅ content of minimum 15-20%, and are specifically intended to be used as a P-fertiliser.
3900 Therefore, **no additional requirements are proposed on minimum nutrient or**
3901 **neutralising value for thermal oxidation materials & derivatives.**

3904 5.5.4.2 Salinity

3905 Salinity is a generic term used to describe elevated concentrations of **soluble salts** in soils
3906 and water. Comprised primarily of the most easily dissolved ions - sodium (Na) and chloride
3907 (Cl), and to a lesser extent calcium, magnesium, sulfate, and potassium - salinity in the
3908 environment adversely impacts water quality, soil structure, and plant growth (Pichtel, 2016).
3909 Although minimal accumulations (some in trace amounts) are required for normal biological
3910 function, excess salinisation might constrain crop productivity and threaten the presence of
3911 salt-intolerant plant and epiphyte species in natural ecosystems, as high dissolution rates of
3912 salts may impact upon the vegetation community. Excess sodicity can cause clays to
3913 deflocculate, thereby lowering the permeability of soil to air and water. Sodium (Na) and Cl
3914 are often present in thermal oxidation materials as inorganic salts such as sylvite (KCl) and
3915 halite (NaCl) in relatively high concentrations (Freire et al., 2015).

- 3916 a. **Chloride** contents in thermal oxidation materials & derivatives can be very high
3917 (e.g. in ashes from cereal and straw combustion; up to 35% of the total dry
3918 matter content), especially when expressed relative to other micronutrients
3919 (section 16.2.1). On average 67% of the chlorides present in ashes is water-
3920 soluble (Vassilev et al., 2013b). Hence, in specific settings and ecosystems, a
3921 significant risk is present for crops, natural vegetation and long-term soil
3922 quality when thermal oxidation materials are applied during prolonged periods
3923 of time. The Finnish legislation on the use of ashes in forest ecosystems
3924 contains a limit value of 2% for chloride (Haglund and Expertsgrup, 2008).
3925 In the proposal for the Revised Fertiliser Regulation (Annex III of the proposal
3926 – Labelling requirements), it is stated that the phrase 'poor in chloride' or
3927 similar may only be used if the chloride (Cl-) content is below 3%. It is agreed
3928 that a labelling requirement cannot prevent that a product high in chloride
3929 causes adverse impacts on the environment, but at the same time, the
3930 STRUBIAS sub-group indicated that this CMC offers the possibility to
3931 recover KCl, a micronutrient fertiliser, from ashes (e.g. "Ash2Salt" process;
3932 Easymining Sweden). Therefore, it is proposed to set **a limit value of 3% for**

3933 **Cl⁻, only applicable when Cl⁻ is an unintentional substance constituent**
3934 **coming from the starting material(s).**

3935 b. **Sodium** contents in thermal oxidation materials & derivates are generally low
3936 (<1%), although some residues such as olive husks can have higher contents.
3937 Moreover, Na plays a role as a “functional nutrient”, with a demonstrated
3938 ability to replace K in a number of ways for vital plant functions, including
3939 cell enlargement and long-distance transport, and its presence is even a
3940 requirement for maximal biomass growth for many plants (Subbarao et al.,
3941 2003). **Therefore, no limits on the Na content of thermal oxidation**
3942 **materials & derivates are proposed.**

3943 c. At present, reliable methods other than leaching tests to characterise ash with
3944 regard to the speed of salt dissolution in the field are missing. One way of
3945 estimating the stability of thermal oxidation materials & derivates is to
3946 measure the conductivity in water extracts. This gives a total measurement of
3947 the dissolution of salts from the ash and indicates the risk of acute damage to
3948 vegetation, especially mosses and lichens. Given the labelling provisions for
3949 the closely related parameter Cl⁻, it is, however, proposed to add no further
3950 criteria or labelling requirements for **electrical conductivity**.

3951

3952 5.5.4.3 Boron toxicity

3953 **Boron** is a very common element that may be present **in coal and some biomass ashes**, and
3954 is **readily water soluble** (Pagenkopf and Connolly, 1982; Basu et al., 2009). Boron
3955 phytotoxicity is a major potential problem associated with the use of fresh fly ash as a
3956 fertilising material. Although boron is an essential nutrient in plants at low concentrations, it
3957 becomes toxic in many plants at concentrations only slightly higher than the optimal range
3958 (Ayers and Westcot, 1985; Sartaj and Fernandes, 2005). A number of studies have indicated
3959 that the solubilisation of B in coal ashes may lead to B toxicity in plants and aquatic
3960 organisms (Adriano et al., 1978; Straughan et al., 1978; Zwick et al., 1984; Aitken and Bell,
3961 1985) and could cause B-induced inhibition of microbial respiration (Page et al., 1979)
3962 depending on the form and concentration of boron, type and characteristics (e.g. life stages)
3963 of the organism, and period and type of exposure to boron (acute or chronic). Recent
3964 evidence indicates that human B intake from food and water in EU are below the tolerable
3965 upper intake level (EFSA, 2004), and that increased human B uptake is even promoted to
3966 enhance health due to the beneficial effects at low B concentrations (Nielsen, 2014; Pizzorno,
3967 2015). Moreover, the most extensive and most recent dataset for rivers/catchments or regions
3968 in the EU contains consistently low B values (Heijerick and Van Sprang, 2004).

3969 Fertilising products derived from thermal oxidation materials, including those derived from
3970 sewage sludge ashes, animal manures and wood bottom ashes, contain B contents well below
3971 the limits applicable in Lithuania and Sweden for ash-based fertilising products (500 mg B
3972 kg⁻¹) (see section 16.2.2), and typically well below the B concentrations encountered in
3973 mineral P fertilisers (on average 1291 mg B kg⁻¹ for superphosphates; Kratz et al., 2016).
3974 Moreover, potentially boron rich coal ashes are excluded from thermal oxidation materials &
3975 derivates because of the limitations on eligible input materials (see section 5.5.2.1).

3976 Therefore, it is concluded that negligible risks are associated to thermal oxidation materials &
3977 derivates for aquatic organisms, plants and humans. Hence, **it is proposed not to set a limit**
3978 **for the B content of thermal oxidation materials & derivates at CMC level.**
3979

3980 5.5.5 Environmental and human health safety aspects

3981 5.5.5.1 *Metals and metalloids*

3982 This section considers concerns associated to the exposure **to alkali, alkaline earth metals,**
3983 **transition metals and other metals.** Whereas some of them are plant micronutrients, the
3984 potential **dissolution and accumulation to toxic levels of these inorganic metals and**
3985 **metalloids present in thermal oxidation materials & derivates requires a more in-depth**
3986 **risk assessment.** Metal or metalloid species may be considered “contaminants” if their
3987 presence is unwanted or occurs in a form or concentration that causes detrimental human or
3988 environmental effects.

3989
3990 The primary response **of plants upon exposure to high levels of metals and metalloids in**
3991 **soils is the generation of reactive oxygen species and oxidative stress** (Mithöfer et al.,
3992 2004). The **indirect mechanisms** include their interaction with the antioxidant system
3993 (Srivastava et al., 2004), disrupting the electron transport chain (Qadir et al., 2004) or
3994 disturbing the metabolism of essential elements (Dong et al., 2006). One of the most
3995 deleterious effects induced by metals in plants is lipid peroxidation, which can directly cause
3996 biomembrane deterioration.

3997
3998 Living organisms require varying amounts of metals and metalloids. Iron, cobalt, copper,
3999 manganese, molybdenum, and zinc are required by humans, but all are **toxic** at higher
4000 concentrations (Singh et al., 2011a). Other heavy metals such as Cd, Hg and Pb are toxic
4001 elements that have no known vital or beneficial effect on organisms, and their accumulation
4002 over time in the bodies of animals can cause serious illness. **The ingestion of metals and**
4003 **metalloids by humans may disrupt metabolic functions, as they can accumulate in vital**
4004 **organs and glands such as the heart, brain, kidneys, bone, liver, etc. and could displace**
4005 **the vital nutritional minerals from their original binding sites, thereby hindering their**
4006 **biological function** (Singh et al., 2011a).

4007

4008 *Aluminum, Iron and Manganese*

4009 Aluminium (Al) is the most commonly occurring metallic element, comprising eight percent
4010 of the earth's crust (Press and Siever, 1974). It is a major component of almost all common
4011 inorganic soil particles, with the exception of quartz sand, chert rock fragments, and
4012 ferromanganiferous concretions. The typical range of Al in soils is from 1% to 30%, with
4013 naturally occurring concentrations varying over several orders of magnitude. The available
4014 data on the environmental chemistry and toxicity of Al in soils to plants, soil invertebrates,
4015 mammals and birds indicate that total Al in soil is not correlated with toxicity to the tested
4016 plants and soil invertebrates (EPA, 2003a). However, **aluminium toxicity is associated with**
4017 **soluble Al** and thus dependent upon the chemical form (Storer and Nelson, 1968). Insoluble

4018 Al compounds such as Al oxides are considerably less toxic compared to the soluble forms
4019 (aluminium chloride, nitrate, acetate, and sulfate), and only moderately toxic effects of
4020 insoluble Al for humans have been observed at extremely high intake ratios that are
4021 unrealistic through fertiliser-based exposure pathways (Krewski et al., 2007). Aluminium in
4022 ashes is dominantly present in stable forms, and the **Al content in the soluble and**
4023 **exchangeable forms is extremely low** (~0.2%) (Lapa et al., 2007; Ibrahim, 2015).
4024 Aluminium from ashes is mainly released as Al(OH)_4^- (99%) (Ibrahim, 2015). Although
4025 Al(OH)_4^- is considered to be non-toxic, phytotoxic effects could occur due to the gradual
4026 formation of toxic Al species in the bulk nutrient solution, resulting from the acid soil pH or
4027 the acidification of the alkaline nutrient solution by the plant roots (Kopittke et al., 2005).
4028 Ecological risks associated with the addition of Al could therefore be present, especially in
4029 acidic soils ($\text{pH}_{\text{H}_2\text{O}} < 5.5$). The mechanism that underlies Al phytotoxicity is that Al displaces
4030 Ca from the apoplast and thus reduces the number of exchange sites for Ca uptake (Godbold
4031 et al., 1988). Therefore, not the concentration of Al in itself is critical, but rather the molar
4032 ratio of Ca/Al. Hence high Ca concentrations may reduce the toxic effects of Al (Godbold et
4033 al., 1988). Ashes derived from the eligible input materials are typically rich in Ca that is
4034 easily leached (Vassilev et al., 2013b). The leaching of Ca from the ashes is much more
4035 pronounced than the leaching of soluble Al (Neupane and Donahoe, 2013; Ibrahim, 2015).
4036 Hence, it is concluded that most Al in (the neutral to basic) ashes is present as insoluble
4037 aluminium oxides and hydroxides, and that the availability of Ca in the ashes and slags
4038 derived from the eligible input materials far exceeds that of Al. Therefore, **no specific**
4039 **criterion is proposed for Al content in thermal oxidation materials & derivatives.**

4040
4041 Also iron (Fe) is a commonly occurring metallic element, with typical soil concentrations
4042 ranging from 0.2% to 55%. Iron can occur in either the divalent (Fe^{+2}) or trivalent (Fe^{+3})
4043 valence states under typical environmental conditions. The valence state is determined by the
4044 activity of the hydrogen cation (pH), the activity of electrons (Eh) of the system, and the
4045 chemical form is dependent upon the availability of other chemicals. Iron is essential for
4046 plant growth, and is generally considered to be a micronutrient. Iron is considered the key
4047 metal in energy transformations needed for syntheses and other life processes of the cells
4048 (Merchant, 2010). The main concern from an ecological risk perspective for iron is not direct
4049 chemical toxicity per se, but the effect of iron as a mediator in the geochemistry of other
4050 (potentially toxic) metals (EPA, 2003b). Similar to Al, Fe in ashes is dominantly present in
4051 stable forms, and the **Fe content in the soluble and exchangeable forms is low** (~0.3%)
4052 (Vassilev et al., 2013b; Ibrahim, 2015). Moreover, in well aerated soils between $\text{pH}_{\text{H}_2\text{O}}$ 5 and
4053 8, **iron is not expected to be harmful to plants** (Römheld and Marschner, 1986), but under
4054 specific conditions it can become toxic (e.g. in rice plants). Therefore, **no specific criterion**
4055 **is proposed for Fe content in thermal oxidation materials & derivatives.**

4056
4057 Regulatory interest in the assessment of the potential risks to soil from **manganese (Mn)**
4058 exposures has increased with increasing anthropogenic activity and industrial development.
4059 Not only can Mn be **toxic for plants and animals**; toxicity for **humans** has been reported as
4060 well from occupational (e.g. welder) and dietary overexposure. Toxicity has been
4061 demonstrated primarily in the central nervous system, although lung, cardiac, liver,

4062 reproductive and foetal toxicity have been equally noticed (Crossgrove and Zheng, 2004). In
4063 contrast to Al and Fe, Mn concentrations in ashes might be up to 10 times higher than the soil
4064 background Mn concentrations, for which reason potentially substantial risks are associated
4065 to the application of Mn-rich thermal oxidation materials & derivatives. Moreover, up to 46%
4066 of the Mn present in ashes may be water-soluble (Vassilev et al., 2013b). The limit values for
4067 soil Mn concentrations associated to toxic effects on organisms are below the background
4068 concentrations of most soils, thus making their use in the assessment of potential risks
4069 impossible (EPA, 2003c; ESDAT, 2017). Also, little is known about the toxicity of colloidal,
4070 particulate, and complexed manganese, though the toxicities of metals bound into these forms
4071 are assumed to be less than those of the aqua-ionic forms (World Health Organization, 2004),
4072 Hence, there are some important challenges when it comes to deriving limit values to address
4073 potential terrestrial risks, including the variability of ambient soil background concentrations,
4074 the changing form and subsequent ecotoxicology of Mn with changing soil conditions, as
4075 well as the poor relationship between standard ecotoxicity test data for all trophic levels and
4076 the reality in the field (International Manganese Institute, 2012). As a matter of fact, it has
4077 been acknowledged by the WHO that, due to the highly variable natural background
4078 concentrations and the influence of transient water logging and pH changes on manganese
4079 speciation, **deriving a single guidance value for the terrestrial environment is**
4080 **inappropriate** (World Health Organization, 2004). Therefore, existing national legislative
4081 frameworks do not contain limit levels for maximal Mn contents in thermal oxidation
4082 materials, with the exception of the UK poultry litter ash quality protocol (limit of 3.5% on a
4083 dry matter basis). The values observed for thermal oxidation materials & derivatives are below
4084 the 3.5%, with the highest Mn concentrations observed for fly and bottom wood ashes (up to
4085 1.3% and 2.9%, respectively; section 16.2.2). Ashes and slags derived from other eligible
4086 input material typically show Mn concentrations that are 1-2 orders of magnitude lower than
4087 the limit value of 3.5% of the UK poultry litter ash quality protocol (section 16.2.2).
4088 Therefore, **no specific criterion is proposed for Mn content in thermal oxidation**
4089 **materials & derivatives.**

4090 **Assessment on the potential accumulation of trace metals/metalloids in soil**

4091 The pathways that lead to the presence of **metals and metalloids in eligible input material**
4092 **for thermal oxidation materials** often start within the food chain via plant and water uptake
4093 by roots, and by adsorption from the air. Additionally, fossil fuels and ore concentrates can
4094 have high concentration of particular toxic metals, such as Tl, Cr and V that were present in
4095 specific geological substrates (Karbowska, 2016). Wood contains generally higher amounts
4096 of metals than short-lived biomass sources, because of the accumulation during the long
4097 rotation period of forests, the higher deposition rates in forests and possibly the lower pH
4098 value of forest soils (Vamvuka and Kakaras, 2011) (section 16.2.2). Because of the transfer
4099 from one link in the chain to another, some heavy metals may end up being accumulated by
4100 humans (Hapke, 1996). The recycling of metals and metalloids in the environment is evident
4101 as metals being taken up by plants used as animal feed or food end up in excreta, which are
4102 spread on land, and can ultimately lead to increasing concentrations in agricultural soils over
4103 time. Even relatively small additions to the cycle may thus lead to high soil concentrations
4104 over time (van der Voet et al., 2010). This indicates that not only ecotoxicity associated to the

4105 dispersion of metals in the atmosphere or towards freshwater bodies should be taken into
4106 account, but also the vulnerability of the soil ecosystem. Root exudates, particularly organic
4107 acids, are able to increase metal mobility, solubility and bioavailability in soil and enhance
4108 consequently the translocation and bioaccumulation of metals (Ma et al., 2016). To avoid an
4109 increase of unwanted toxic heavy metals in food for human consumption **it is necessary to**
4110 **limit the concentrations upstream in the food chain.**

4111
4112 In line with the objective of the STRUBIAS sub-group, a **broad range of eligible input**
4113 **materials** has been proposed for the CMC thermal oxidation materials & derivatives. Amongst
4114 others, non-hazardous waste and non-hazardous industrial by-products, animal by-products,
4115 ore concentrates and fossil fuels could be used as eligible input materials. This is possible
4116 because the combustion process enables an effective removal of most organic contaminants
4117 present in the eligible feedstocks, and **on the singular condition that the adverse effects**
4118 **associated to the presence of metals and metalloids is carefully evaluated.** Thermal
4119 oxidation processes result in the losses of organic matter and several volatile nutrients (e.g. N
4120 and S), whereas metals and metalloids are only partially removed. The temperature of
4121 between 800–1050°C in the combustion chamber of a fluidised bed boiler is high enough to
4122 vaporise some of the elements. In addition to element volatilisation characteristics, element
4123 retention through other processes in fly ash (primarily condensation processes) determines
4124 the final fate of volatisable elements (Álvarez-Ayuso et al., 2006; Kuokkanen et al., 2006).
4125 Most of these species form compounds that condense on the surface of particles in the flue
4126 gas, leading to the enrichment of some elements in the fly ash fraction. The bottom ash has an
4127 enhanced content of non-volatile components, and frequently contains sintered or melted
4128 particles. **The direct result is the significant concentration of metals/metalloids in**
4129 **thermal oxidation materials (Demirbas, 2003).**

4130
4131 Unlike organic contaminants, which may be oxidised by microbial action, most metals do not
4132 undergo microbial or chemical degradation, and they remain in the soil for a long time after
4133 their introduction. Changes in their chemical forms (speciation) and bioavailability are,
4134 however, possible. **Metal and metalloid contamination of soil may pose risks and hazards**
4135 **to humans and the ecosystem through direct ingestion or contact with contaminated**
4136 **soil, the food chain (soil-plant-human or soil-plant-animal-human), drinking of**
4137 **contaminated ground or surface water, effects on aquatic organisms, reduction in food**
4138 **quality (safety and marketability) via phytotoxicity, reductions in soil quality and soil**
4139 **faunal biodiversity, and the reduction in land usability for agricultural production**
4140 **causing food insecurity** (World Health Organization, 1996; Demirbas, 2003; Wuana and
4141 Okieimen, 2011).

4142
4143 It has been reported that metals such as cobalt (Co), copper (Cu), chromium (Cr), magnesium
4144 (Mg), molybdenum (Mo), nickel (Ni), selenium (Se) and zinc (Zn) are essential nutrients that
4145 are required for various biochemical and physiological functions, but the inadequate supply
4146 of these micro-nutrients results in a variety of deficiency diseases or syndromes (described in
4147 detail in World Health Organization, 1996). Other metals such as aluminium (Al), antimony
4148 (Sb), arsenic (As), barium (Ba), beryllium (Be), bismuth (Bi), cadmium (Cd), gallium (Ga),

4149 germanium (Ge), gold (Au), indium (In), lead (Pb), lithium (Li), mercury (Hg), nickel (Ni),
4150 platinum (Pt), silver (Ag), strontium (Sr), tellurium (Te), thallium (Tl), tin (Sn), titanium (Ti),
4151 vanadium (V) and uranium (U) have no established biological functions and are considered
4152 as non-essential metals (Chang et al., 1996). In humans and biological systems of soil and
4153 aquatic organisms, these metals/metalloids have been reported to affect cellular organelles
4154 and components such as cell membranes, mitochondriae, lysosomes, endoplasmic reticula,
4155 nuclei, and to inhibit some enzymes involved in metabolism, detoxification, and damage
4156 repair (World Health Organization, 1996; Wang and Shi, 2001).

4157
4158 Trace elements found in ashes from the eligible input materials that could accumulate in soils
4159 include **As, Ba, Be, Cd, Cr, Co, Cu, Hg, Mo, Ni, Pb, Sb, Se, Tl, V, and Zn** (Pitman, 2006;
4160 Vassilev et al., 2013a; Vassilev et al., 2013b; Rohr et al., 2015; Karbowska, 2016). Most
4161 studies and risk assessments have primarily focussed on inorganic elements of major
4162 environmental concern, such as As, Cd, Cr (VI), Pb, Ni or Hg among others, while
4163 overlooking other constituents (e.g. Ba, Be, Mn, Mo, Sb, Tl and V are poorly studied) which,
4164 inaccurately, have been considered as generally posing little risk to the environment.

4165
4166 Some inorganic metals and metalloids are already regulated for different PFCs in the
4167 proposal for the Revised Fertiliser Regulation. Specifically, limit values for Cd, Cr (VI), Hg,
4168 Ni, and Pb have already been formulated in the proposal for the Revised Fertiliser Regulation
4169 for the different PFCs where thermal oxidation materials & derivatives could be used as
4170 ingredients. Also, Zn and Cu are elements that may be regulated at PFC level for which
4171 reason these elements are not included in this assessment at CMC level. Therefore, the
4172 present assessment will be restricted to **As, Ba, Be, Co, Cr, Mo, Sb, Se, Tl and V** (see
4173 section 17.1). The methodology of the assessment is centred on a three-step approach:

4174 1) In a first step, soil screening values are collected for the different EU Member States.
4175 **Soil Screening Values** are generic quality standards that are used to regulate land
4176 contamination and are adopted in many Member States in Europe in order to protect
4177 the environment and human health (Carlson, 2007). The soil screening values were
4178 compiled for the different EU Member States, and it was assessed if the list of
4179 elements covers all relevant hazards associated to metals/metalloids based on the
4180 techno-scientific literature for thermal oxidation materials derived from the eligible
4181 input materials. If not, complementary evidence was sought in scientific literature, as
4182 was the case for Thallium (see details in section 17.1, as well as the specific section
4183 below on Thallium).

4184 2) In a second step, a maximal permissible concentration of the element in the CMC
4185 derived fertilising material is calculated based on the principle that predicted
4186 metals/metalloid accumulation as a result of the long-term application of the
4187 fertilising material and the atmospheric deposition in the soil shall not exceed the so-
4188 called soil screening value ("*soil screening acceptable limit concentration*"). A mass
4189 balance approach is applied assuming that the **non-soluble fraction of metals and**
4190 **metalloids accumulates in soils**, and that the soluble metal fraction is removed from
4191 the soil through leaching and plant uptake. The calculated accumulation of the

4192 respective trace metal in soils is then dependent on (1) farming duration (years), (2)
4193 the application rate of the fertilising products, (3) the concentration of the trace metal
4194 in the fertiliser and (4) the fate and transport of the trace metal in soils. A simple
4195 spreadsheet-based model based on a set of reasonable assumptions is applied for this
4196 purpose as outlined in detail in section 17.1. The **calculated soil screening**
4197 **acceptable limit contents are then qualitatively** compared to metal/metalloid
4198 concentrations that are typically found across the diverse range of thermal oxidation
4199 materials & derivatives derived from different eligible input materials. This assessment
4200 is applied **to spot possible issues** that might lead to human health and environmental
4201 protection issues due to the accumulation of metals and metalloids present in the
4202 CMC material.

4203 3) In a final step, **an interpretation and validation of the soil screening acceptable**
4204 **limit concentration is performed by reviewing metal-specific available**
4205 **information in a risk-based context.** This is especially relevant for thermal
4206 oxidation materials & derivatives as some of the elements for scrutiny are not routinely
4207 present in fertilising materials. Based on the precautionary principle, technical
4208 requirements on maximal permissible limit values for metals/metalloids in thermal
4209 oxidation materials & derivatives could be proposed in case there is techno-scientific
4210 evidence to suggest that the use of specific thermal oxidation materials & derivatives
4211 could lead to unacceptable human health or environmental risks.

4212
4213 Hence, the assessment is **principally based on the soil screening values for metal and**
4214 **metalloid concentrations in the soil as established by the EU Member States.** A full risk
4215 assessment of ecological and human health risks from the presence of the metals and
4216 metalloids in fertilising materials falls beyond the scope of this study.

4217 4218 Acceptable soil screening limit concentrations

4219 The outcome of this analysis indicates the soil screening acceptable limit concentrations of
4220 selected metals and metalloids in CE fertilising products derived from thermal oxidation
4221 materials & derivatives as given in Table 4.

4222 **Table 4: Outcome of the soil screening acceptable limit concentrations of selected metals and**
 4223 **metalloids in CE fertilising products derived from thermal oxidation materials & derivates; -**
 4224 **indicates that the calculated maximal trace metal concentrations are well-above concentrations**
 4225 **found for thermal oxidation materials & derivates (section 16.2.2) for which reason no**
 4226 **maximum value is proposed.**

	<u>maximal trace metal concentration (mg kg⁻¹)</u>	<u>proposed limit (mg kg⁻¹)</u>
As	52	-
Ba	2225	-
Be	90	-
Co	168	-
Cr	406	400
Mo	87	-
Sb	20	-
Se	179	-
Tl	11	10
V	628	600

4227
4228

4229 Interpretation and validation of the soil screening acceptable limit concentration

4230 The obtained numbers were compared to typical values observed in thermal oxidation
 4231 materials & derivates (see section 16.2.2 in Annex). It was observed that for As, Be, Co, Mo
 4232 and Se, typical values present in the materials are much lower than the derived soil screening
 4233 acceptable limit concentrations. Sensitivity analyses indicated that variations in model
 4234 parameters, such as for instance the variation of K_d values along the ranges observed for
 4235 European soils (Janik et al., 2015b), did not change the outcome. **Therefore, it is proposed**
 4236 **not to set legal requirements for As, Be, Co, Mo and Se for this CMC.**

4237
 4238 For Barium, it is indicated that most thermal oxidation materials & derivates show Ba
 4239 contents that are below the derived soil screening acceptable limit concentrations (typical
 4240 range, 100 – 1500 mg kg⁻¹). Nonetheless, **wood fly ashes** could show values up to 4000 mg
 4241 kg⁻¹ (section 16.2.2). Also ashes derived from **coal** could show values up to 5000 mg kg⁻¹
 4242 (WHO, 1990), but the presence of coal ashes in the final CE fertiliser product will be limited
 4243 by the proposed criteria on minimum nutrient content (see section 5.5.4.1). It is also indicated
 4244 that Ba contents in Ba-rich thermal oxidation materials & derivates closely correlate to other
 4245 contaminants, such as Pb and Cd (section 16.2.2). Wood fly ash, the lightest component that
 4246 accumulates in the flue system, can contain high concentrations of cadmium, copper,
 4247 chromium, lead and arsenic for which reason this ash cannot be used as a CE marked
 4248 fertiliser (Pitman, 2006). Therefore, thermal oxidation materials & derivates that exceed the
 4249 proposed Ba limit value of 2200 mg kg⁻¹ will also exceed the metal limit values at PFC levels
 4250 for any of the PFC classes that could be targeted by these materials (e.g. macro- and
 4251 micronutrient fertilisers, liming materials, etc.). For all these reasons, it is proposed **not to set**
 4252 **legal requirements for Ba for this CMC.**

4253
 4254 For the remaining elements Cr, Sb, Tl and V a more in-depth assessment to evaluate the risks
 4255 was performed:

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Chromium:

Chromium is considered to be **non-essential for plant growth** and the consumption of Cr-contaminated food can cause human health risks by inducing severe clinical conditions (Shahid et al., 2017). Chromium ore deposits are primarily used for **metallurgical applications** such as the production of stainless steel, but other uses in wood preservation, leather tanning, pigments, and refractories exist (Barnhart, 1997). Chromium has several oxidation states (-2 to +6), but hexavalent chromate [Cr(VI)] and trivalent chromite [Cr(III)] forms are the most common and stable in the natural environment, with the former being less abundant than the latter. Therefore, Cr(total) is a good proxy for Cr(III). At PFC level, limits for Cr(VI) have been proposed in the revised Fertiliser Regulation but given that mineral ores are a possible input material for thermal oxidation materials & derivatives and the fact that many EU Member States have established soil screening values for Cr(total) indicates the need for a more detailed assessment on Cr(total). Specific fertilising products, especially industrial by-products, can contain high Cr(III) concentrations. Slags from the steel industry and by-products from the tannery industry have Cr(III) concentrations that range from 250 mg kg⁻¹ to 2 – 3% (Pillay et al., 2003; Cornelis et al., 2008; Wang et al., 2015; Reijonen, 2017). The concentrations of Cr(III) in steel slags can thus be up to 4 orders of magnitude higher than the limit value as established for Cr(VI) in the proposal for the revised Fertiliser Regulation (2 mg kg⁻¹ for PFC 1 - fertilisers).

Environmental and human health risks due to the presence of Cr(III) in fertilising materials could occur through: (i) the conversion of Cr(III) to Cr(VI), and (ii) through the leaching of Cr(III):

- i. The two **species of Cr differ greatly with respect to their sorption and bioavailability in soil, root absorption, translocation to aerial plant parts and plant toxicity**. In most plant species, Cr is poorly translocated towards aerial parts and is mainly retained in the root tissues and converted into Cr(III) (Kabata-Pendias and Mukherjee, 2007; Peralta-Videa et al., 2009; Jaisan and Muthukumar, 2017), thereby reducing the possible risks for human uptake for most crops. Also, most soils microorganisms are only marginally affected by the presence of Cr(III) in the soil (European Chemicals Bureau, 2005). Nonetheless, **experimental test work with a number of slag materials indicates that very gradual oxidation of trivalent to hexavalent chromium does occur when the slag is exposed to atmospheric oxygen, rendering a quantifiable but small portion of chromium in this much more mobile and toxic form**. Pillay et al (2003) showed that steel slag with a 1-3% Cr(III) content, released 1000 - 10000 mg kg⁻¹ Cr(VI) within 6-9 months of exposure to an ambient atmosphere. Apte et al. (2006) showed that Cr(OH)₃ slowly converts to hexavalent chromium, with short-term (90 days) conversion rates of up to 0.05% in moist soils and in the presence of MnO₂. When CaO and Cr₂O₃ coexist in the slag, oxidation of Cr₂O₃ occurs, and Cr(III) can be transformed into Cr(VI) under the action of O₂ from the atmosphere (Li et al., 2017b). CaCrO₄ formed at the surface area of the particles, and this Cr(VI) enriched phase is freely soluble and almost dissolved completely at pH 7 (Li et al., 2017b).

4300 ii. **The leaching of Cr(III) from steel slags has been documented.** Li et al. (2017a)
4301 indicated, for instance, average and maximum Cr concentrations in leachates from
4302 steel slags (3500 mg Cr kg⁻¹) from steel slags that were 15 µg L⁻¹ and 42 µg L⁻¹,
4303 respectively. Proctor et al. (2000) indicated Cr leaching values from steel slags (132
4304 mg Cr kg⁻¹ – 3046 mg Cr kg⁻¹) that range from 10 µg L⁻¹ to 60 µg L⁻¹. Using a
4305 modelling approach, De Windt et al. (2011) even indicated higher potential leaching
4306 from basic oxygen steel slags (1900 mg Cr kg⁻¹) of up to 325 µg L⁻¹. The adsorption
4307 of chromium (III) onto soil follows the pattern typical of cationic metals and increases
4308 with increasing pH (lowering pH results in increased protonation of the adsorbent
4309 leading to fewer adsorption sites for the cationic metal) and the organic matter content
4310 of the soil and decreases when other competing (metal) cations are present (Jing et al.,
4311 2006; Kabata-Pendias, 2011). Certain dissolved organic ligands may also reduce the
4312 adsorption of chromium (III) to the solid phase by forming complexes which enhance
4313 the solubility of chromium (III) in the aqueous phase (Richard and Bourg, 1991).
4314 Moreover, Cr present in fertilising materials can reach surrounding water bodies in a
4315 concentrated form through erosion and soil redistribution processes. Thus, **there is a**
4316 **risk for Cr(III) to be transferred from the soil towards the water bodies and**
4317 **consequently for possible adverse impacts upon aquatic biotic communities.** The
4318 European Chemical Bureau (2005) predicted no effect concentrations (PNEC) for
4319 water bodies of 3.4 µg L⁻¹, which is in the same order as the value for Cr(VI). The
4320 PNEC is the concentration of a chemical below which no adverse effects of exposure
4321 of the substance is expected to occur. This value is two orders of magnitude lower
4322 than the Cr leaching potential from steel slags as documented by De Windt et al.
4323 (2011).

4324
4325 Considering the possible transformation of Cr(III) to the highly toxic Cr(VI), the proposal is
4326 to retain the assessment based on the maximal permissible soil concentration limit value of
4327 100 mg Cr kg⁻¹ soil as determined based on the soil screening values of EU Member States.
4328 Moreover, limiting the maximal Cr concentration in thermal oxidation material will further
4329 limit ecotoxicity effects due to the leaching of Cr(III).

4330
4331 For thermal oxidation materials & derivatives derived from certain eligible input materials (e.g
4332 sewage sludge, tannery sludge, textile waste, basic oxygen furnace slags derived from
4333 mineral ores and ore recycles), the proposed chromium limit of 400 mg kg⁻¹ could be a
4334 limitation. Possibly, the permitted post-combustion manufacturing processes could aid to
4335 decrease the Cr levels to acceptable levels.

4336
4337 Antimony:
4338 Antimony has a wide range of uses, including in the **manufacture of semiconductors,**
4339 **diodes, flameproof retardants, lead hardeners, batteries, small arms, tracer bullets,**
4340 **automobile brake linings, and pigments** (Filella et al., 2002a). The use of antimony in
4341 many different applications can be expected to drop in the future (van Vlaardingen et al.,
4342 2005). Antimony is not an essential element in plants or animals (Fowler and Goering, 1991).

4343 Its bioavailability and toxicological effects depend on its chemical form and oxidation state.
4344 The two common inorganic forms of antimony present in natural waters are antimonate
4345 ($\text{Sb}(\text{OH})_6^-$) and antimonite ($\text{Sb}(\text{OH})_3$) (Filella et al., 2002b). Experimental and clinical trials
4346 with compounds containing antimony have shown that the trivalent compounds are generally
4347 more toxic than the pentavalent compounds (Winship, 1987; Filella et al., 2002a; WHO,
4348 2006).

4349
4350 Antimony can be present in thermal oxidation materials & derivatives that are produced from
4351 the eligible input materials. Especially **ashes of crop residues and sewage sludges show the**
4352 **highest Sb concentrations**, with values up to **70 mg Sb kg⁻¹** (section 16.2.2; Kruger et al.,
4353 2015; Izquierdo et al., 2008). The bioavailability as expressed by the **leaching potential of**
4354 **Sb present in thermal oxidation materials & derivatives ranges typically from 0% to 10%**
4355 (Kim et al., 2003; Cornelis et al., 2008; Izquierdo et al., 2008), but values **up to 36%** have
4356 been observed (Miravet et al., 2006). Antimony is **mostly retained in soils** (McLaren et al.,
4357 1998; Flynn et al., 2003; Wilson et al., 2010). Obviously, the extent of retention influences
4358 the bioavailable and mobile fraction. Many factors impact retention, but Sb is generally
4359 retained on silicate clay minerals, iron oxides and hydroxides and organic matter. In many
4360 natural environments adsorption on the Mn and Fe oxyhydroxides is responsible for retention
4361 of a high proportion of the soil bound Sb.

4362
4363 Information on the acute and chronic toxicity of dissolved antimony to a variety of aquatic,
4364 soil and sediment organisms is reviewed in the risk assessment report prepared by the EU
4365 (EURAR, 2008) and van Vlaardingen (2005). The EURAR risk assessment is for antimony
4366 trioxide and is only available in draft status. The data reviewed indicate that soluble forms of
4367 antimony generally only have a **low to moderate potential to cause harm to aquatic, soil**
4368 **and sediment organisms**. Relevant predicted no effect concentrations (PNEC), as derived by
4369 dividing lowest no observed effect concentration with an assessment factor of 10, in the
4370 EURAR report are as follows: $\text{PNEC}_{\text{surface water}}$: 113 $\mu\text{g Sb/L}$; $\text{PNEC}_{\text{sediment}}$: 11.2 mg Sb/kg(dry
4371 weight); $\text{PNEC}_{\text{microorganisms}}$: 2.55 mg Sb/L; $\text{PNEC}_{\text{soil}}$: 37 mg Sb/kg (dry weight). Van
4372 Vlaardingen (2005) determined a serious risk concentration value for the soil compartment of
4373 54 mg kg⁻¹ soil and chronic ecotoxicological serious risk concentration values of 11 mg Sb L⁻¹.
4374 **The values for the soil compartment are much higher than the value applied in this**
4375 **assessment, based on the 25th percentile of the soil screening value as determined by the**
4376 **EU Member States (3 mg Sb/kg; see above)**. Moreover, experimental bioconcentration
4377 factors obtained for fish, aquatic invertebrates, plants and algae vary between 0.19 and 24
4378 L/kg wet weight (Shigeru et al., 1997; Tschan et al., 2008), **much lower than the limit**
4379 **values for the bioaccumulation criterion (>2000)** as established by Regulation (EC)
4380 1907/2006.

4381
4382 Based on the information presented, **it is concluded that the risk for Sb to enter the**
4383 **environment in a quantity or concentration or under conditions that have or may have**
4384 **an immediate or long-term harmful effect on the environment or its biological diversity**
4385 **due to the application of thermal oxidation materials & derivatives is low**. Therefore, the
4386 proposal is to not retain the assessment based on the maximal permissible soil concentration

4387 limit value of 3 mg Sb kg⁻¹ soil as determined based on the soil screening values of EU
4388 Member States, and no limits for Sb in thermal oxidation materials & derivatives are proposed.

4389

4390 Thallium:

4391 Thallium (Tl) is ubiquitous in nature and is found especially in sulphide ores, usually at low
4392 concentrations (WHO, 1996). An estimated global industrial consumption of 10-15
4393 tonnes/year was estimated for 1991. **Activity of mineral smelters, coal burning power
4394 generating plants, brickwork and cement plants** generate man-made emissions to air and
4395 in waste deposits of approx. 2000-5000 tonnes/year. A large fraction of thallium is released
4396 into the atmosphere, since thallium compounds are volatile at high temperatures. Further
4397 sources of thallium emission are iron and steel production, nonferrous-metal (e.g. Zn, Cd)
4398 smelting and gold production (WHO, 1996). Thallium occurs in **two oxidation states** in the
4399 environment: monovalent Tl(I) and trivalent Tl(III). The oxidation state directly influences
4400 the toxicity of thallium—trivalent Tl is approximately 50,000 times more toxic compared to
4401 monovalent Tl. Furthermore, Tl(I) may be oxidized to Tl(III) due to the activity of
4402 phytoplankton (Twining et al., 2003). As a result, the toxicity of both species is influenced by
4403 their stability, which is associated with the type of sample matrix and the corresponding
4404 environmental conditions. Specific ashes and melting materials, mainly those partially
4405 derived from coal and mineral ores can be rich in Tl, with concentrations ranging from **7 – 11
4406 mg kg⁻¹ for steel slags** (Proctor et al., 2000) and from **1 – 76 mg kg⁻¹ for coal ashes** (Frattini,
4407 2005; Lopez Anton et al., 2013; Karbowska, 2016; Świetlik et al., 2016; Vaněk et al., 2016).

4408

4409 Data regarding significant sources of thallium in the environment and risks for the
4410 environment and human health have been reviewed by Karbowska (2016). **Thallium is
4411 considered as toxic for human and animal organisms, microorganisms and plants**
4412 (Makridis and Amberger, 1996; Nriagu, 1998; Peter and Viraraghavan, 2005). The toxicity of
4413 this element is higher compared to mercury, cadmium and lead (maximum admissible
4414 concentration at 0.1 mg mL⁻¹) (Repetto et al., 1998; Peter and Viraraghavan, 2005). The
4415 toxicity of thallium-based compounds is mainly caused by the similarity between thallium (I)
4416 ions and potassium ions (Grösslová et al., 2015), which results in the disorder of potassium-
4417 associated metabolic processes due to thallium interference (Wojtkowiak et al., 2016).
4418 **Human exposure** to thallium is mainly associated with the consumption of contaminated
4419 food or drinking water. Thallium rapidly enters the bloodstream and is transported across the
4420 whole organism, which leads to accumulation in bones, kidneys and the nervous system. In
4421 consequence, the functioning of several relevant enzymes is disrupted. Stomach and intestinal
4422 ulcers, alopecia and polyneuropathy are considered as classic syndromes of thallium
4423 poisoning. Other symptoms include astral disorders, insomnia, paralysis, loss of body mass,
4424 internal bleeding, myocardial injury and, in consequence, death (Peter and Viraraghavan,
4425 2005). Ingestion of more than 1.5 mg of thallium per kg of body mass may be fatal. Recent
4426 studies also indicate that high levels of Tl may be associated with an increased risk of low
4427 birth weight (Xia et al., 2016).

4428

4429 Świetlik et al. (2016) indicated that **13-30% of the Tl of coal ashes can be present in the
4430 water soluble and weak acid soluble fractions**, considered as mobile fractions or

4431 bioavailable fractions (Pettersen and Hertwich, 2008). Standard leaching tests in acidic and
4432 neutral conditions indicated that **thallium leaching from steel slags was negligible** (Proctor
4433 et al., 2000). **No information is, however, available on the long-term release patterns of**
4434 **Tl for these materials**. In the terrestrial environment, thallium is usually bound with the soil
4435 matrix, which considerably limits its transport, although dissolved thallium (soluble thallium
4436 salts) are susceptible to flushing and may be introduced to the aquatic environment. A high
4437 concentration of thallium in shallow soil also poses a notable threat due to possible uptake by
4438 plant roots and storage in plant biomass. Thallium concentrations in soils are closely
4439 correlated to **phytotoxicity** (Makridis and Amberger, 1996). Thallium has been used as
4440 rodenticide and insecticide and there are indications of inhibition of soil nitrification in the
4441 range of **1-10 mg kg⁻¹ soil** (van Vlaardingen et al., 2005). Van Vlaardingen et al. (2005) also
4442 indicated low chronic ecotoxicological serious risk concentration values of 6.5 µg L⁻¹.
4443 Experimental bioconcentration concentration factors obtained for aquatic above **the limit**
4444 **values for the bioaccumulation criterion** (2000; as established by Regulation (EC)
4445 1907/2006 have been reported (7000 L/kg wet weight; Smith and Kwan, 1989). Hence,
4446 **thallium-based compounds exhibit a high tendency to accumulate in the environment,**
4447 **and prolonged presence of thallium in terrestrial, aerial and aquatic systems may**
4448 **notably increase the exposure risks** (Karbowska, 2016).

4449
4450 In order to prevent that thallium enters the food chain and affects the functioning of living
4451 organisms poisoning, **safe limits for Tl concentration in soils have been proposed by**
4452 **regulatory bodies** (1 mg Tl kg⁻¹; Canadian Council of Ministers of the Environment, 2003)
4453 and **risk assessment studies** (1 - 2 mg Tl kg⁻¹; van Vlaardingen et al., 2005; Xia et al.,
4454 2016). Considering the risks for human health and the environment due to the application of
4455 Tl-rich thermal oxidation materials, the proposal is to retain the assessment based on the
4456 maximal permissible soil concentration limit value of 2 mg Tl kg⁻¹ soil.

4457
4458 Based on the information received from the STRUBIAS sub-group, **the proposed Tl limit**
4459 **value of 10 mg Tl kg⁻¹ should not be a limitation for any of the thermal oxidation**
4460 **materials & derivatives that are targeted as ingredients for CE marked fertilising**
4461 **products**, including slags from the iron and steel industry.

4462
4463 Vanadium:
4464 Vanadium (Z = 23) is a hard, steel-gray metal listed as a transitional element (Imtiaz et al.,
4465 2015). Along with the transition elements Mo, W, Mn, Fe, Co, Ni, Cu and Zn, vanadium is an
4466 essential bioelement, but in contrast to most of these elements functional vanadium
4467 compounds have so far been detected only in the form of vanadium nitrogenases and
4468 vanadate-dependent haloperoxidases in a comparatively restricted number of organisms
4469 (Rehder, 2015). Vanadium can exist in a variety of oxidation states: - 1, 0, + 2, + 3, + 4, and
4470 + 5 (Larsson et al., 2013). In solution, under environmental conditions, mainly vanadium(IV)
4471 and vanadium(V) are present (Wanty and Goldhaber, 1992). Vanadium(IV) is an oxocation
4472 that occurs in moderately reducing environments. Under more aerobic conditions, the
4473 oxocation of vanadium(V), VO₂⁺, prevails at a solution pH below 4, whereas the oxyanion
4474 vanadate(V), H₂VO₄⁻, dominates above that pH (Baes and Mesmer, 1976). About 80% of the

4475 globally produced V is being used in the steel industry as an additive. As a result, **slags from**
4476 **the steel industry can show high V contents, with values documented that range from 54**
4477 **to 26 000 mg kg⁻¹** (Proctor et al., 2000; Cornelis et al., 2008; Reijkonen, 2017).
4478

4479 The bioavailability and toxicity of vanadium to soil microorganisms and plants has been
4480 reviewed by Larsson et al. (2013). Toxicity of vanadium to plants has mainly been studied in
4481 nutrient solution, and acute toxicity starts between 1 mg V L⁻¹ and 5 mg V L⁻¹ for the most
4482 sensitive species (Kaplan et al., 1990; Carlson et al., 1991; Imtiaz et al., 2015). Larsson et al.
4483 (2013) and Smith et al. (2013b) reported **soil vanadium toxicity thresholds (EC50) for**
4484 **higher plants**, ranging from 18 mg V kg⁻¹ to 510 mg V kg⁻¹ with a median of **91 mg V kg⁻¹**
4485 in 5 different soils. In their review, Smit (2012) proposed a long-term environmental risk
4486 limit for freshwater organisms at 1.2 µg V L⁻¹. Chronic ecotoxicological serious risk
4487 concentration values of 99 µg V L⁻¹ have been documented by van Vlaardingen et al. (van
4488 Vlaardingen et al., 2005)
4489

4490 Depending on the type of slag, the immediate V release from steel slags can be high
4491 (Chaurand et al., 2006; Reijkonen, 2017). In the short-term (15 days), 1.7% of the V present
4492 in blast oxygen furnace slag may be leached (De Windt et al., 2011). Reijonen indicated that
4493 up to 8–12% of the total V in (blast oxygen furnace slag, 14 000 mg V kg⁻¹) and high
4494 vanadium slag (26 000 mg V kg⁻¹) was in the **water-soluble form**. The fate of released V
4495 depends on soil pH, redox potential and organic matter content (Larsson et al., 2015;
4496 Reijonen et al., 2016). Moreover, in non-acidic soils, the soluble V exists predominantly as
4497 vanadium(V), considered more harmful to biota than vanadium(IV). Overall, it is clear that a
4498 significant proportion of the V in slags is potentially bioavailable or susceptible to be leached
4499 into recipient water systems (Larsson et al., 2015; Reijkonen, 2017). Moreover, the **surface**
4500 **runoff** from slag-amended fields increases the risk of V release to aquatic organisms. This is
4501 attributable to the fact that desorption of V from the particle surfaces is favoured by
4502 increasing the solution to soil ratio (De Windt et al., 2011; Reijkonen, 2017). The risk limits
4503 associated to extremal V additions in soils are also defined in a report by the National
4504 Institute for Public Health and the Environment of the Netherlands (van Vlaardingen et al.,
4505 2005). In this work, the addition of 25 mg V kg⁻¹ (total concentration of 67 mg kg⁻¹) was
4506 considered a serious risk for terrestrial ecosystems.
4507

4508 Considering the toxicity of vanadium to soil microorganisms and plants, the proposal is to
4509 retain the assessment based on the maximal permissible soil concentration limit value of 125
4510 mg V kg⁻¹ soil as determined based on the soil screening values of EU Member States.
4511 Moreover, limiting the maximal V concentration in thermal oxidation materials will further
4512 limit ecotoxicity effects due to the leaching of vanadium.
4513

4514 For thermal oxidation materials & derivatives derived from the eligible input materials, with
4515 the exception of basic oxygen furnace slag, there is no techno-scientific evidence that the
4516 proposed vanadium limit of 600 mg kg⁻¹ will be a major limitation for the targeted
4517 STRUBIAS materials on the emergent market.
4518

4519 Conclusion and proposals

4520 In summary, **it is indicated that the long-term application of thermal oxidation materials**
4521 **& derivates can contain Cr, Tl and V concentrations that could accumulate in soils and**
4522 **lead to the exceeding of soil quality standards as established by EU Member States and**
4523 **possibly jeopardise environmental and human health protection.** The soil quality
4524 standards applied in this assessment for Cr, Tl and V are respectively 67%, 200% and 107%
4525 higher than the current median soil background concentrations for these elements in Europe.
4526 The assessment revealed that only risks are indicated for thermal oxidation materials &
4527 derivates that are derived from minerals, ores, ore concentrates and coal. Therefore, following
4528 proposal is made for the CMC requirements:

4529

4530 6. Thermal oxidation materials & derivates incorporated into the CE marked fertilising
4531 product shall:

4532 a) [not related to metal limit values];

4533 b) [not related to metal limit values];

4534 c) contain no more than 400 mg kg⁻¹ dry matter of total Chromium (Cr), if derived
4535 from materials listed under point e), f) or g) of paragraph 1;

4536 d) contain no more than 10 mg kg⁻¹ dry matter of Thallium (Tl), if derived from
4537 materials listed under point f) or g) of paragraph 1; and

4538 e) contain no more than 600 mg kg⁻¹ dry matter of Vanadium (V), if derived from
4539 materials listed under point f) or g) of paragraph 1.

4540

4541 Limit values for Cr, Tl and V for ash-based materials have also been included in national
4542 legislation; Denmark, Finland, Germany and Sweden have established limit values for Cr that
4543 range from 100 – 300 mg Cr kg⁻¹; German legislation has a limit value of 1 mg kg⁻¹ for Tl,
4544 Finnish legislation has a limit value of 70 mg kg⁻¹ for V.

4545

4546 Leaching of metals, metalloids, non-metals and halogens

4547 Due to the combination of high bulk contents and solubility, the most prominently leached
4548 elements from ashes are Ca and SO₄²⁻, followed by Cl, Na and K to a lesser extent.
4549 Nevertheless, the large number of trace elements that are leached in generally lower levels
4550 are of the highest concern due to their toxicity to **aquatic organisms** and the significant
4551 **human health hazard** they may entail for groundwater resources (Hjelmar, 1990; Izquierdo
4552 et al., 2008; Freire et al., 2015). The risks associated to the leaching of metals and metalloids
4553 are included in the assessment above, and risks are thus controlled for. **Moreover, leaching**
4554 **tests have shown that the environmental impact of most trace elements present in ashes**
4555 **upon their application or disposal is expected to be rather low** due to the relatively low
4556 water solubility of most trace metals and their tendency to sorb to soil particles (Sheppard et
4557 al., 2009; Barbosa et al., 2011; Vassilev et al., 2013b). Leachability of chemicals is known to
4558 increase with the presence of organic matter (European Commission, 2006c; Secretariat of
4559 the Stockholm Convention on Persistent Organic Pollutants, 2008); the proposed 3% organic
4560 carbon limit for ashes and slags will thus also effectively reduce the leaching of metals.

4561 Given the linear correlation between the bulk and leachable content of trace elements in ashes
4562 (Izquierdo et al., 2008), this holds especially true if the proposed concentration criteria at
4563 PFC or CMC level of the metal/metalloid are respected (STRUBIAS sub-group comments
4564 from PT; Vamvuka et al., 2005; Skodras et al., 2006; Izquierdo et al., 2008; Vamvuka and
4565 Kakaras, 2011; Freire et al., 2015).

4566

4567 In the study of Barbosa et al. (2011), the majority of the chemical species quantified in ash
4568 eluates, namely **phenol compounds, sulphates, fluorides, chlorides, dissolved organic C**
4569 **(DOC), total dissolved solids**, presented concentrations below the limit values defined for
4570 acceptance of inert waste at landfills (European Council Decision 2003/33/EC).

4571

4572 Barber et al. (2003) and Barbosa et al. (2011) indicated that the leachable cyanide
4573 concentrations in ash were low, and similar to those in biomass and soil. This is in line with
4574 observations that leachable cyanide in residual ash is <1% of the mass of cyanide emitted to
4575 the atmosphere (Barber et al., 2003). Any dilution of ash with soil after ash applications gives
4576 rise to low, acceptable cyanide concentrations in leachate and run-off water from the field
4577 samples. Therefore, it is proposed that **cyanide content in biomass ashes should not be**
4578 **regulated**.

4579

4580 Therefore, it is concluded that the **leaching of abovementioned minor and trace elements**
4581 **from ashes is not of particular concern, and no specific limits are proposed for the**
4582 **leachable ash fraction**.

4583

4584 5.5.5.2 PAH, PCDD/F and PCB

4585 The combustion of plant and animal biomass, waste and other materials can cause the
4586 generation of persistent organic pollutants (**POPs**), such as **polycyclic aromatic**
4587 **hydrocarbons (PAHs), dioxins and furans (polychlorinated dibenzo-p-dioxins and**
4588 **dibenzofurans - PCDD/F)), and dioxin-like polychlorinated biphenyls (PCBs)**. The
4589 presence of POPs is thus a major issue of concern for thermal oxidation materials & derivatives
4590 (Pitman, 2006; Insam and Knapp, 2011; Freire et al., 2015; Masto et al., 2015). Persistent
4591 organic pollutants are **toxic** chemicals that adversely affect human health and the
4592 environment around the world. They **persist** for long periods of time in the environment, and
4593 can accumulate and pass from one species to the next through the food chain. Because they
4594 can be **transported** by wind and water, most POPs generated in one country can and do
4595 affect people and wildlife far from where they are used and released. To address this global
4596 concern, the United States joined forces with 90 other countries and the European
4597 Community to sign a ground-breaking United Nations treaty in Stockholm, Sweden, in May
4598 2001. Under the treaty, known as the Stockholm Convention, countries agreed to reduce or
4599 eliminate the production, use, and/or release of particular POPs, and specified under the
4600 Convention a scientific review process that has led to the addition of other POP chemicals of
4601 global concern.

4602

4603 Most POPs present in the input materials destined for thermal oxidation materials are
4604 **destroyed** during thermal oxidation, but the **formation of new POPs may occur** because of
4605 incomplete combustion or formation in the flue gas path at levels that depend both on the fuel
4606 composition, combustion conditions and flue gas treatment (Lavric et al., 2004; Enell et al.,
4607 2008; Mastro et al., 2015). Persistent organic pollutants are subsequently distributed between
4608 flue gas and ash streams, but the distribution of POPs among fly ashes and bottom ashes is
4609 different between PAH (higher in bottom ashes) and PCDD/F and BCBs (higher in fly ashes
4610 (Gulyurtlu et al., 2007; Lopes et al., 2009). During combustion, POPs are formed via organic
4611 precursors like phenols and lignin, via *de novo* reactions in the presence of particulate carbon
4612 and chloride or by pyrosynthesis (high temperature gas phase formation) (Lavric et al., 2004;
4613 Gulyurtlu et al., 2007; Shibamoto et al., 2007; Van Caneghem et al., 2010).

4614
4615 The **technology used in modern incineration and biomass plants**, including grinding the
4616 feedstock into very fine particles, a short residence time of the particles in the boiler and
4617 optimum fuel to air ratio, **ensures nearly complete combustion to low organic C levels in**
4618 **the ashes and slags while preventing the creation of such pollutants and their**
4619 **accumulation in the ash at hazardous concentrations**. Indeed, the findings of tests that
4620 were performed on various ashes in Europe confirm this assessment (European Commission,
4621 2006c).

4622

4623 Polycyclic aromatic hydrocarbons (PAHs)

4624 **Polycyclic aromatic hydrocarbons are typical products of incomplete combustion** and should
4625 be lower in concentration in all residue streams the more efficient the combustion control and
4626 the burnout are. **A review of the data indicates that the concentrations of PAH in the**
4627 **boiler and filter residues are, apart from some exceptions, lower than those in bottom**
4628 **ashes (Vehlow et al., 2006)**. This behaviour is to be expected since the burnout of the
4629 particulate matter in the flue gas is typically higher than that of the bottom ashes as is
4630 documented by the lower total organic carbon in those residues. In principle, for residues
4631 from modern waste thermal oxidation plants no major problems concerning PAH should be
4632 expected (European Commission, 2006c; Vehlow et al., 2006). However, **the database for**
4633 **this class of compounds is too weak to support that statement, and also higher PAH**
4634 **values have been observed in practice** (European Commission, 2006c; Vehlow et al., 2006;
4635 Van Caneghem and Vandecasteele, 2014). Concentrations of specific and highly toxic
4636 compounds, for example of benzo(a)pyrene, were not found. Rey-Salgueiro et al. (2016) also
4637 indicated that the concentrations of **benzene, toluene, ethylbenzene, the ortho-, para- &**
4638 **meta-xylenes and styrene** (BTEX + S) in all samples analysed in their study **were low for**
4639 **bottom and fly ashes** with maximum concentrations of 0.3 mg kg⁻¹.

4640

4641 Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F)

4642 PCDD/Fs are emitted from thermal processes involving **organic matter and chlorine as a**
4643 **result of incomplete combustion or chemical reactions**. It is well known that transient
4644 combustion conditions and especially the start-up and shut-down procedure are characterized

4645 by elevated PCDD/F levels in the raw gas (Hunsinger et al., 2002); PCDD/Fs **form in the**
4646 **temperature window of 200 to about 450°C** (Lundin and Marklund, 2005). **Also feedstock**
4647 **characteristics** play a major role in PCDD/Fs formation during biomass combustion.
4648 PCDD/Fs are always formed during wood combustion via precursors such as phenols and
4649 lignin, or via *de novo* reactions in the presence of particulate carbon and chlorine. High
4650 emission levels can also be expected from burning treated wood and wood waste (Lavric et
4651 al., 2004). Temperatures in the range of 1,100°C – 1,200°C are considered to be most
4652 efficient for destroying halogenated hazardous compounds, including PCDD/PCDF
4653 (Secretariat of the Stockholm Convention on Persistent Organic Pollutants, 2008).
4654 Nonetheless, depending on the composition of the fly ash, also lower temperatures have been
4655 shown to enable the destruction of PCDD/F (Lundin and Marklund, 2005). **The**
4656 **concentration of PCDD/Fs in the fly ash is typically higher than in the bottom ash**
4657 (Lavric et al., 2004; Vehlow et al., 2006). The bottom ash PCDD/F inventory correlates well
4658 with the organic carbon content, and PCDD/F levels are usually below 20 ng WHO toxicity
4659 equivalents kg⁻¹ when the organic carbon content in the ashes is below 1% (Vehlow et al.,
4660 2006). Nonetheless, **the adsorption of PCDD/Fs on fly ashes can be relatively high**, and
4661 depends on the presence of elementary carbon or soot particles in the fly ashes, since
4662 inorganic surfaces have a poor adsorption potential for PCDD/F (Vehlow et al., 2006).
4663 PCDD/F concentrations in the range of 100 to 10 000 ng WHO toxic equivalents kg⁻¹ have
4664 actually been found in fly ashes from modern waste incineration plants for municipal solid
4665 waste, sewage sludge and poultry litter (Vehlow et al., 2006; Rigby et al., 2015; Egle et al.,
4666 2016). Moreover, the database on PCDD/F for sewage sludge mono-incinerators and biomass
4667 combustion plants is limited.

4668

4669 Dioxin-like polychlorinated biphenyls (PCBs)

4670 Dioxin-like polychlorinated biphenyls are organic chlorine compounds with the formula
4671 C₁₂H_{10-x}Cl_x. PCBs are formed **through a similar mechanistic pathway as PCDD/Fs**, and
4672 maximum PCB formation occurs at temperatures around 350°C (Lemieux et al., 2001). PCBs
4673 are more efficiently destroyed if higher combustion temperatures are used (e.g. above
4674 1200°C); however, lower temperatures (e.g. 950 °C) together with appropriate conditions of
4675 turbulence and residence time have also been found to be effective for PCB removal. Van
4676 Caneghem and Vandecasteele (2014) indicated low PCB ranges in ashes, with average
4677 concentrations for ashes derived from refuse derived fuels and sewage sludge samples of 8.57
4678 and 4.90 µg per kg dry matter, respectively. PCB data for poultry litter ashes (Rigby et al.,
4679 2015) and sewage sludge ashes and their derivatives (Egle et al., 2016) also indicated very low
4680 PCB concentrations. Hence, **ashes of a low organic C content and PAH as result of a**
4681 **complete combustion process show low PCDD/F concentrations**. Moreover, a close
4682 relationship between PCDD/F and PCB concentrations has been observed (Lemieux et al.,
4683 2001; Pandelova et al., 2006; Li et al., 2018).

4684

4685 EU and National regulations in EU Member States on POPs in fertilising materials
4686 Commission Regulation (EU) No 756/2010, amending Regulation (EC) No 850/2004 of the
4687 European Parliament and of the Council **on persistent organic pollutants as regards**
4688 **Annexes IV and V, lays down limit values for wastes for thermal processes.** The limit
4689 values in that Regulation are 15 µg kg⁻¹ for PCDD/F and 50 mg kg⁻¹ for PCBs.

4690 The POP content in ash-based fertilising products is regulated as follows in different EU
4691 Member States (Haglund and Expertsgrup, 2008):

4692 ○ In **Denmark** (BEK1636 of 22 December 2006), the PAH content has to be
4693 analysed only if the loss on ignition (LOI) is > 5%. The limit value for PAHs
4694 is 3 mg/kg dry ash (12 mg/kg dry ash in the proposed update).

4695 ○ **Portugal's** legislation: DL 103/2015 for non-harmonized fertilisers imposes,
4696 only for fertilisers containing industrial sludge or their mixtures with sewage
4697 sludge, limits for PCDD/F (100 ng TEQ/kg), PAH (6 mg/kg) and PCB (0.8
4698 mg/kg). Ashes (EWC 100101, 100102 and 100103) may be incorporated in
4699 several fertilising types without limits for these organic pollutants.

4700 ○ The application of ashes in **Austria** is regulated through "Rückführung von
4701 Pflanzenaschen auf Böden" [Recycling of plant ashes to the soil]. In the
4702 Salzburg area there is "Amt der Salzburger Landesregierung Abt4/Abt16
4703 Richtlinien 2006 – Richtlinien für die Aufbringung von Asche aus
4704 Holzfeuerungsanlagen auf landwirtschaftlich genutzte Böden". These
4705 regulations indicate that if the total of unburnt C is above 5%, PAH₆ should be
4706 < 6 mg kg⁻¹ and PCDD/F < 20 ng WHO TE kg⁻¹.

4707 ○ For the **UK**, a **Quality Protocol for Poultry Litter Ash** (End of Waste
4708 Criteria for the Production and Use of Treated Ash from the Incineration of
4709 Poultry Litter, Feathers and Straw - Waste and Resources Action Programme
4710 and Environment Agency) is available with a limit value for PCDD/F of 10 ng
4711 TEQ/kg.
4712
4713

4714 Conclusion and proposals

4715 **Modern thermal oxidation plants with good combustion control produce bottom wood**
4716 **ashes** with inventories of POPs that are not much higher than those encountered in European
4717 soils (Lavric et al., 2004; Pitman, 2006; Vehlow et al., 2006; Rohr et al., 2015). Hence, even
4718 without post-combustion treatment (e.g. 3R process, acid extraction followed by secondary
4719 thermal treatment) for the abatement of organic compounds, acceptable levels of POPs can be
4720 achieved for the proposed input materials if **stable combustion conditions are established**
4721 **and no unburnt residues remain.** **Bottom ashes** are typically more enriched in **PAHs**,
4722 whereas **PCDD/Fs and PCBs are abundantly adsorbed to the fly ash fraction.**

4723

4724 Nonetheless, some thermal oxidation materials & derivatives show **high PAH and PCDD/F**
4725 **values.** **PCB levels are typically low in the ash fraction,** and levels of PCBs and PCDD/F

4726 are closely correlated in ashes. This conclusion is **confirmed by the (mostly confidential)**
4727 **data that was received from the STRUBIAS sub-group**. National legislation also typically
4728 focuses on PAH and PCDD/Fs, and none of the national legislative frameworks impose
4729 additional limits for PCBs in the ashes and slags.

4730
4731 Based on the data collected, the following technical requirement for this CMC is proposed:
4732

4733 **The slags and ashes obtained by thermal oxidation shall have:**

- 4734 ○ No more than 6 mg/kg dry matter of PAH₁₆²¹, and
- 4735 ○ No more than 20 ng WHO toxicity equivalents/kg dry matter of PCDD/F²²,

4736

4737

4738 5.5.5.3 *Other organic chemical pollutants*

4739 Other pollutants of concern may be present in sewage sludge (e.g. **pharmaceuticals,**
4740 **personal care products, nanomaterials,** etc.) and animal by-products (e.g. **hormones,**
4741 **veterinary medicines, metabolites**). However, the concentration of these compounds is
4742 generally less than 1% halogenated organic substances, expressed as chloride. Thermal
4743 destruction is generally considered to be an effective method for the removal of these
4744 pollutants that occur in diluted form in non-hazardous waste streams to levels below
4745 environmental or human health concern (UNEP, 2004). The ability of temperatures
4746 exceeding 850°C to destroy or inactivate organic contaminants with high destruction
4747 efficiencies have been measured for aldrin, dieldrin, HCB, DDT, BSE, pharmaceutical
4748 compounds and other organic pollutants (UNEP, 2004; INTECUS GmbH, 2013).

4749

4750 5.5.5.4 *Biological pathogens*

4751 Heat acts to kill or inactivate by denaturation of essential proteins (enzymes, viral capsids)
4752 and nucleic acids. From the biological pathogens that could be present in the eligible input
4753 materials, spore-forming bacteria such as *Bacillus* and *Clostridium* are the most resistant to
4754 heat inactivation. Of the non-spore-forming waterborne and foodborne enteric pathogens,
4755 enteric viruses are the most heat-resistant, followed by bacteria and protozoa. Parvoviruses
4756 are among the most heat-resistant heat viruses. The thermal destruction has been studied in
4757 great detail by the food industry because of the importance of this process in killing
4758 pathogenic bacteria and preventing foodborne spoilage. The findings from this indicated that
4759 much lower temperatures are required for the dry heat deactivation of biological pathogens,
4760 than those required for the production of thermal oxidation materials. **Above temperatures**
4761 **of 120°C, minimal thermal death times are required to inactivate biological pathogens,**
4762 even under dry conditions. The thermal oxidation process efficiently causes the **thermal**

²¹ Sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene, dibenzo[a,h]anthracene and benzo[ghi]perylene

²² van den Berg M., L.S. Birnbaum, M. Denison, M. De Vito, W. Farland, et al. (2006) The 2005 World Health Organization Re-evaluation of Human and Mammalian Toxic Equivalency Factors for Dioxins and Dioxin-like Compounds. *Toxicological sciences: an official journal of the Society of Toxicology* 93:223-241. doi:10.1093/toxsci/kfl055

4763 **death of all biological microorganisms** present in the selected input materials (Gerba,
4764 2015). Therefore, no specific measurements on biological pathogens are proposed as criteria.
4765

4766 5.5.5.5 *Radioactivity*

4767 Concerns over the potential radioactivity of ashes stem from the expectation that natural or
4768 manufactured radioactivity present in the input material can become concentrated in ash upon
4769 combustion. This is majorly a concern for **wood ashes, as trees may accumulate**
4770 **radioactive nuclides over prolonged periods of time**. Overall, the concern has been less for
4771 natural radiation (which is generally considered to be negligible), and more for anthropogenic
4772 radionuclides that may be present at higher levels in plants and soils in areas that have
4773 **experienced nuclear fall-out** (Pitman, 2006).
4774

4775 The principal radionuclide of concern is **Cesium-137**, with a half-life (time taken for
4776 radioactivity to decay to 50% of the original levels) of 30.2 years. The half-life of this isotope
4777 results in contamination remaining for many decades after the original event, and significant
4778 quantities were released into some regions of Europe from the 1986 Chernobyl accident
4779 (Steinhauser et al., 2014). Based on the data available in the biodat database (ECN, 2017), the
4780 activity concentration of ¹³⁷Cs in wood ashes varies between 81 and 4460 Bq/kg (limited
4781 dataset of 15 samples of unknown geographic origin), with more than 50% of the samples
4782 having activity values above 1000 Bq/kg. In order to protect human health safety aspects of
4783 workers, the risk assessment of the International Atomic Energy Agency (IAEA, 2003)
4784 recommended a unified ¹³⁷Cs limit value of 1000 Bq kg⁻¹ for timber and wood products that
4785 is applicable to all the considered conditions, i.e. local (contaminated areas), regional,
4786 national and international (IAEA, 2003). Hence, there is a possible risk associated to ¹³⁷Cs
4787 radioactivity in wood ashes.
4788

4789 The main legal instrument for radiation sources and protection from these is **Council**
4790 **Directive 2013/59/Euratom²³ laying down basic safety standards for protection against**
4791 **the dangers arising from exposure to ionising radiation**. The Directive provides a legal
4792 framework for the regulatory control of practices involving radiation sources and provisions
4793 for the protection of workers and the public exposed to these radiation sources that show
4794 activities above specific threshold values, being 100 Bq/kg for ¹³⁷Cs. Member States are
4795 responsible to establish legal requirements and an appropriate regime of regulatory control
4796 for radioactive exposure based on a risk assessment.
4797

4798 Sweden is the only EU Member State that has set restrictions in place to limit radioactive
4799 exposure through ashes (Regulation SSI FS 2005.1). The limit has been set at 10 000 Bq/kg
4800 for ashes applied on forest land and **500 Bq/kg for agriculture** and for reindeer grazing land.
4801

²³ Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom, Official Journal of the European Union (OJ L13, 17.01.2014, p. 1 -73)

4802 As potential risks associated to radioactivity in wood ashes is regulated through Directive
4803 2013/59/Euratom, **no specific provisions or activity concentration limit values are**
4804 **proposed for the CMC thermal oxidation materials & derivatives.**

4805

4806 5.5.5.6 Emissions

4807 **The mechanisms that lead to emissions from the handling and application of fertilising**
4808 **during material are outlined in section 5.4.5.4.**

4809

4810 One of the mechanisms may generate **airborne dusts and particulate matter emissions.**
4811 Epidemiological and toxicological studies have shown particulate mass $<2.5 \mu\text{m}$, $<100 \mu\text{m}$
4812 and $<10 \mu\text{m}$ (PM_{2.5}, PM₁₀ and PM₁₀₀) comprises fractions with varying types and degrees
4813 **of health effects for workers** that are involved in the handling of ashes. This suggests a role
4814 for both the chemical composition (such as transition metals and combustion-derived primary
4815 and secondary organic particles) and physical properties (size, particle number and surface
4816 area). Exposure to particles from biomass may be associated not only with respiratory, but
4817 also with cardiovascular health issues (United Nations Economic Commission for Europe
4818 (UN ECE), 2009). A particularly relevant aspect of thermal oxidation materials & derivatives is
4819 that they contain **silica** among the ash-forming material in significant quantities (section
4820 16.2.1). Respirable free crystalline silica (*i.e.*, quartz) is associated with silicosis (a nodular
4821 pulmonary fibrosis), lung cancer, pulmonary tuberculosis, and other airway disorders
4822 (NIOSH—Publications Dissemination, 2002). In view of potential risk associated to airborne
4823 dusts and particulate matter emissions, following aspects are relevant to consider:

- 4824 a) The dustiness of a powder product, defined as the propensity of a material to generate
4825 airborne dust during its handling (Lidén, 2006), not only depends on the **intrinsic**
4826 **physical properties of the material but also on the handling scenario.**
- 4827 b) Exposure to ash results in exposure to respirable free silica, but no well-designed
4828 epidemiological study has established an association between silica exposure from
4829 this source and adverse health effects (Meij et al., 2000; Hicks and Yager, 2006).
4830 Some research has demonstrated that the lack of health effects may be because the
4831 free quartz in combusted material is vitrified and unable to interact with biological
4832 targets (Van Eijk et al., 2011). The tendency for silica in biomass ash to fuse has also
4833 been observed (Van Loo and Koppejan, 2008). This feature, in conjunction with the
4834 understanding that in general biomass has a lower silica content than conventional
4835 solid fuel, indicates that the silica in ash is unlikely to pose an occupational health
4836 concern (Meij et al., 2000; Rohr et al., 2015).

4837

4838 In line with the discussion provided in 5.4.5.4, it is concluded that **correct classification and**
4839 **labelling as foreseen in EU legislations allows downstream users to assess the risk**
4840 **associated airborne dust emissions and other air emissions during the handling and**
4841 **application of certain products, and to take the necessary measures to prevent any**
4842 **potential adverse impacts in case a risk has been identified. It is indicated that the**
4843 **provisions in the proposal for the Revised Fertiliser Regulation on labelling and**

4844 **European Regulations are sufficiently effective to control for any adverse impacts**
4845 **associated to emissions during the handling and application of thermal oxidation**
4846 **materials & derivatives.**

4847

4848 5.5.5.7 *Occupational health*

4849 **Council directive 89/391/EEC on the introduction of measures to encourage**
4850 **improvements in the safety and health of workers at work seeks to adequately protect**
4851 **workers and encourages improvements in occupational health and safety in all sectors**
4852 **of activity, both public and private.** The Directive also promotes workers' rights to make
4853 proposals relating to health and safety, to appeal to the competent authority and to stop work
4854 in the event of serious danger. No further legal requirements are therefore proposed.

4855

4856 5.5.6 Physico-chemical properties

4857 5.5.6.1 *Dry matter content*

4858 Biological pathogens are destroyed during the combustion process, for which reason there is
4859 no risk for biological re-contamination of the thermal oxidation materials after combustion.
4860 Therefore, no further criteria on moisture content are proposed.

4861

4862 5.5.6.2 *pH*

4863 Reactive ash with high pH and high dissolution rates of salts may cause burns to the
4864 vegetation, for instance to *Sphagnum* mosses which have been found especially sensitive.
4865 Reactive ashes with a very high or low pH are not suitable for land application as they will
4866 induce a pH shock effect to soil fauna and flora. Therefore, **it is proposed to limit the pH_{H2O}**
4867 **(in water) for pyrolysis material to the 4 – 12 range.**

4868

4869 5.5.6.3 *Granulometry*

4870 Agglomeration is used as a means of improving product characteristics and enhancing
4871 processing conditions. In addition to these benefits, agglomeration also solves a number of
4872 problems associated with ash fines:

- 4873 ○ Significant dust reduction/elimination and mitigation of product loss;
- 4874 ○ Improved handling and transportation;
- 4875 ○ Improved application and use;
- 4876 ○ Increased water infiltration as there is no risk for the blocking of soil pores.

4877

4878 At the same time, it should be noted that thermal oxidation materials & derivatives are CMCs,
4879 for which reason they can be mixed with other CMCs prior to becoming a PFC (e.g. compost,
4880 etc.).

4881 Moreover, it is noted that particle form (granule, pellet, powder, or prill) of the product shall
4882 be indicated on the **label** of solid inorganic macronutrient fertilisers (see labelling

4883 requirements in the proposal for the Revised Fertiliser Regulation). Therefore, no **criteria on**
4884 **granulometry or particle size distribution are proposed at CMC level.**

4885

4886 5.5.7 Handling and storage

4887 It is proposed that physical contact between input and output materials must be avoided,
4888 including during storage.

4889

DRAFT - WORK IN PROGRESS

4890 **5.6 Pyrolysis & gasification materials**

4891 5.6.1 Scope delimitation and possible uses

4892 This CMC comprises organic materials that have **undergone a thermochemical conversion**
4893 **in an oxygen-limiting environment**, resulting in the production of carbonaceous materials
4894 like char, charcoal, soot and graphite (see section 5.1.3). Such black carbon materials, or
4895 combinations thereof, are often referred to as "biochar" when applied as a soil amendment.
4896 The scope of this CMC aims to cover carbonaceous materials that are not fully oxidised, and
4897 thus fall in between thermal oxidation materials (section 5.5, with a maximum organic C
4898 content of 3%) and non-carbonised biomass along the biomass transformation spectrum.
4899 These materials are the result of different production processes that take place in an oxygen
4900 limiting environment, including gasification, dry pyrolysis and wet pyrolysis (also referred to
4901 as hydrothermal carbonisation). In line with the other STRUBIAS CMCs, a reference will be
4902 made to the production process and the name **pyrolysis & gasification materials will be**
4903 **used to cover the spectrum of production processes that take place under oxygen-**
4904 **limiting conditions**. The produced materials are of very heterogeneous nature, and their
4905 properties also depend on the time-temperature profiles applied and the feedstock used.

4906 The variability in biomass feedstock and production process conditions makes that **pyrolysis**
4907 **& gasification materials cover a very heterogeneous product property spectrum that**
4908 **may fulfil a variety of fertilising functions** when applied onto the soil (Neves et al., 2011).

4909 ○ Pyrolysis & gasification materials may be used as a **nutrient source for**
4910 **plants**. Pyrolysis & gasification materials may contain inorganic plant
4911 nutrients. Macronutrients such as P, K, Mg, and Ca are largely conserved in
4912 the end-material (60% to 100%, Gaskin et al., 2008), and their bio-available
4913 nutrient content is generally correlated to total concentration (Ippolito et al.,
4914 2015). Phosphorus availability is, however, not controlled by total P content,
4915 but is likely determined by the coordinated cations present (Al, Fe, Ca, Mg) in
4916 the feedstock (Wang et al., 2012b). The loss of N is highly variable during
4917 pyrolysis (0%-80%, depending on the process conditions applied), but the
4918 pyrolysis/gasification process may transform a large share of N to complexes
4919 that are unavailable to plants (Biederman and Harpole, 2013). These
4920 observations illustrate the overall importance of feedstock source for the
4921 potential of pyrolysis & gasification materials to supply nutrients to plants.
4922 The pyrolysis of feedstock from animal production systems (bone material,
4923 manure) and human waste treatment (sewage sludge) creates nutrient-rich end-
4924 materials, while most plant-based pyrolysis & gasification materials have
4925 lesser quantities of macronutrients (section 16.3.1).

4926 ○ Pyrolysis & gasification materials may in some cases, independent of the
4927 feedstock they are produced from, act as a **soil improver** (Chia et al., 2015).
4928 The addition of pyrolysis & gasification materials to soils may lead to unique
4929 interactions that influence **soil physical properties** such as porosity, particle
4930 size distribution, density and packing. Plant yield can then be impacted
4931 through, for example, the availability of water and air in the vicinity of the

4932 plant root, or the **stimulation of soil microbial activities in the plant**
4933 **rhizosphere** (Jeffery et al., 2015). It should be noted that the effect of adding
4934 nutrient-poor pyrolysis & gasification materials without complementary
4935 fertilisation to soils of temperate climates, on average, does not increase plant
4936 yield (Biederman and Harpole, 2013). This may be attributed to the fact that
4937 most European soils have good physical properties and the addition of C-rich
4938 pyrolysis & gasification materials to soils might stimulate microbial nutrient
4939 scavenging, ultimately decreasing nutrient availability for plants in the short-
4940 term (Biederman and Harpole, 2013).

4941 ○ There are claims that some pyrolysis & gasification materials can increase the
4942 **efficiency of mineral fertiliser** due to their ability to retain nutrients within
4943 the soil matrix as a result of the increase in surface area and cation and anion
4944 exchange capacity (Ippolito et al., 2015; Aller, 2016). Also, the addition of
4945 pyrolysis & gasification materials to soil may improve root traits, particularly
4946 root mass density and root length density (Brennan et al., 2014).

4947 ○ Studies in soilless systems indicate that some pyrolysis & gasification
4948 materials can provide nutrients (Ruamrungsri et al., 2011; Locke et al., 2013),
4949 reduce nutrient leaching (Beck et al., 2011; Altland and Locke, 2012) and
4950 improve both the biological (Graber et al., 2010a) and physical properties of
4951 growing media as a whole (Dumroese et al., 2011). The use of pyrolysed
4952 materials might, therefore, represent a promising development for **soilless**
4953 **growing media** components (Barrett et al., 2016; Kern et al., 2017). The
4954 potential use of pyrolysis & gasification materials for soilless growing media
4955 was also subscribed by various participants at the STRUBIAS Kick-off
4956 Meeting and supported by the feedback received via the ensuing
4957 questionnaires.

4958 ○ Pyrolysis at high temperatures removes acidic functional groups and increases
4959 the ash content, ultimately causing increased **basicity** of pyrolysis &
4960 gasification materials (Novak et al., 2009; Cantrell et al., 2012). Because of its
4961 basic pH, pyrolysis & gasification materials have been used to ameliorate
4962 acidic soil conditions, thus it could serve as a **liming agent** (Hass et al., 2012;
4963 Kloss et al., 2012). Whereas an increase of soil pH might have beneficial
4964 effects for the plant, it should be noted that the liming equivalent of pyrolysis
4965 & gasification materials is typically much lower than that of commonly
4966 applied liming products (Ippolito et al., 2015; Jeffery et al., 2015). As a matter
4967 of fact, it is unlikely that pyrolysis & gasification materials will meet the
4968 liming requirements at PFC level in the proposal for the Revised Fertiliser
4969 Regulation (Feedback on questionnaires received from the STRUBIAS sub-
4970 group; Ippolito et al., 2015). It may thus not be economically feasible for
4971 farmers to use pyrolysis & gasification materials in crop production solely for
4972 pH adjustment due to the high cost (Collins, 2008; Galinato et al., 2011).
4973 Similarly to thermal oxidation materials, it is proposed to **label the**

4974 **neutralising value if pyrolysis & gasification materials are used as a CMC**
4975 **in quantities >50% in the PFCs fertiliser (PFC 1), soil improver (PFC 3),**
4976 **growing medium (PFC 4) and plant biostimulants 6 (PFC).**

4977 ○ Finally, pyrolysis & gasification materials are used as a compost additive and
4978 as admixtures in NPK fertiliser **blends** (Steiner et al., 2015). The utilisation of
4979 the absorptive binding capacity of pyrolysis & gasification materials to alter
4980 the nutrient-release patterns of other fertilising products is often referred to as
4981 the "charging" of pyrolysis & gasification materials. It should, however, be
4982 noted that even without the admixing of other CMCs onto pyrolysis &
4983 gasification materials, the end material of a pyrolysis/gasification process
4984 should have a demonstrated agricultural value (see section 4.2.1).

4985
4986 It is concluded that the inclusion of pyrolysis & gasification materials as a CMC in the
4987 Revised Fertiliser Regulation enables potential applications for **PFC 1 (fertiliser), PFC 3**
4988 **(soil improver), PFC 4 (growing medium) and PFC 6 (non-microbial plant**
4989 **biostimulant)**. The proposal for the Revised Fertiliser Regulation, however, does not place
4990 any restriction on the use of CMCs for any of the PFCs. Hence, the information presented
4991 here is only informative to set a possible window of opportunities for pyrolysis & gasification
4992 materials in view of their possible intended uses and associated application rates.

4993
4994 The efforts on the standardisation of the technical specifications of pyrolysis & gasification
4995 materials have resulted in voluntary industry-driven product standards and harmonisation
4996 actions. Especially relevant are the quality standards that have been developed by the
4997 International Biochar Initiative (IBI) (International Biochar Initiative, 2016b) and the
4998 European Biochar Certificate (EBC, 2012). **These voluntary standards form the basis for**
4999 **many legislative initiatives in the European Union and the European Free Trade**
5000 **Association (see Bachmann et al., 2016; Meyer et al., 2017 for an excellent overview).**

5001 5002 5.6.2 Input materials

5003 Pyrolysis is a thermochemical decomposition of **organic material**, for which reason the input
5004 material list is confined to materials that originate from or contain matter from plants,
5005 animals, waste water treatment sludges, and certain organic industrial by-products that are
5006 generated during the processing of organic materials (e.g. paper sludge and distillers grain).

5007
5008 Pyrolysis & gasification materials derived from **plant-based materials, bio-waste and**
5009 **certain animal by-products** (e.g. inedible animal by-products such as bone material) form
5010 the basis of the currently used input materials for pyrolysis/gasification processes, voluntary
5011 standardisation schemes (EBC, 2012; International Biochar Initiative, 2016a) and national
5012 legislation (Meyer et al., 2017). The presence of organic contaminants in these input
5013 materials is limited, as well as the concentration of inorganic metals and metalloids such as
5014 Cd, Cr, Pb, Hg, and Ni (Gaskin et al., 2008; Uchimiya et al., 2012; Beesley et al., 2015;
5015 Someus, 2015; ECN, 2017). The manufacturing of pyrolysis & gasification materials may

5016 also be an attractive alternative for **manure or processed manure**, especially in those
5017 situations where no local disposal is available and the feedstock is applied on land in a non-
5018 sustainable manner that negatively impacts upon the environment. Also other animal by-
5019 products, such as meat and bone meal or animal bones can be pyrolysed (e.g. 3R agrocabon
5020 process).

5021
5022 At present, very little research results are available on the **behaviour during the**
5023 **pyrolysis/gasification process of the many organic contaminants** (e.g. phthalates,
5024 surfactants present in cleaners and detergents (e.g. linear alkylbenzene sulphonates (LAS), Di
5025 (2-ethylhexyl) phthalate (DEHP), and personal-care products, pharmaceuticals and
5026 endocrine-disrupting compounds) **that are possibly present in sewage sludge and other**
5027 **highly contaminated materials** (Lehmann and Joseph, 2015; Aller, 2016). Whereas organic
5028 compounds can be degraded under oxidative conditions at high temperatures, the necessary
5029 techno-scientific evidence is lacking that demonstrates their removal under oxygen-limiting
5030 conditions. It is known that stringent temperature/time pyrolysis profiles ($>550^{\circ}\text{C}$, > 20 min)
5031 induce a weight loss in pyrolysis & gasification materials due to burning out of organic
5032 compounds (Deydier et al., 2005b; Koutcheiko et al., 2007; Ro et al., 2010; Marculescu and
5033 Stan, 2012), but the knowledge base of studies that assessed the proportional removal of
5034 specific organic pollutants is limited and restricted to only a few organic pollutants (Weiner
5035 et al., 2013; Ross et al., 2016; vom Eyser et al., 2016; Liang et al., 2017). Although a
5036 significant reduction in contaminant levels can be achieved, limitations in the potential of dry
5037 and wet pyrolysis/gasification processes to remove organic pollutants can be seen for, for
5038 instance, nonylphenol, chlorinated aromatic fractions and specific veterinary antibiotics
5039 (Weiner et al., 2013; Ross et al., 2016; vom Eyser et al., 2016). Moreover, the formation of
5040 transformation products that may exhibit higher toxicity or persistency than the parent
5041 compound can occur. Such processes might be particularly relevant for pyrolysis/gasification
5042 processes because the presence of elementary carbon and soot particles show a high
5043 adsorption potential for organic contaminants (Vehlow et al., 2006). Hence, the mechanisms,
5044 nature and soil residence times of any decay products of organic contaminants that could be
5045 formed remain unclear (Weiner et al., 2013; Ross et al., 2016; vom Eyser et al., 2016). The
5046 absence of those organic contaminants in pyrolysis & gasification materials derived from
5047 contaminated feedstocks is, therefore, not guaranteed. **Based on the precautionary**
5048 **principle and in view of the broad list of emerging contaminants in human-derived**
5049 **waste streams (Petrie et al., 2015), it is justified to exclude highly contaminated**
5050 **feedstocks (e.g. sewage sludge, municipal solid waste, hazardous waste) from the**
5051 **positive input material list to ensure human health and environmental safety.**
5052 Contaminated input materials such as sewage sludge and mixed municipal solid waste are
5053 also absent on the list of allowed input materials according to voluntary standardisation
5054 schemes for pyrolysis & gasification materials (EBC, 2012) and national legal frameworks
5055 (Meyer et al., 2017).

5056
5057 Moreover, there is a substantial **risk for the accumulation of non-volatile pollutants such**
5058 **as inorganic metals and metalloids in the pyrolysis & gasification materials** as these
5059 mostly remain in the solid phase and become concentrated during the production process. In

5060 contrast to thermal oxidation materials & derivatives, no post-combustion manufacturing
5061 processes have been described that are able to remove inorganic metals and metalloids from
5062 the final material. Pyrolysis & gasification materials obtained from **contaminated organic**
5063 **input materials such as sewage sludge** (He et al., 2010; Hossain et al., 2010; Gascó et al.,
5064 2012; Méndez et al., 2012; Van Wesenbeeck et al., 2014; Lu et al., 2016), **mixed municipal**
5065 **solid waste** (Henrich et al., 1999; Vassilev and Braekman-Danheux, 1999; Vassilev et al.,
5066 1999) and **chemically treated wood** (Helsen et al., 1997; Lievens et al., 2009; ECN, 2017)
5067 appear often unable to comply with the limits suggested for these elements at PFC level.
5068 Inorganic metals and metalloids like Cd, Pb and Ni encountered in such pyrolysis &
5069 gasification materials typically exceed the limit levels set for fertilisers and soil improvers at
5070 PFC level from the proposal for the Revised Fertiliser Regulation (Shackley et al., 2013).
5071 Therefore, the potential of pyrolysis & gasification materials derived from sewage sludge,
5072 municipal waste and industrial by-products for the internal fertilising market appears limited.

5073

5074 The choice of a positive input material list for pyrolysis & gasification materials may help to
5075 avoid pollution risks which cannot be easily addressed by limits for organic pollutants due to
5076 their inherent heterogeneous chemical nature. A **positive input material list is thus**
5077 **proposed** to ensure the production of pyrolysis & gasification materials associated to
5078 associated acceptable risks for adverse environmental or human health impacts that can be
5079 enforced through straightforward and cost-effective compliance schemes:

5080

5081 1. A CE marked fertilising product may contain materials exclusively obtained
5082 through the thermochemical conversion under oxygen-limiting conditions of one or
5083 more of the following input materials:

5084 a) animal by-products or derived products of category 2 and 3 falling within the
5085 scope Regulation (EC) No 1069/2009;

5086 b) living or dead organisms or parts thereof, which are unprocessed or processed
5087 only by manual, mechanical or gravitational means, by dissolution in water, by
5088 flotation, by extraction with water, by steam distillation or by heating solely to
5089 remove water, or which are extracted from air by any means, except:

5090 o materials originating from mixed municipal waste,

5091 o sewage sludge, industrial sludge or dredging sludge, and

5092 o animal by-products or derived products falling within the scope
5093 Regulation (EC) No 1069/2009;

5094 c) bio-waste within the meaning of Directive (EU) 2018/851 amending Directive
5095 2008/98/EC resulting from separate bio-waste collection at source, other than
5096 those included above; or

5097 d) pyrolysis/gasification additives which are necessary to improve the process
5098 performance or the environmental performance of the pyrolysis/gasification
5099 process, provided that the additives classify as intermediates within the
5100 meaning of Regulation (EC) No 1907/2006 and with the exception of:

5101 o those listed under points a) – c),

5102 o animal by-products or derived products falling within the scope of
5103 Regulation (EC) No 1069/2009,

5104 o waste within the meaning of Directive 2008/98/EC, and

5105 ○ non-biodegradable polymers.
5106 The total concentration of all additives must not exceed 25 % of the total input
5107 material fresh weight.

5108 In addition, CE marked fertilising product may contain pyrolysis & gasification
5109 materials obtained through thermochemical conversion under oxygen-limiting
5110 conditions of any material listed in points (a)-(d), or combination thereof, processed
5111 by manual, mechanical or gravitational means, by solid-liquid fractionation using
5112 biodegradable polymers, by dissolution in water, by flotation, by extraction with
5113 water, by steam distillation or by heating solely to remove water, by composting, or
5114 by anaerobic digestion.

5115 *[Note: The exclusion of a material from a lettered item does not prevent it from being an*
5116 *eligible component material by virtue of another lettered item]*

5117
5118 Note that the input material list is similar to the input material list as proposed in the first
5119 draft of this document (STRUBIAS Interim Report of May 2017). It is noted that this
5120 proposed input material list is also generally **in line with the positive input material list**
5121 **proposed by the European Biochar Certificate** (EBC, 2012).

5122 5123 5.6.3 Production process conditions

5124 Pyrolysis processes generate three main materials: gases (syngas), condensable vapours (oil)
5125 and solid (char-rich) materials. This implies that pyrolysis can be used for two specific aims:
5126 (1) the recovery of energy embedded in the feedstock through the combustion of syngas or oil
5127 fractions, and (2) the production of solid pyrolysis & gasification materials that can possibly
5128 be applied on agricultural land. As there is some degree of complementarity between the
5129 different phases from the pyrolysis of biomass, it is proposed that the end-material can be
5130 obtained from pyrolysis facilities that are specifically designed for the **purpose** of producing
5131 pyrolysis & gasification materials for further **fertiliser use** as well as from a process aimed at
5132 serving **energy recovery purposes** as long as product quality conditions are fulfilled.

5133
5134 The pyrolysis/gasification process is also used in the **chemical industry** to produce non-food
5135 products, for example, to produce activated carbon, charcoal, methanol, and other chemicals
5136 from wood, to convert ethylene dichloride into vinyl chloride to make PVC, to produce coke
5137 from coal, to turn waste plastics into usable oil, and for transforming medium-weight
5138 hydrocarbons from oil into lighter ones like gasoline. Pyrolysis is also used in the creation of
5139 nanoparticles, zirconia and oxides utilizing an ultrasonic nozzle in a process called ultrasonic
5140 spray pyrolysis. These specialized uses of pyrolysis may be called various names, such as dry
5141 distillation, destructive distillation, or cracking. As the solid end-materials of these processes
5142 do not have agricultural value, pyrolysis & gasification materials from the chemical industry
5143 are not considered for the purpose of this document (see section 5.6.2 – eligible input
5144 materials).

5145
5146 The proposal is to include pyrolysis plants that operate as a **stand-alone** installation as well
5147 as integrated systems in line with the principle of technological neutrality. After all, the

5148 integration of pyrolysis units into an integrated system will not necessarily affect end-
5149 material quality.

5150

5151 5.6.3.1 *Pre-processing*

5152 For dry pyrolysis, input materials with high **moisture content** are typically subjected to
5153 mechanical processes such as solid-liquid separation, thickening, dewatering, or drying
5154 treatments. The **energy and nutrient density of the feedstock can be increased** by applying
5155 techniques (e.g. hydrothermal carbonisation, fast pyrolysis, anaerobic digestion, composting,
5156 etc.) to produce intermediate nutrient carriers. Increasing the dry matter content of the
5157 feedstock decreases the volumes that have to be processed in the pyrolysis reactor, as well as
5158 the supplementary energy requirements. Pyrolysis co-products (syngas, pyrolysis oil) could
5159 also pass through an energy recovery system at the pyrolysis plant, whereby the energy can
5160 be (partly) recovered in the form of heat or electricity. The heat can be used for heating the
5161 pyrolysis reactor or for **pre-drying** the input material prior to pyrolysis. Such practices
5162 increase the possibility for long range transportation from several regionally distributed
5163 conversion plants to few central large scale pyrolysis plants. Wet pyrolysis or hydrothermal
5164 carbonisation involves the thermochemical dehydration of biomass in a closed vessel under
5165 autogenous pressure of water. Under these conditions and a residence time of several hours,
5166 the biomass is chemically dehydrated and its carbon content concentrated. Hence, the
5167 chemical composition becomes less polar, enabling a significant reduction in moisture
5168 content (to ~50%) by mechanical techniques, such as filter pressing.

5169

5170 While sometimes the output materials obtained through wet pyrolysis or fast pyrolysis are
5171 marketed as end materials that can be applied on agricultural land, some of the output
5172 materials might lack material properties that are in line with their intended use as a soil
5173 improver (Kambo and Dutta, 2015; Aller, 2016) or may contain high amounts of organic
5174 micropollutants that cause negative effects on plant growth and productivity (Becker et al.,
5175 2013; Wang et al., 2016). **Note that according to the draft proposals, none of the
5176 pyrolysis spectrum variants are excluded as core processes in the present study, as long
5177 as the end-material meets the product quality standards.**

5178

5179 Also, the physical material properties of pyrolysis & gasification materials can be modified
5180 by applying a so-called "**physico-chemical activation process**" (Kambo and Dutta, 2015), a
5181 process similar to the commercial production of activated carbon. Activation of pyrolysis &
5182 gasification materials can significantly increase the surface area thanks to the development of
5183 internal porous structures within a biomaterial (Gratuito et al., 2008). Physical and chemical
5184 activation methods are the two common techniques used for the activation of chars (Chia et
5185 al., 2015). In both techniques, char is exposed in a pyrolysis reactor to elevated temperatures
5186 in the presence of activation agents such as CO₂ or steam, which develops and improves the
5187 porous structure through the removal of C atoms or volatiles (Rodríguez-Reinoso and
5188 Molina-Sabio, 1992; Alaya et al., 2000). Activation through chemical reagents such as zinc
5189 salts, metal hydroxides (KOH, NaOH) or phosphoric acid can also induce very high pore
5190 densities (Lillo-Ródenas et al., 2007; Lin et al., 2012). In such a case, it is proposed to

5191 consider the physico-chemical activation process as part of the core pyrolysis/gasification
5192 process (and not as a post-production process) and any materials that are added to the reactor
5193 as **additives** (see section 5.6.3.3). The STRUBIAS sub-group indicated, however, that such
5194 production techniques are unlikely to be deployed for materials that will be used as soil
5195 amendments due to the high production costs.

5196
5197 **No major limitations** on any pre-processing steps are proposed as long as the positive input
5198 material list is respected. This implies that the input materials, and a combination thereof,
5199 may be physically mixed, screened, sized and chemically reacted. Following provision is
5200 therefore foreseen in paragraph 1 of the proposals for the legal requirements on the input:

5201
5202 CE marked fertilising product may contain pyrolysis & gasification materials obtained
5203 through thermochemical conversion under oxygen-limiting conditions of any material
5204 listed in points (a)-(d), or combination thereof, processed by manual, mechanical or
5205 gravitational means, by solid-liquid fractionation using biodegradable polymers, by
5206 dissolution in water, by flotation, by extraction with water, by steam distillation or by
5207 heating solely to remove water, by composting, or by anaerobic digestion.

5208

5209

5210 5.6.3.2 Core process

5211 The pyrolysis technology spectrum covers a broad range of production process conditions,
5212 with **slow pyrolysis** processes (300-700°C, long residence time in reactor) being the most
5213 common for the production of pyrolysis & gasification materials that can be applied on
5214 agricultural land. Nevertheless, also other processes such as **fast-pyrolysis** (300-700°C, short
5215 residence time in reactor), **gasification** (low-oxygen environment, temperatures > 500 °C),
5216 **wet pyrolysis** (sometimes referred to as hydrothermal carbonization - HTC, in sub-critical
5217 water conditions, 175°C – 300°C) and **torrefaction** (200-320°C) fall under the umbrella of
5218 the pyrolysis technology spectrum. Hence, it is proposed to permit their application as long as
5219 the output material meets the product quality criteria. **With product quality of primordial**
5220 **importance, it is proposed not to impose any constraints on the pyrolysis/gasification**
5221 **process, as long as the output material meets the product quality criteria.**

5222

5223 It has been indicated that it is challenging to predict the molecular structure and agronomic
5224 value of pyrolysis & gasification materials based on the specific temperature profile applied
5225 because of the complex and **little understood interactions** of heating temperature, heat
5226 exposure time, feedstock properties, mineral admixtures, reaction media, etc. (Kleber et al.,
5227 2015). Therefore, it does not appear suitable **to set strict criteria for production conditions**
5228 **provided that the pyrolysis material has a demonstrated agronomic value and does not**
5229 **pose a risk for human health and the environment.**

5230

5231 5.6.3.3 Additives

5232 Similar to ashes, non-biomass materials are sometimes added as **a catalyst or additive** to the
5233 pyrolysis/gasification process with the aim of changing the relative proportions or quality of

5234 the altering solid, liquid, and gaseous compounds produced during the pyrolysis/gasification
5235 process (Jensen et al., 1998; Wang et al., 2010; Li et al., 2014), at addition rates up to 22%.
5236 The supply of additives shall serve to improve and facilitate the pyrolysis/gasification
5237 process, and should, rationally, not be used to improve the nutrient content of the pyrolysis &
5238 gasification materials obtained. It is, therefore, proposed to enable **a maximum of 25% of**
5239 **additives defined as intermediates within the meaning of Regulation (EC) No 1907/2006,**
5240 **with the exception of waste, materials which have ceased to be waste, polymers and**
5241 **animal by-products.** An intermediate is defined as "a substance that is manufactured for and
5242 consumed in or used for chemical processing in order to be transformed into another
5243 substance". Note that also minerals are classified as substances. The use of this terminology
5244 will prevent that inert materials are added for the manufacturing of CE fertilising products
5245 with the sole intention of reducing contaminant levels of the final CE product.
5246 Therefore, it is proposed to add following text part to the proposals for the legal requirements
5247 on the input materials for pyrolysis & gasification materials:
5248

- 5249 a) pyrolysis/gasification additives which are necessary to improve the process
5250 performance or the environmental performance of the pyrolysis/gasification
5251 process, provided that the additives classify as intermediates within the
5252 meaning of Regulation (EC) No 1907/2006 and with the exception of:
- 5253 o those listed under points a) – c);
 - 5254 o animal by-products or derived products falling within the scope of
5255 Regulation (EC) No 1069/2009;
 - 5256 o waste within the meaning of Directive 2008/98/EC;
 - 5257 o non-biodegradable polymers.
- 5258 The total concentration of all additives must not exceed 25 % of the total input
5259 material fresh weight;
5260

5261 5.6.3.4 Post-processing

5262 Pyrolysis & gasification materials leaving the pyrolysis reactor may undergo further post-
5263 processing steps with the intention to:

- 5264 a. **Agglomerate** the material as pellets or granules through adding binder
5265 solutions (Bowden-Green and Briens, 2016) or pelletizing with additives as
5266 with wood flour, polylactic acid and starch (Dumroese et al., 2011)
- 5267 b. Increase the chemical and physical stability by **washing and rewetting** with
5268 water (Schulze et al., 2016).
- 5269 c. Alter product granulometry through **mechanical treatments such** as
5270 screening, sizing, etc.

5271 It is proposed to allow these post-processing steps. No supplementary requirements related to
5272 these post-processing techniques have to be included at CMC level.
5273

5274 5.6.4 Agronomic value

5275 Pyrolysis & gasification materials can be applied with two different objectives in agricultural
5276 ecosystems: (1) to increase the primary production of agroecosystems as a **fertilising**
5277 **product**, and (2) to **impact upon the global C balance**, greenhouse gas emissions and
5278 climate change (Lehmann and Joseph, 2015). It should be clear that the primary focus of this
5279 work is on its use as a fertilising product, as defined in Article 2 of the proposal for the
5280 Revised Fertiliser Regulation.

5281
5282

5283 5.6.4.1 Carbon stability

5284 Considering the intended uses of pyrolysis & gasification materials as a soil amendment,
5285 **pyrolysis & gasification materials** should have:

- 5286 ○ Product properties and compound release dynamics that have a positive
5287 influence on plant growth and by no means cause plant toxicity;
- 5288 ○ Physico-chemical properties (e.g. surface area, porosity, ion exchange
5289 capacity, etc.) that have the potential to positively influence air, water, and
5290 microbial nutrient dynamics in the soil;

5291 Nutrient-rich pyrolysis & gasification materials that are applied as fertilisers should also have
5292 sufficient quantities of one or more of the following macronutrients (P, N, K, Mg and Ca)
5293 that are available for plants in the short-term.

5294

5295 The **stability of the carbon** present in the pyrolysis material is a determining factor for the
5296 potential of pyrolysis & gasification materials to be applied on soils because of its close
5297 relationship with:

- 5298 a. **Toxicity and air quality:** Volatile organic compounds²⁴ with a boiling point
5299 lower than the pyrolysis temperature might, depending on the extent and
5300 nature of interaction between pyrolysis gases and solids, end up in the
5301 pyrolysis material (Spokas et al., 2011; Buss et al., 2015). Moreover, re-
5302 condensation and trapping of volatile organic compounds that are normally
5303 associated with the pyrolysis liquid fraction in the pores of pyrolysis &
5304 gasification materials is possible (Spokas et al., 2011). During the posterior
5305 handling and use of pyrolysis & gasification materials, these compounds can
5306 be emitted to the atmosphere, to the soil matrix and to the water bodies as
5307 water soluble leachates (Spokas et al., 2011; Smith et al., 2013a; Buss and
5308 Mašek, 2016). **Plant toxicity and adverse effects on soil and aquatic**
5309 **organisms and plants have been documented due to the VOC release**
5310 **from pyrolysis & gasification materials** (Titirici et al., 2008; Spokas et al.,
5311 2011; Becker et al., 2013; Buss and Mašek, 2014; Buss and Mašek, 2016;
5312 Smith et al., 2016). Dutta et al. (2016) reported 76 different types of VOCs
5313 that exist in the pyrolysis & gasification materials, some of which being
5314 highly toxic (e.g. benzene, toluene). The volatile organic compounds impact

²⁴ For pyrolysis & gasification, the term “volatile matter” refers to the proportion of carbon that is easily removed (labile), but not necessarily as a gas. This class of compounds includes, for instance, pyrazines, pyridines, pyrroles and furans.

5315 upon various plant and microbial responses by mimicking plant hormones and
5316 impacting seed germination, herbivore resistance, and nutrient uptake
5317 (Almeida et al., 2009; Insam and Seewald, 2010; Dutta et al., 2016). Volatile
5318 short carbon chain alkanes with less than 11 carbon atoms are the most
5319 phytotoxic while non-volatile long carbon chain hydrocarbons (nC₁₂ to
5320 nC₂₀) in soil have no apparent toxic effect on germination of perennial
5321 ryegrass and are generally attacked most readily by microorganisms (Siddiqui
5322 and Adams, 2002; Wang et al., 2016). The possible presence of potentially
5323 harmful compounds, such as benzene, toluene, ethylbenzene, xylenes,
5324 phenols, volatile fatty acids, and polycyclic aromatic hydrocarbons in
5325 pyrolysis & gasification materials with a H/C ratio > 0.7, highlights the
5326 importance of directing the biochar production process towards stable
5327 compounds (Ghidotti et al., 2017a). **A negative correlation has been
5328 observed between the abundance of volatile organic compounds and
5329 molar H/C ratios** (Aller, 2016; Conti et al., 2016; Ghidotti et al., 2017b). The
5330 pyrolysis & gasification materials assessed by Ghidotti et al. with a molar
5331 H/C < 0.70 did not release VOCs at ambient temperatures, and showed no
5332 presence of specific toxic volatile organic compounds such as benzene and
5333 toluene (Ghidotti et al., 2017a). Also Smith et al. (2016) indicated that
5334 pyrolysis & gasification materials should be produced with more severe time
5335 temperature profiles in order to increase the carbon stability and to limit its
5336 effects through the leaching of dissolved organic matter into the environment.
5337 Hence, it is concluded that **targeting process conditions towards the
5338 formation of stable pyrolysis & gasification materials significantly
5339 reduces the risks associated with the release of VOCs towards the
5340 atmosphere, the soil matrix and the percolation water.**
5341 Nonetheless, also the **design and configuration of the pyrolysis reactor is
5342 critical.** More specifically, it should be ensured that pyrolysis oils and
5343 vapours are promptly evacuated from the pyrolysis reactor and even
5344 temperature profiles should be ensured to prevent pyrolysis oils vapours from
5345 recondensing onto the solid material in so-called "cold zones" of the reactor
5346 (Buss and Mašek, 2016; Smith et al., 2016). However, in case of
5347 contamination by (re-condensed) pyrolysis vapours, not only VOCs would be
5348 trapped in the pyrolysis & gasification materials, but also PAHs (Buss et al.,
5349 2015) and other persistent organic pollutants (PCDD/F, PCB), compounds for
5350 which strict limits have been proposed in the compliance scheme for this
5351 CMC (see section 5.6.5.2). Hence, it is indicated that, especially in
5352 pyrolysis/gasification reactors of low technological readiness level often used
5353 for scientific research, significant VOC contents could be trapped in the solid
5354 material, but that one could effectively exclude those materials from entering
5355 the EU fertilising market by including POPs as part of the compliance scheme
5356 for pyrolysis & gasification materials.
5357 Therefore, **it is concluded that VOC concentrations in pyrolysis &
5358 gasification materials of high carbon stability (molar H:C_{org} < 0.7) and**

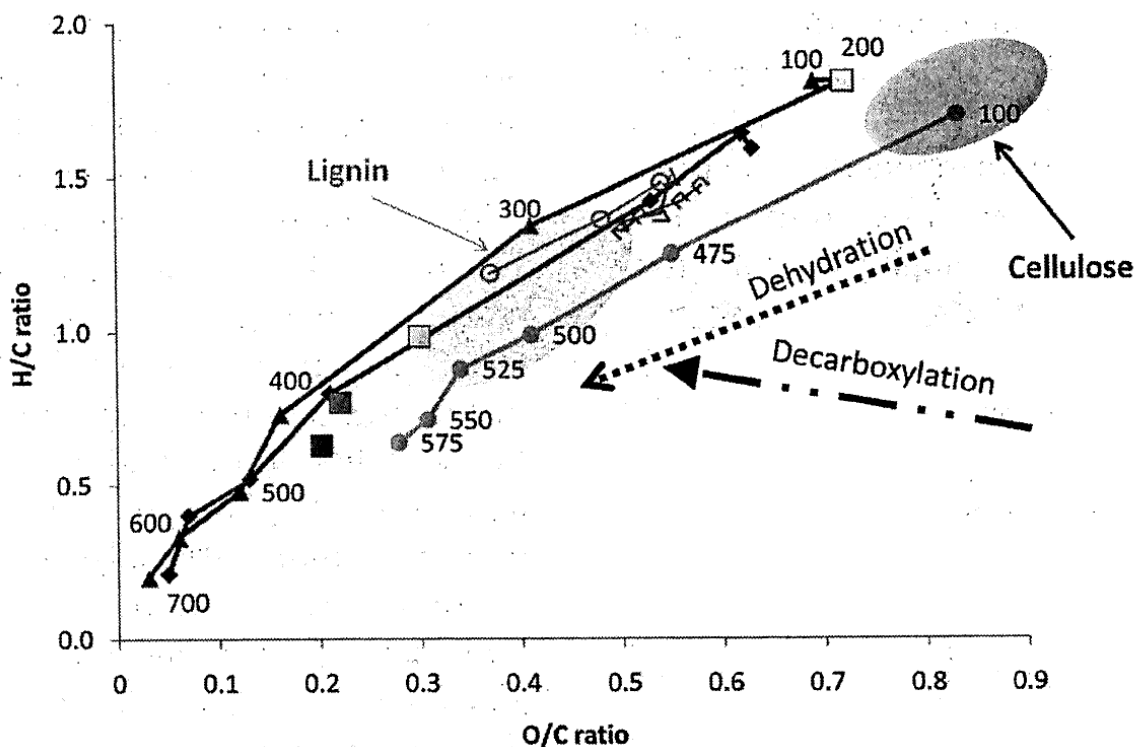
5359 **with minimal pyrolysis liquid contamination are generally below limits**
5360 **that could cause phytotoxic effects or adverse impact on aquatic**
5361 **organisms through leaching under realistic field application conditions**
5362 (Buss et al., 2015; Smith et al., 2016; Ghidotti et al., 2017a).

5363 b. **Physical properties:** Structure, porosity, pore size distribution, total amount
5364 of pores, surface area, and adsorption capacity are the physical properties of
5365 pyrolysis & gasification materials most frequently described in the literature.
5366 Rutherford et al. (2004) found evidence that aliphatic C in feedstocks **must**
5367 **first be converted into fused-ring, aromatic C before porosity can**
5368 **develop**. Fused ring structures of aromatic C provide a matrix in which
5369 micropores can be created. Moreover, most of the surface area and thus cation
5370 exchange capacity derives from pores created during the
5371 pyrolysis/gasification process (Schimmelpfennig and Glaser, 2012).
5372 Interplanar distances of aromatic C forms decrease with increased ordering
5373 and, thus, the surface area per total volume increases alongside with
5374 aromaticity. However, upon heating to temperatures in the range of 800 °C -
5375 1000 °C the C crystallites reorient themselves into parallel sheets of C atoms,
5376 causing the destruction of the porosity of the material (Brown et al., 2015).
5377 The high porosity and surface area of pyrolysis & gasification materials may
5378 also provide a habitat for microbial communities in the soil.

5379 c. **Nutrient properties:** Soil microorganisms are largely homeostatic, implying
5380 that they need to assimilate energy and nutrient sources in relatively fixed
5381 proportional quantities (Griffiths et al., 2012). Therefore, the addition of
5382 pyrolysis & gasification materials that contain large amounts of non-
5383 stabilised, labile C to agricultural soils but low amounts of available nutrients
5384 may actually cause microorganisms to **immobilise soil nutrients, especially**
5385 **nitrogen**, in order to enable microbial homeostasis. Such an effect is
5386 particularly of concern for pyrolysis & gasification materials that contain at
5387 least some nitrogen in a largely plant-unavailable form (see section 5.6.4.2).
5388 Hence, the microbial immobilisation of plant nutrients is sometimes observed
5389 when pyrolysis & gasification materials with a high labile C content are
5390 added to the soil, for which reason nutrient availability to plants is decreased
5391 (Bruun et al., 2012; Nelissen et al., 2012; Schimmelpfennig et al., 2014;
5392 Reibe et al., 2015). While such an effect is mostly temporary and can
5393 potentially be overcome by applying the pyrolysis material some months prior
5394 to planting, it should be considered that it may be rather challenging to
5395 convince farmers to use pyrolysis & gasification materials and pay for the
5396 product under market competitive conditions where products are available
5397 that have a guaranteed economical return within a much shorter time frame.
5398 Hence, in order to safeguard short-term returns of increased plant yield after
5399 the addition of pyrolysis & gasification materials to the soil, the pyrolysis &
5400 gasification materials should be characterised by C atoms that are present in a
5401 stabilised form. Moreover, higher emissions of greenhouse gases after the

5402 application of pyrolysis & gasification materials with a low C stability in the
 5403 soil have been observed (Maestrini et al., 2015), which are most likely the
 5404 result of increased microbial activity due to easy degradability of C. In
 5405 contrast, slow-pyrolysis & gasification materials were found to be more stable
 5406 in the soil and showed a reduced effect on GHG emissions (Kambo and
 5407 Dutta, 2015).

5408 Hence, the extent to which the C in pyrolysis & gasification materials has been transformed
 5409 into **energetically stable aromatic ring structures contributes decisively to the agronomic**
 5410 **value of pyrolysis & gasification materials (Schimmelpfennig and Glaser, 2012)**. The
 5411 carbonisation of the input materials is a complex process in which many reactions such as
 5412 dehydrogenation, hydrogen transfer and isomerisation take place concurrently. Consequently,
 5413 there is great interest in methods that are able to characterise in a simple and effective manner
 5414 the proportion of C in condensed ring structures relative to total C. By far the most common,
 5415 economical and straightforward approach used is to assess **elemental ratios of H, C and O**.
 5416 In general, molar H/C ratios decrease with increasing heat treatment temperature from ~1.5 to
 5417 a level significantly below 0.5 for pure compounds such as lignin and cellulose as well as for
 5418 more complex biomass. Similarly, O/C ratios decline with duration and intensity of heat
 5419 treatments (Kleber et al., 2015). Hence, the elemental ratios are excellent and robust tools to
 5420 show an estimate of general structural characteristics of pyrolysis & gasification materials
 5421 (Kleber et al., 2015).



5422
 5423 **Figure 4: H/C versus O/C ratios for several temperature series of pyrolysis & gasification**
 5424 **materials along with areas of pure cellulose and lignin. Dehydration and carboxylation lines**
 5425 **indicate the direction those processes move a material on a 'van Krevelen' diagram (adopted**
 5426 **from Kleber et al., 2015).**
 5427

5428 Elemental ratios of O/C, O/H, and C/H have been found to provide a reliable measure of both
5429 the extent of pyrolysis and level of oxidative adjustment of pyrolysis & gasification materials
5430 (Crombie et al., 2013; Aller, 2016; Xiao et al., 2016). Especially the H/C ratio value is a
5431 reflection of the basic and elemental structure of the pyrolysis & gasification materials, which
5432 further constitutes the different pore size, surface area of pyrolysis & gasification materials.
5433 Xiao et al. (2016) established, for instance, a quantitative relationship between H/C atomic
5434 ratio and pyrolytic temperature, and aromatic structure.

5435

5436 Following criterion is proposed:

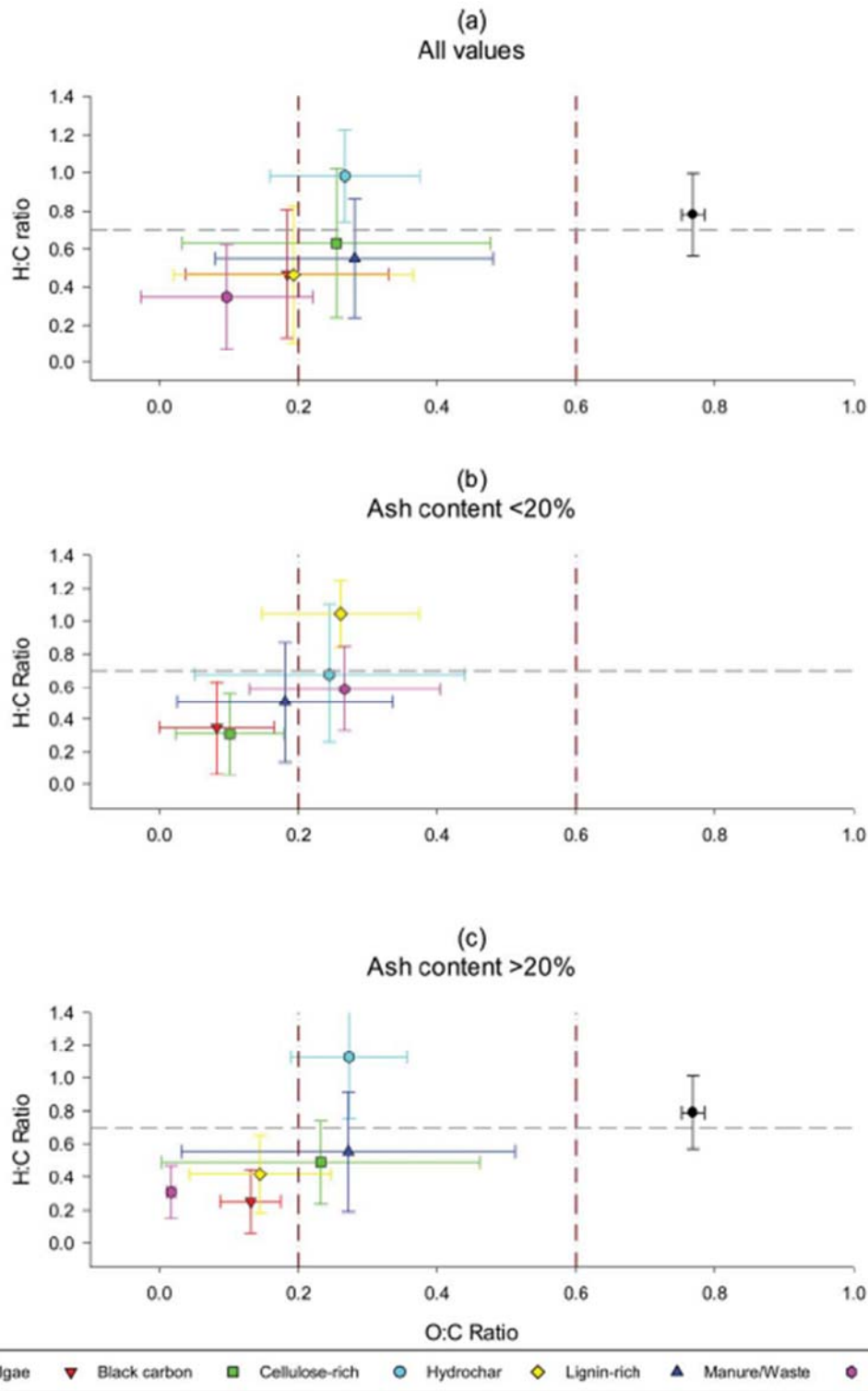
5437 The pyrolysis & gasification materials shall have a molar ratio of H/organic C of less
5438 than 0.7, with testing to be performed in the dry and ash-free fraction for materials
5439 that have an organic C content of <50%;

5440

5441 Based on the review of Aller (2016) (Figure 5), it can be observed that most pyrolysis &
5442 gasification materials of different feedstocks (lignin-rich, manure/waste, black carbon (other),
5443 nuts/shells cellulose-rich) meet the H/C conditions proposed, with the exception of wet
5444 pyrolysis & gasification materials ("hydrochars") with a high ash content and lignin-rich
5445 materials of low ash content (Figure 5).

5446

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Figure 5: 'van Krevelen plots' that define a space determined by a horizontal axis of O/C molar ratio and a vertical axis of H/C molar ratio for different pyrolysis & gasification materials; the colour codes indicate the feedstock source for slow-pyrolysis & gasification materials (lignin-rich, manure/waste, black carbon (other), nuts/shells and cellulose-rich) and hydrothermal carbonisation products (hydrochar, irrespective of its feedstock) (adopted from Aller et al., 2016)

5456 5.6.4.2 *C-rich and nutrient-rich pyrolysis & gasification materials*

5457 Pyrolysis & gasification materials derived from plant-based input materials such as crop and
5458 wood residues are characteristically C-rich materials that are mostly applied as soil
5459 improvers, liming materials, growing media or plant biostimulants. Their intention of
5460 application is to improve soil characteristics such as organic matter, soil pH, physical
5461 properties such as water holding capacity, or a combination of different soil properties. These
5462 pyrolysis & gasification materials typically have a carbon content of > 50% (see section
5463 16.3.1).

5464

5465 Specific pyrolysis & gasification materials derived from mineral-rich eligible input materials
5466 (manure, animal bone materials, food and kitchen waste, etc.) could also serve to supply plant
5467 available nutrients such as P, K and Ca. Pyrolysis & gasification materials from these input
5468 materials show a nutrient content with $P_2O_5 + CaO + K_2O + MgO + N$ that ranges from 15%
5469 to more than 75% (section 16.3.1). The plant availability of nutrients in pyrolysis &
5470 gasification materials varies widely for the different elements and is also dependent on
5471 production process conditions (Camps-Arbestain et al., 2015; Ippolito et al., 2015):

5472 ▪ Phosphorus: The availability of P present in pyrolysis & gasification materials
5473 depends primarily on P-solubility. At temperatures <760°C, P availability is
5474 likely controlled by pH and the coordinated cations present (Al, Fe, Ca, Mg)
5475 (Wang et al., 2012b; Ippolito et al., 2015); it is therefore largely dependent on
5476 the input material applied in the pyrolysis production processes. Ca-P and Mg-
5477 P complexes, dominant in pyrolysis & gasification materials from the eligible
5478 mineral-rich input materials manure and bone, are relatively plant available,
5479 although some contrasting results of high temperatures (>760°C) on P-
5480 availability have been observed (Kercher and Nagle, 2003; Ippolito et al.,
5481 2015).

5482 ▪ Potassium: Due to the high solubility of K-containing salts, K in pyrolysis &
5483 gasification materials has been shown to be readily available (Yao et al., 2010;
5484 Gunes et al., 2015).

5485 ▪ Calcium and magnesium: It is indicated that the availability depends on the
5486 presence of other elements and compounds such as P and silicates, with the
5487 elements being relatively less available under basic conditions for Si-rich
5488 pyrolysis & gasification materials, such as those derived from plant materials
5489 (Angst and Sohi, 2013). Calcium and magnesium in pyrolysis & gasification
5490 materials obtained from nutrient-rich input materials are, however, largely
5491 available, especially in plant rhizospheres of a somewhat lower pH than bulk
5492 soils (Martins Abdao dos Passos et al., 2015).

5493 ▪ Sulphur: The availability of S depends on whether it is available as C-bonded
5494 S, ester-S or sulfate-S. Sulphur in mineral-rich pyrolysis & gasification
5495 materials produced at a temperature of 550 °C was found to be non-crystalline,
5496 and is therefore readily available to plants as it easily dissolves (Yao et al.,
5497 2010; Churka Blum et al., 2013).

- 5498 ▪ **Nitrogen:** Low extractable mineral N concentrations in pyrolysis &
5499 gasification materials have been observed. As a result of charring, aromatic
5500 and heterocyclic N-ring structures are formed that are considered mostly
5501 unavailable to plants (Almendros et al., 1990; Almendros et al., 2003).
5502 Nonetheless, some recent publications also indicate the presence of
5503 hydrolysable N fractions in pyrolysis & gasification materials. The N
5504 fertilisation value of pyrolysis & gasification materials under realistic
5505 application scenarios is considered low to moderate at best (Camps-Arbestain
5506 et al., 2015).

5507
5508 Pyrolysis & gasification materials from eligible input materials are mostly expected to show a
5509 good plant nutrient availability as mineral-rich eligible input materials (animal by-products of
5510 category 2 and 3 as well as specific bio-wastes) are depleted in Al, Fe and Si. Therefore,
5511 nutrients will be likely bound into labile complexes such as K-containing salts and Ca and
5512 Mg- phosphate salts.

5513
5514 It is **proposed to classify the pyrolysis & gasification materials in a non-exclusive**
5515 **manner depending on their carbon content.** Such distinction is useful as the STRUBIAS
5516 sub-group indicated that the application rates are typically larger for C-rich pyrolysis &
5517 gasification materials (up to 20 tonne material ha⁻¹ yr⁻¹) than for nutrient-rich pyrolysis &
5518 gasification materials (up to 5 tonne material ha⁻¹ yr⁻¹). As a result, the intended use and
5519 elemental composition has an influence on the load of material that will be applied, and will
5520 consequently impact upon the permissible limit values for relevant contaminants (see section
5521 5.6.5).

5522
5523 It is proposed to adhere to the minimum C-content set by the European Biochar Certificate
5524 (EBC, 2012) to differentiate between C-rich and nutrient-rich pyrolysis & gasification
5525 materials:

5526 *C-rich pyrolysis & gasification materials: total C \geq 50% by mass of dry matter*

5527 and

5528 *Nutrient-rich pyrolysis & gasification materials: total C $<$ 50% by mass of dry matter*

5530 5.6.4.3 Salinity

5531 Salinity is a generic term used to describe elevated concentrations of **soluble salts** in soils
5532 and water. Comprised primarily of the most easily dissolved ions - sodium (Na) and chloride
5533 (Cl), and to a lesser extent calcium, magnesium, potassium, and sulfate - salinity in the
5534 environment adversely impacts water quality, soil structure, and plant growth (Pichtel, 2016).
5535 Although minimal accumulations (some in trace amounts) are required for normal biological
5536 function, excess salinisation is becoming one of the leading constraints on crop productivity
5537 and could reduce the diversity of salt-intolerant plant and epiphyte species in natural
5538 ecosystems. Reactive ash with high dissolution rates of salts may cause burns to the

5539 vegetation and excess sodicity can cause clays to deflocculate, thereby lowering the
5540 permeability of soil to air and water.

5541 d. **Chloride.** Feedstocks such as grasses, straws and food waste (which contains
5542 sodium chloride, i.e., salt) can be a source of chloride. Other potential sources
5543 of chloride in feedstocks include biomass that has been exposed to salt (such
5544 as crops or trees grown near seashores). The Cl⁻ contents for pyrolysis &
5545 gasification materials are limited, but documented values in the ECN database
5546 vary from 0.2% to 3.6% (ECN, 2017). Therefore, a significant risk is present
5547 for crops when pyrolysis & gasification materials are applied during prolonged
5548 periods of time. Therefore, no further criteria for Cl⁻ at CMC level are
5549 proposed. The Finnish legislation on the use of ashes in forest ecosystems
5550 contains a limit value of 2% for chloride (Haglund and Expertsgroup, 2008).
5551 In the proposal for the Revised Fertiliser Regulation (Annex III of the proposal
5552 – Labelling requirements), it is stated that the phrase 'poor in chloride' or
5553 similar may only be used if the chloride (Cl⁻) content is below 3%.
5554 Nonetheless, a labelling requirement cannot prevent that a product high in
5555 chloride causes adverse impacts on the environment. Therefore, **it is proposed**
5556 **to set a 3% limit value for chloride for pyrolysis & gasification materials.**
5557

5558 a. **Sodium** plays a role as a “functional nutrient”, with a demonstrated ability to
5559 replace potassium in a number of ways for vital plant functions, including cell
5560 enlargement and long-distance transport, and is even a requirement for
5561 maximal biomass growth for many plants (Subbarao et al., 2003). Considering
5562 the relative low Na contents in pyrolysis & gasification materials, no limits are
5563 proposed for the Na content of pyrolysis & gasification materials, but the total
5564 Na content should be declared on the label.

5565 b. At present, reliable methods other than leaching tests to characterise pyrolysis
5566 & gasification materials with regard to the speed of salt dissolution in the field
5567 are missing. One way of estimating the salinity of pyrolysis & gasification
5568 materials is to measure the conductivity in water extracts. This gives a total
5569 measurement of the dissolution of salts from the pyrolysis material and
5570 indicates the risk of acute damage to vegetation. Given the labelling provisions
5571 for the closely related parameter Cl, it is, however, proposed to add no further
5572 criteria or labelling requirements for **electrical conductivity**.
5573

5574 5.6.4.4 Boron toxicity

5575 **Boron** is a very common element that may be present **in some pyrolysis & gasification**
5576 **materials**, and is **readily water soluble from pyrolysis & gasification materials** (Gunes et
5577 al., 2015). Although boron is an essential nutrient in plants at low concentrations, it becomes
5578 toxic in many plants at concentrations only slightly higher than the optimal range (Ayers and
5579 Westcot, 1985; Sartaj and Fernandes, 2005). Boron toxicity depends, however, not only on
5580 the concentration, but also on the form, since the element can occur in an undissociated form

5581 as boric acid (B(OH)₃), which the plant does not absorb. To the best of our knowledge, no
5582 research has been published on the forms of boron that are leached from pyrolysis &
5583 gasification materials, and their potential toxic effects for plants.

5584

5585 The B levels in pyrolysis & gasification materials are typically $\leq 100 \text{ mg B kg}^{-1}$ (ECN, 2017),
5586 and about one order of magnitude lower than most mineral and organo-mineral fertilisers
5587 (Kratz et al., 2016).

5588

5589 Recent evidence indicates that human B intake from food and water in the EU are below the
5590 tolerable upper intake level (EFSA, 2004), and that increased human B uptake is even
5591 promoted to enhance health due to the beneficial effects at low B concentrations (Nielsen,
5592 2014; Pizzorno, 2015). Moreover, the most extensive and most recent dataset for
5593 rivers/catchments or regions in the EU contains consistently low B values (Heijerick and Van
5594 Sprang, 2004). This observation is in line with a publication by Neal et al. (2010) examining
5595 changes in boron concentrations for the Thames catchment (UK-England) over a decade. The
5596 observed decreases correspond with the timing and extent of an EU-wide trend for B
5597 reduction in industry and domestic usage, such as the reductions in the direct application of
5598 sewage sludges (Schoderboeck et al., 2011). In the EU, the harmonised classification as toxic
5599 to reproduction category 1B (H360: may damage fertility or the unborn child) is regulated
5600 pursuant Regulation (EC) No. 1272/2008 - classification, labelling and packaging of
5601 substances and mixtures. According to this Regulation, consumer products that have
5602 concentrations of $>1\%$ of some boron compounds should be labelled accordingly as toxic.

5603

5604 For all these reasons, **it is proposed not to set a limit for the B content of pyrolysis &**
5605 **gasification materials at CMC level.**

5606

5607 5.6.5 Environmental and human health safety aspects

5608 Based on the feedback received from the STRUBIAS sub-group, it has become clear that
5609 modern pyrolysis plants show a **high technological readiness level** and that both pyrolysis
5610 material properties and the environmental footprint of their production **are highly dependent**
5611 **on the technological readiness level of pyrolysis plants and the type of feedstocks.**

5612

5613 Similar to thermal oxidation materials & derivatives, contaminants present in pyrolysis &
5614 gasification materials may originate from **the feedstock source** used (e.g. inorganic metals
5615 and metalloids, veterinary medicines, etc.) or **can be formed** by the thermochemical
5616 processes used to make pyrolysis & gasification materials (e.g. persistent organic pollutants
5617 such as PAH, PCDD/Fs, PCBs).

5618

5619 5.6.5.1 Metals and metalloids

5620 This section considers concerns associated to the exposure **to alkali, alkaline earth metals,**
5621 **transition metals and other metals.** Whereas some of them are plant micronutrients, the

5622 potential **dissolution and accumulation to toxic levels of these inorganic metals and**
5623 **metalloids present in pyrolysis & gasification materials requires a more in-depth risk**
5624 **assessment.** Metal or metalloid species may be considered “contaminants” if their presence is
5625 unwanted or occurs in a form or concentration that causes detrimental human or
5626 environmental effects.

5627 In broad terms, the addition of pyrolysis material has been indicated to reduce the metal and
5628 metalloid concentrations in plant tissues, possibly because of metal adsorption on the reactive
5629 surface of the pyrolysis material (Peng et al., 2018). The effects of pyrolysis & gasification
5630 materials on residual metals and metalloids in the soil have, however, not been considered in
5631 this assessment as the long-term fate of the adsorbed contaminants remains unknown.
5632 Instead, this analysis is focussed on the supplementary addition of metals and metalloids to
5633 soils through the application of pyrolysis & gasification materials.

5634 Aluminum, Iron and Manganese

5635 The assessment for aluminum, iron and manganese in pyrolysis & gasification materials is
5636 largely similar to that performed for thermal oxidation materials & derivatives (see section
5637 5.5.5.1). Although the leaching of Al from pyrolysis & gasification materials is somewhat
5638 higher than for thermal oxidation materials & derivatives (Hernandez et al., 2011), the leaching
5639 of Al is still about 1-2 orders of magnitude lower than for Ca. Given the critical importance
5640 of the Ca/Al ratio of the leachate to influence plant phytotoxicity (Godbold et al., 1988), no
5641 major risks are indicated for Al. Iron leaching from pyrolysis & gasification materials is
5642 indicated to be very low, similar to thermal oxidation materials (Hernandez et al., 2011).

5643 Therefore, **no specific criterion is proposed for Al, Fe and Mn contents in pyrolysis &**
5644 **gasification materials.**

5645

5646 Assessment on the potential accumulation of trace metals/metalloids in soil

5647 Metals and metalloids present in feedstock will mostly likely **concentrate in pyrolysis &**
5648 **gasification materials**, although methods such as the selective removal of metal-
5649 concentrated ashes and high temperature pyrolysis might possibly reduce the contaminant
5650 levels in pyrolysis & gasification materials (Shackley et al., 2013). Relative to thermal
5651 oxidation materials & derivatives, little information on the content of metals and metalloids in
5652 pyrolysis & gasification materials is available (section 16.3.2).

5653

5654 Possible environmental and human health risks due to the presence of inorganic metals and
5655 metalloids (As, Be, Ba, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, V, and Zn) in pyrolysis material
5656 should therefore be evaluated. An overview of the inorganic metals and metalloids present in
5657 pyrolysis & gasification materials has been compiled in section 16.3.2, based on the
5658 information found in the scientific literature and the completed questionnaires from the
5659 STRUBIAS sub-group.

5660

5661 Some inorganic metals and metalloids are already regulated for different PFCs in the
5662 proposal for the Revised Fertiliser Regulation. Specifically, limit values for Cd, Cr (VI), Hg,
5663 Ni, and Pb have already been brought forward in the proposal for the Revised Fertiliser
5664 Regulation for the different PFCs where pyrolysis & gasification materials might be used as

5665 ingredients. Also, it is being discussed to regulate Zn and Cu at PFC level, for which reason
5666 these elements are not included in this assessment at CMC level. **Based on the information**
5667 **presented, the present assessment is restricted to As, Ba, Be, Co, Mo, Sb, Se and V.**
5668

5669 Considering the large overlap in input materials for thermal oxidation processes and
5670 pyrolysis/gasification processes, a similar approach for inorganic metals and metalloids will
5671 be considered, focusing primarily on the risk of **accumulation of inorganic metals and**
5672 **metalloids in soils.**
5673

5674 In a **first step**, soil screening values were collected for the different EU Member States as
5675 given in section 17.1. **Soil Screening Values** are generic quality standards that are used to
5676 regulate land contamination and are adopted in many Member States in Europe in order to
5677 protect the environment and human health (Carlon, 2007).

5678 In a **second step**, a maximal permissible concentration of the element in the CMC derived
5679 fertilising material is calculated based on the principle that predicted metals/metalloid
5680 accumulation as a result of the long-term application of the fertilising material and the
5681 atmospheric deposition in the soil shall not exceed the so-called soil screening value ("*soil*
5682 *screening acceptable limit concentration*") (see section 17.1 for methodological details). A
5683 mass balance approach is applied assuming that the **non-soluble fraction of metals and**
5684 **metalloids accumulates in soils**, and that the soluble metal fraction is removed from the soil
5685 through leaching and plant uptake. The calculated accumulation of the respective trace metal
5686 in soils is then dependent on (1) farming duration (years), (2) the application rate of the
5687 fertilising products, (3) the concentration of the trace metal in the fertiliser and (4) the fate
5688 and transport of the trace metal in soils. A simple spreadsheet-based model using a set of
5689 reasonable assumptions is applied for this purpose as outlined in detail in section 17.1. The
5690 **calculated soil screening acceptable limit contents are then qualitatively** compared to
5691 metal/metalloid concentrations that are typically found across the diverse range of pyrolysis
5692 & gasification materials derived from different eligible input materials. This assessment is
5693 applied **to spot possible issues** that might lead to human health and environmental protection
5694 due to the accumulation of metals and metalloids present in the CMC material. The outcome
5695 of this analysis indicated soil screening acceptable limit concentrations of selected metals and
5696 metalloids as given in Table 5.

5697 **Table 5: Outcome of the soil screening acceptable limit concentrations of selected metals and**
 5698 **metalloids in CE fertilising products derived from pyrolysis & gasification materials**

	maximal trace metal concentration (mg kg ⁻¹) (nutrient-rich/carbon-rich pyrolysis materials)
As	31/8
Ba	1335/334
Be	54/14
Co	101/25
Cr	243/61
Mo	52/13
Sb	12/3
Se	108/27
V	377/94

5699
5700

5701 In a final step, a validation of the soil screening acceptable limit concentration is
 5702 performed by comparing them to the concentrations of the metals and metalloids
 5703 observed in pyrolysis & gasification materials (see section 16.3.2 in Annex). It is indicated
 5704 that by effectively restricting the eligible input materials for pyrolysis & gasification
 5705 materials to bio-waste, category 2 and 3 animal by-products, living and dead organisms and a
 5706 limited share of additives (see section 5.6.2), the concentrations of metals and metalloids
 5707 that could possibly accumulate in pyrolysis & gasification materials is reduced (section
 5708 16.3.2; Beesley et al., 2015; confidential information received from the STRUBIAS sub-
 5709 group), and mostly well below the soil screening acceptable limit concentration as given
 5710 in Table 5, with the exception of Sb. However, as outlined in section 5.5.5.1 for thermal
 5711 oxidation materials & derivatives, the low soil screening value of 3 mg kg⁻¹ used in this
 5712 assessment might not be justified due to the low to moderate potential to cause harm to
 5713 aquatic, soil and sediment organisms and the lack of Sb bioaccumulation in the soil. As a
 5714 matter of fact, the value is about a factor 20 lower than the value of 54 mg kg⁻¹ soil as
 5715 determined for a serious risk by van Vlaardingen et al. (2005). It is indicated that the
 5716 possibility for the concentration of these metals and metalloids to levels of unacceptable risk
 5717 is limited because (1) the pyrolysis/gasification process only concentrates elements to a
 5718 limited extent relative to raw feedstock applied (typically factor 2-5; Boateng et al., 2015),
 5719 and (2) feedstocks that could be enriched in metals and metalloids, such as sewage
 5720 sludge, fossil fuels and ore and ore concentrates, are not listed as eligible input materials
 5721 (see section 5.6.2). The voluntary standardisation scheme of the European Biochar Certificate
 5722 has established limit values for Pb, Cd, Cr, Cu, Ni, Hg, and Zn (section 16.3.2). With the
 5723 exception of Cr, all these metals are regulated at PFC level in the Revised Fertiliser
 5724 Regulation. The values for Cr for pyrolysis & gasification materials derived from the eligible
 5725 input materials range are typically much lower than the soil screening acceptable limit
 5726 concentration, both for carbon-rich as for nutrient-rich pyrolysis & gasification materials
 5727 (section 16.3.2).

5728

5729 In conclusion, the proposal is to not set limit values for metals and metalloids at CMC
 5730 level for pyrolysis & gasification materials.

5731

5732 Leaching of metals, metalloids, non-metals and halogens

5733 Similar to thermal oxidation materials & derivatives, no environmental risks are expected **due**
5734 **the leaching of inorganic metals and metalloids when their concentration in the**
5735 **pyrolysis & gasification materials does not exceed the proposed limits.** As a matter of
5736 fact, the percolation of these is **highly reduced** due to the physico-chemical properties of the
5737 pyrolysis & gasification materials, and their accretion in a stable, aromatic matrix.

5738

5739 5.6.5.2 PAH, PCDD/F and PCB

5740 Three particular classes of contaminants that are not strictly feedstock-dependent can be
5741 **formed by the thermochemical processes** used to produce pyrolysis & gasification
5742 materials. These *de novo* formed compounds are polycyclic aromatic hydrocarbons (PAH),
5743 and dioxins and furans (PCDD/F), and polychlorinated biphenyls (PCB).

5744

5745 Low temperature formation (<600°C) of PAHs takes place as a result of condensation,
5746 carbonisation and aromatisation of the solid material as it transforms (Bucheli et al., 2015).
5747 During biomass pyrolysis, PAHs are also formed by pyrosynthesis, i.e. where different
5748 gaseous hydrocarbon radicals are generated by cracking of organic material under high
5749 temperature conditions. These radicals then undergo a series of bimolecular reactions to form
5750 larger polyaromatic ring structures (Bucheli et al., 2015). A wide range of PAHs has been
5751 detected in pyrolysis & gasification materials (Bucheli et al., 2015; for a good overview and
5752 summary tables), for which reason it **is proposed to limit PAH content** and to include this
5753 parameter as part of the Conformity Assessment Procedure for pyrolysis & gasification
5754 materials.

5755

5756 Little information on PCDD/F and PCB contents in pyrolysis & gasification materials is
5757 available. In principle, the **formation of these contaminants requires both the presence of**
5758 **significant amounts of chlorine in the feedstock (e.g. specific herbaceous biomass types)**
5759 **and a high pyrolysis temperature** (~750 °C) (Libra et al., 2011; Aller, 2016). Nonetheless,
5760 PCDD/F and PCBs can be formed at temperatures starting at 300°C (Lundin and Marklund,
5761 2005), and their formation might thus occur at the typical operation temperatures applied in
5762 pyrolysis plants. Moreover, the **adsorption of PCDD/Fs and PCBs can be favoured by**
5763 presence of elementary carbon or soot particles in the pyrolysis & gasification materials
5764 (Vehlow et al., 2006). At present, there is only limited information available on the presence
5765 of PCDD/Fs and PCBs in pyrolysis & gasification materials (section 16.3.2; Bucheli et al.,
5766 2015)(confidential information from the STRUBIAS sub-group), for which reason the
5767 precautionary principle should apply. For that reason, also the European Biochar Certificate
5768 not only includes PAH, but also PCDD/F and PCB as part of the compliance scheme.

5769

5770 As indicated by the STRUBIAS sub-group and scientific literature (Buss et al., 2016), **the**
5771 **current technology readiness level enables the production of pyrolysis & gasification**
5772 **materials with low levels of persistent organic pollutants.** Even without post-combustion

5773 treatment for the abatement of organic compounds, acceptable levels of POPs can be reached
5774 for many pyrolysis & gasification materials (Bucheli et al., 2015).

5775

5776 Therefore, it is proposed to adhere to the PAH limit proposed for some other CMCs and to
5777 the strictest levels for PCDD/Fs and PCBs as set by existing national legislation and quality
5778 standards, specifically those of the European Biochar Certificate (EBC, 2012):

5779 ○ **PAH (16 US EPA congeners, mg kg⁻¹ dry matter): < 6**

5780 ○ **PCDD/F (ng WHO toxicity equivalents kg⁻¹dry matter): < 20**

5781 ○ **PCB (sum of 6 congeners PCB 28, 52, 101, 138, 153, 180, mg kg⁻¹): < 0.2**

5782

5783 Note that these values are substantially lower than the limit values established in EU
5784 Regulation (EU) No 756/2010 amending Regulation (EC) No 850/2004 of the European
5785 Parliament and of the Council on persistent organic pollutants as regards their Annexes IV
5786 and V (limit values of 15 µg kg⁻¹ for PCDD/F and 50 mg kg⁻¹ for PCBs).

5787

5788 *5.6.5.3 Other organic chemical pollutants*

5789 At present, **relatively little research has been conducted on the subject of organic**
5790 **pollutants**, other than PAH, PCBs and PCDD/F, present in pyrolysis & gasification
5791 materials. As indicated in section 5.6.3.2, **the weight loss from pyrolysis & gasification**
5792 **materials at temperatures of > 500°C is due to the removal of organic compounds**
5793 (Deydier et al., 2005b; Koutcheiko et al., 2007; Ro et al., 2010; Marculescu and Stan, 2012).
5794 The high-temperature process **reduces to a variable extent the concentrations of organic**
5795 **micropollutants**, including those originating from veterinary medicines, hormones, and
5796 herbicides that may be present in the input materials (Ross et al., 2016). Therefore, main
5797 important organic chemical pollutants, such as veterinary antibiotics, have been largely
5798 removed from pyrolysis & gasification materials that show an increased C stability and low
5799 H:Corg ratio < 0.7 (STRUBIAS sub-group information received from testing by Hitz; Ross
5800 et al., 2016; Liang et al., 2017). Nonetheless, little is known about concentration,
5801 bioavailability, and possible decay products that can be formed and adsorbed during the
5802 production process. This has been one of the major reasons to propose **a positive input**
5803 **material list** for pyrolysis & gasification materials that includes only materials for which the
5804 pyrolysis/gasification process might lead to acceptable risks for the environment and human
5805 health (see section 5.6.2). Considering that (1) the eligible input materials list only comprises
5806 bio-waste, animal by-products and living or dead organisms and that (2) purging of veterinary
5807 drugs takes place during the pyrolysis production process, **it is proposed not to request any**
5808 **additional chemical analyses for organic contaminants other than those already**
5809 **mentioned for PAHs, PCDD/Fs and PCBs.**

5810

5811

5812 5.6.5.4 *Biological pathogens*

5813 The pyrolysis process has been shown to thermally decompose biological pathogens and to
 5814 effectively reduce microbial communities (Liu et al., 2014; Uchimiya, 2014). The thermal
 5815 destruction has been studied in great detail by the food industry because of the importance of
 5816 this process in killing pathogenic bacteria and preventing foodborne spoilage. It was observed
 5817 that much lower temperatures than those observed in pyrolysis/gasification are required for
 5818 the dry heat deactivation of biological pathogens. **Above temperatures of 120°C, minimal
 5819 thermal death times are required to inactivate biological pathogens**, even under dry
 5820 conditions (Gerba, 2015). Microorganisms as well as viruses and enzymes are thus denatured
 5821 at the temperatures applied during pyrolysis, with survival rates decreasing exponentially as a
 5822 function of temperature and reaction time (Gerba, 2015).

5823 **Slow or mild pyrolysis** takes place at 300–650 °C with relatively long residence times.
 5824 Based on the proposed requirement of a maximal H/Corg ratio of 0.7 (see section 5.6.4.1), the
 5825 minimal residence times will be at least be a few minutes (Kambo and Dutta, 2015) (Table 6).
 5826 Higher temperatures (500 – 900°C) but lower residence times (10–20 seconds) are typical for
 5827 **gasification processes** (Table 6). Also **hydrothermal carbonisation**, a wet heating process
 5828 in which the input materials are placed in a closed reactor (i.e. autoclave) and treated at about
 5829 180-250°C in a confined system under pressure (2–6 MPa) for 5–240 minutes (Table 6) will
 5830 result in the effect inactivation of all biological pathogens. The heat resistance of microbial
 5831 cells even decreases with increasing humidity and moisture (Gerba, 2015).

5832

5833 **Table 6: Classification of different pyrolysis/gasification processes in terms of operating**
 5834 **conditions (adopted from Kambo and Dutta, 2015)**

Pyrolysis process	Operating temperature (°C)	Residence time	Heating rate
Slow pyrolysis	300–650	5 min–12 h	10–30 °C/min
Mild pyrolysis	200–300	30 min–4 h	10–15 °C/min
Gasification	600–900	10–20 s	50–100 °C/s
Wet pyrolysis	180–260	5 min–12 h	5–10 °C/min

5835

5836

5837 Specific criteria to control for biological pathogens have been proposed in the Revised
 5838 Fertiliser Regulation at PFC level (for organic and organo-mineral fertilisers included in PFC
 5839 1, organic soil improvers (PFC 3), growing media (PFC 4), and non-microbial biostimulants
 5840 (PFC 6). Therefore, **no specific criteria for biological pathogens are proposed**.

5841 Many of the standard processing techniques for animal by-products (see Regulation (EU)
 5842 142/2011, e.g. pressure sterilisation, Brookes gasification, etc.) could potentially be included
 5843 as part of the production process of pyrolysis & gasification materials. Therefore, **it is
 5844 proposed that the end point in the manufacturing chain as defined in the Animal by-
 5845 products Regulation can be reached at a stage prior or during the pyrolysis material**

5846 **production process.** As such, the compliance with the Animal By-products Regulation will
5847 be met for all pyrolysis & gasification materials derived from animal by-products.
5848

5849 According to Article 32 of Regulation (EC) 1069/2009, animal by-products derived from
5850 category 2 or category 3 material are allowed for the production of organic fertilisers and soil
5851 improvers provided that they have **been produced in accordance with the conditions for**
5852 **pressure sterilisation or have been digested or composted.** Moreover, the Brookes'
5853 gasification process as described in point E, section 2, chapter IV, of Annex IV of Regulation
5854 (EU) No 142/2011, is considered as a processing method for animal by-products of category
5855 2 and 3.

5856 As outlined in section 5.3.5, **the placing on the market of processed manure, derived**
5857 **products from processed manure and guano from bats is subject to the requirements**
5858 **laid down in Annex XI (Chapter I, section 2) of Regulation (EU) 142/2011.** The standard
5859 processing method that such material must undergo includes a heat treatment process of at
5860 least 70 °C for at least 60 minutes and they shall have been subjected to reduction in spore-
5861 forming bacteria and toxin formation, where they are identified as a relevant hazard.
5862 Nonetheless, the competent authority may authorise the use of other standardised process
5863 parameters than those referred to above, **provided that such parameters ensure the**
5864 **minimising of biological risks.** This involves, amongst others, the identification and analysis
5865 of possible hazards, a validation of the intended process by measuring the reduction of
5866 viability/infectivity of endogenous indicator organisms, including, for instance, *Enterococcus*
5867 *faecalis*, thermoresistant viruses such as parvovirus, parasites such as eggs of *Ascaris sp.*,
5868 *Escherichia coli*, *Enterococcaceae*, and *Salmonella*. It can be reasonable assumed that the
5869 combination of the proposed production techniques (Table 6) and the maximum H:C_{org} ratio
5870 of 0.7 (~high degree of carbonisation) will ensure process conditions that are more stringent
5871 than the default heat treatment process (at least 70 °C for at least 60 minutes) for the
5872 placement of **processed manure** on the market.

5873

5874 Therefore, it is proposed as follows (see also section 5.3.5):

5875 Animal by-products and derived materials from Category 2 or Category 3 material of
5876 Regulation (EC) No 1069/2009, other than manure, non-mineralised guano, and
5877 digestive tract content, should undergo one of the following treatments at a stage prior
5878 to or during the pyrolysis & gasification material production process:

- 5879 ○ pressure sterilisation or with other conditions to prevent risks arising to public
5880 and animal health, in accordance with the requirements laid down pursuant to
5881 Article 15 of Regulation (EC) No 1069/2009,
 - 5882 ○ transformation into biogas or compost as set out set out in Annex V of (EU) No
5883 142/2011, or
 - 5884 ○ Brookes' gasification process as described in point E, section 2, chapter IV, of
5885 Annex IV of Regulation (EU) No 142/2011.
- 5886

5887 5.6.5.5 Emissions

5888 **The mechanisms that lead to emissions from the handling and application of fertilising**
5889 **during material are outlined in section 5.4.5.4.**

5890
5891 One of the mechanisms may generate may generate **airborne dusts and particulate matter**
5892 **emissions**. There are concerns that pyrolysis & gasification materials can be lost from the soil
5893 during and after the application through the **physical erosion and the abrasion of pyrolysis**
5894 **material particles**, thus offsetting any delayed decomposition on account of chemical
5895 recalcitrance (Ravi et al., 2016). Additionally, particulate matter emissions from soils
5896 amended with pyrolysis & gasification materials may impact upon on air quality. In this
5897 respect, following aspects are relevant to consider:

5898 a) The dustiness of a powder product, defined as the propensity of a material to generate
5899 airborne dust during its handling (Lidén, 2006), not only depends on the **intrinsic**
5900 **physical properties of the material but also on the handling scenario.**

5901 b) Only significant losses relative to control soils have been observed upon the
5902 application of unsieved pyrolysis & gasification materials (produced at a mild
5903 temperature of 300 °C) at application rates of 10-20% of the soil (v/v) (Ravi et al.,
5904 2016). Assuming a ploughing depth of 20 cm and a bulk density of 1.4 g cm⁻³, this
5905 would correspond to unrealistic application rates of 630 - 1260 tonnes ha⁻¹. At lower
5906 application rates (e.g. 5% of the soil) and following sieving (> 2 mm) no significant
5907 losses were observed of the pyrolysis material. Moreover, the often applied rewetting
5908 practices to levels > 15% provide an effective solution to overcome particulate matter
5909 emissions during the land use phase of the product (Silva et al., 2015).

5910
5911 In line with the discussion provided in 5.4.5.4, it is concluded that **correct classification and**
5912 **labelling as foreseen in EU legislations allows downstream users to assess the risk**
5913 **associated airborne dust emissions and other air emissions during the handling and**
5914 **application of certain products, and to take the necessary measures to prevent any**
5915 **potential adverse impacts in case a risk has been identified. It is indicated that the**
5916 **provisions in the proposal for the Revised Fertiliser Regulation on labelling and**
5917 **European Regulations are sufficiently effective to control for any adverse impacts**
5918 **associated to emissions during the handling and application of thermal oxidation**
5919 **materials & derivates.**

5920

5921 5.6.5.6 Flammability

5922 The handling, storage and application of pyrolysis & gasification materials can represent a
5923 **fire hazard** (Dzonzi-Unidm et al., 2012). Dust particles from pyrolysis & gasification
5924 materials can form explosive mixtures with air in confined spaces, and there is a danger of
5925 spontaneous heating and ignition when biochar is tightly packed. This occurs because fresh
5926 pyrolysis material quickly sorbs oxygen and moisture, and these sorption processes are
5927 exothermic, thus potentially leading to high temperature and ignition of the material. The

5928 volatile compounds present in pyrolysis & gasification materials may also represent a fire
5929 hazard, which is reduced if the proposed criteria on carbon stability are met.

5930

5931 Water can also reduce flammability, but its effectiveness is dependent on the degree of water
5932 saturation of the pyrolysis material. Addition of water to pyrolysis & gasification materials,
5933 however, increases the weight of the material and thus shipping costs. The best way to
5934 prevent fire is to store and transport **biochar in an atmosphere which excludes oxygen**
5935 (Blackwell et al., 2009). Pelletising and admixing of pyrolysis & gasification materials with
5936 composts, or the production of biochar-mineral complexes will also yield materials which are
5937 much less flammable.

5938

5939 Correct classification and labelling of the material properties allows downstream users to
5940 assess the flammability risk during the handling and application of certain products, and to
5941 take the necessary measures to prevent any potential adverse impacts in case a risk has been
5942 identified. Hence, it is indicated that the provisions in the proposal for the Revised Fertiliser
5943 Regulation on labelling and European Regulations ((EC) No. 1272/2008, Regulation (EC) No
5944 1907/2006) are sufficiently effective to control for flammability risks during the handling and
5945 application of pyrolysis & gasification materials. **Therefore, no further requirements are**
5946 **proposed to control for material flammability.**

5947

5948 *5.6.5.7 Occupational health*

5949 **Council directive 89/391/EEC on the introduction of measures to encourage**
5950 **improvements in the safety and health of workers at work seeks to adequately protect**
5951 **workers and encourages improvements in occupational health and safety in all sectors**
5952 **of activity, both public and private.** The Directive also promotes workers' rights to make
5953 proposals relating to health and safety, to appeal to the competent authority and to stop work
5954 in the event of serious danger. No further legal requirements are therefore proposed.

5955

5956 *5.6.6 Physico-chemical properties*

5957 *5.6.6.1 Physical impurities*

5958 Given that the eligible input materials only include bio-waste, living or dead organisms and
5959 animal by-products (but not municipal solid waste, sewage sludge), impurities in the form of
5960 glass, plastics and metals could be present in low to moderate amounts in the input materials.
5961 Materials that are more likely to contain impurities, such as municipal solid waste and
5962 sewage sludge, have been excluded as eligible input materials for pyrolysis & gasification
5963 materials. The general framework of the proposal for a Revised Fertiliser Regulation
5964 explicitly mentions that "impurities in CE marked fertilising products derived from bio-
5965 waste, in particular polymers but also metal and glass, should be either prevented or limited
5966 to the extent technically feasible by detection of such impurities in separately collected bio-
5967 waste before processing". Moreover, the pyrolysis/gasification process may effectively
5968 decompose certain impurities, like plastics. **Therefore, no further criterion is proposed to**
5969 **limit visually detectable physical impurities > 2 mm.**

5970

5971 5.6.6.2 *Dry matter content*

5972 It is proposed to set **no criterion on moisture content**, but to enable the material producer to
5973 adjust dry matter content along with other material properties to manage issues related to
5974 flammability, material handling, storage, transport and application.

5975

5976 5.6.6.3 *pH*

5977 Reactive pyrolysis & gasification materials with a very high or low pH are not suitable for
5978 land application as they will induce a pH shock for effect both on soil and flora. Therefore, it
5979 is proposed to limit the **pH_{H2O} for pyrolysis material to the 4 – 12 range**.

5980

5981 5.6.6.4 *Granulometry*

5982 It is noted that the particle form, i.e. granule, pellet, powder, or prill, of the product shall be
5983 indicated on the **label** of solid inorganic macronutrient fertilisers (see labelling requirements
5984 in the proposal for the Revised Fertiliser Regulation). The particle size distribution of the
5985 pyrolysis & gasification materials is related to the loss, transport and interaction of pyrolysis
5986 & gasification materials in the environment. It has an influence on health and safety protocols
5987 relating to handling, storage, transport, and human exposure in regard to pyrolysis material
5988 dust particles (IUPAC, 1990; Ravi et al., 2016). **Therefore, it is important that the end-**
5989 **users of pyrolysis & gasification materials are informed on the material properties. No**
5990 **further requirements for granulometry are proposed.**

5991

5992 5.6.7 Handling and storage

5993 As indicated above, the pyrolysis/gasification process causes an effective reduction or
5994 complete elimination of microbial communities. Therefore, (re-)contamination of the material
5995 with biological pathogens is unlikely if good management practices during storage are
5996 applied. It is proposed that **physical contacts between input and output materials from the**
5997 **pyrolysis/gasification process must be avoided, including during storage**. Similar
5998 provisions have been formulated for compost (CMC 3) and digestates (CMC 4 and 5).

5999

6000 5.6.8 Bioassays

6001 Pyrolysis & gasification materials have been showing promise for increasing crop
6002 productivity (Jeffery et al., 2015). Nonetheless, in contrast to many traditional fertilising
6003 products, pyrolysis & gasification materials vary widely in their product properties, for which
6004 reason their behaviour in the soil is often difficult to predict. Indeed, despite intensive
6005 research on the interactions between pyrolysis & gasification materials and soils, there is **still**
6006 **not sufficient mechanistic understanding of such interactions to produce a reliable**
6007 **decision supporting tool that would be universal across the different soil-pyrolysis**
6008 **material combinations** (Camps-Arbestain et al., 2015; Jeffery et al., 2015), and **the short-**
6009 **and long-term risks for the environment of some endogenous contaminants present in**

6010 **pyrolysis material** (Clements et al., 2015; Dutta et al., 2016; Kuppusamy et al., 2016; Hilber
6011 et al., 2017).

6012

6013 In the STRUBIAS Interim Report, a bioassay based on earthworm avoidance was proposed to
6014 check for unknown pollutants or contaminants for which no limit value could be established
6015 at that time. For the pre-final report, we have, however, removed that proposal from the
6016 compliance scheme because of following reasons:

6017 • **Supplementary assessments and additional techno-scientific information has**
6018 **been collected and included in the assessment** (e.g. on VOCs, Mn, B; see respective
6019 sections in the report). This information enabled to confirm that pyrolysis &
6020 gasification materials derived from eligible input materials that are compliant with the
6021 proposed limit values for contaminants do not pose unacceptable risks for the
6022 environment and the human health.

6023 • The STRUBIAS sub-group indicated that bioassays could **provide little added value**
6024 **in terms of an increased level of environmental and human health protection for**
6025 **fertilising materials**. The reason is that both the nutrients and the contaminants
6026 contained in the fertilising material could affect the behaviour of test species such as
6027 soil fauna (Abbiramy et al., 2014) or algae (Parker et al., 1997). Therefore, even
6028 inorganic fertilisers with low contaminant levels may fail to pass bioassays tests
6029 (Abbiramy et al., 2014; Abbiramy and Ross, 2016). The compliance costs for
6030 bioassays, varying from 2500 Euro (e.g. algal growth inhibition test) to 4500-6500
6031 Euro (earthworm avoidance test) per sample, are thus not proportionate to the
6032 possibly protective benefit due to the inability to provide a rapid, sensitive,
6033 reproducible and reliable screening of environmental and human health risks. This
6034 observation especially holds true for biochars that contain a significant share of plant
6035 available nutrients (e.g. pyrolysis materials derived from animal by-products).

6036 • At relevant application rates, pyrolysis & gasification materials with low nutrient
6037 amounts (e.g. pyrolysis materials derived from vegetable matter) **as produced by**
6038 **industrial facilities and compliant with the proposed compliance scheme for this**
6039 **CMC generally pass bio-assay tests** (Busch et al., 2012; Domene et al., 2015).
6040 Pyrolysis & gasification materials not passing bioassay tests are often not compliant
6041 with the proposed criteria (e.g. Busch et al., 2012) and/or resulting from production
6042 processes under (deficient) conditions leading to materials that (likely) do not meet
6043 other contaminant limit values such as PAHs, PCDD/F or PCBs (Smith et al., 2016;
6044 Visioli et al., 2016). These observations indicate that the proposed technical
6045 requirements for pyrolysis & gasification materials will result in the selection of
6046 materials that show a high potential to serve as added-value products in EU
6047 agriculture.

6048

6049 For all these reasons, **it is proposed to omit the inclusion of bioassays for pyrolysis &**
6050 **gasification materials**. This proposal is in line with voluntary standardisation schemes (e.g.
6051 European Biochar Certificate) and existing national legislation in the EU and the EFTA state
6052 Switzerland (Meyer et al., 2017).

6053 **5.7 Quality management**

6054 5.7.1 Selection of conformity assessment procedures

6055 In the proposal for the Revised Fertiliser Regulation, the essential requirements relating to
6056 products are laid down in the Union legislation as harmonised standards have not been
6057 adopted for all product requirements, or do not cover with sufficient detail all elements of the
6058 quality system to safeguard the safety requirements for specific manufacturing processes and
6059 fertilising products. Therefore, it is necessary to provide for a presumption of conformity for
6060 EU fertilising products which are in conformity with harmonised standards that are adopted
6061 in the comprehensive regulatory framework of Regulation (EC) No 765/2008 and Decision
6062 No 768/2008/EC²⁵. **The essential objective of a conformity assessment procedure is to**
6063 **demonstrate that products placed on the market conform to the requirements expressed**
6064 **in the provisions of the relevant legislation.** They include procedures for sampling, testing
6065 and inspection; evaluation, verification and assurance of conformity; and registration,
6066 accreditation and approval.

6067
6068 On the basis of ISO/IEC documentation, Regulation (EC) No 768/2008 outlines consolidated
6069 conformity assessment procedures and the rules for their selection and use in legislation. As a
6070 general rule, products are subject to both **design and production modules** before being
6071 placed on the market. There are **eight modules** (named with the letters from A to H). They
6072 lay down the responsibilities of the manufacturer (and his authorised representative) and the
6073 degree of involvement of the accredited in-house body or notified conformity assessment
6074 body. They are the components of the conformity assessment procedures laid down under
6075 Decision No 768/2008/EC, the ‘horizontal menu’. Several modules have their variants (e.g.
6076 A1, D1). The reason for providing variants within modules is **to enable the necessary level**
6077 **of assured protection for products presenting a higher level of risk while avoiding the**
6078 **imposition of a heavier module.** The idea is to minimise the burden on manufacturers to the
6079 extent that is possible.

6080
6081 The legislator selects from the menu of conformity assessment modules/procedures (laid
6082 down under Decision No 768/2008/EC) the most appropriate one(s) in order to address the
6083 specific needs of the concerned sector. **The complexity of the modules selected should be**
6084 **proportional to the risk and the level of safety required** (impact on public interest, health,
6085 safety, environment) of the product, its design complexity, the nature of its production (large
6086 series vs small series, custom-made, simple vs complex production mechanism, etc.). It is
6087 necessary to offer a choice of clear, transparent and coherent conformity assessment
6088 procedures, restricting the possible variants.

6089
6090 In the proposal for the revised Fertiliser Regulation, modules A, A1, B + C, and D1 are listed,
6091 but the selection of the modules is dependent on the PFC and CMC under which the fertiliser
6092 material will be placed on the market.

6093

²⁵ 2016/C 272/01 Commission Notice — The ‘Blue Guide’ on the implementation of EU products rules 2016

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Table 7: Consolidated conformity assessment modules of Regulation (EC) No 768/2008 used in the proposal for the Revised Fertiliser Regulation

Module	Description
A - Internal production control	Covers both design and production. The manufacturer himself ensures the conformity of the products to the legislative requirements (no EU-type examination).
A1 - Internal production control plus supervised product testing	Covers both design and production. A + tests on specific aspects of the product carried out by an accredited in-house body or under the responsibility of a notified body chosen by the manufacturer.
B - EU-type examination	Covers design. It is always followed by other modules by which the conformity of the products to the approved EU-type is demonstrated. A notified body examines the technical design and or the specimen of a type and verifies and attests that it meets the requirements of the legislative instrument that apply to it by issuing an EU-type examination certificate. There are 3 ways to carry out EU-type examination: 1) production type, 2) combination of production type and design type and 3) design type.
C - Conformity to EU-type based on internal production control	Covers production and follows module B. The manufacturer must internally control his production in order to ensure product conformity against the EU-type approved under module B.
D1 - Quality assurance of the production process	Covers both design and production. The manufacturer operates a production quality assurance system (manufacturing part and inspection of final product) in order to ensure conformity to legislative requirements (no EU-type). The notified body assesses the production quality system.

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Products which are regarded as presenting a high risk to the public interest require conformity assessment by a third party, i.e. a notified body. Notified bodies are conformity assessment bodies which have been officially designated by their national authority to carry out the procedures for conformity assessment within the meaning of applicable Union harmonisation legislation when a third party is required. If the demonstration of conformity of products cannot be left to the manufacturer but requires that products are supervised by a notified body during the production process, then the legislator may require from the manufacturer to operate an **approved quality system** (for example module D). In the case of products of simple design but complicated production/manufacturing, the legislator may consider selecting module variants and using thus the advantages of the main module, without the necessity of recurring to a more formal

6109 specimen examination (for example, as provided under module B that precedes modules D
6110 where the notified body assesses the production quality system).

6111

6112 **It is proposed that Module D1 shall be used for any CE marked fertilising product**
6113 **derived from STRUBIAS materials.** This proposal to request the manufacturer to operate a
6114 production quality assurance system is mainly based on the risks associated to the handling of
6115 the eligible input materials such as animal by-products and wastes pursuant Regulation
6116 2008/98/EC, that are present on the eligible input material list for all STRUBIAS CMCs.
6117 Implementing and applying a module based on quality of the design and production phase is
6118 therefore appropriate to ensure full compliance with the complex and extensive legislative
6119 requirements that apply to the handling, transport, and operating conditions of the
6120 STRUBIAS production processes. Also, the provisions laid down in the parts of EU
6121 legislation that regulate industrial emissions and large combustion plants (Directive
6122 2010/75/EU, including large combustion plants >50 MWth), Directive (EU) 2015/2193 (>1
6123 MWth, but <50 MWth), and Regulation (EU) 2015/1189 (smaller appliances (heaters and
6124 boilers <1 MWth) require that treatment plants and production processes are supervised by a
6125 notified body. In the proposal for the revised Fertiliser Regulation, **module D1 is also the**
6126 **only module available for CMCs that have animal by-products listed as eligible input**
6127 **materials** (i.e. CMC 3 (compost) and CMC 5 (other digestate than energy crop digestate)).
6128 Moreover, **module D1 can be applied for any CE marked fertilising product**, with the
6129 exception of a straight or compound solid inorganic macronutrient ammonium nitrate
6130 fertiliser of high nitrogen content, or a fertilising product blend containing such a product.

6131

6132 For the purpose of complying with the applicable legislation the manufacturer must ensure
6133 that the **quality system is implemented and applied in such a way that it ensures full**
6134 **compliance of the products with the legislative requirements in question.** The D1 module
6135 based on quality assurance techniques describes the elements a manufacturer must implement
6136 in his organisation in order to demonstrate that the product fulfils the essential requirements
6137 of the applicable legislation. This means that a manufacturer is given the possibility of using
6138 an approved quality system for the purpose of demonstrating compliance with regulatory
6139 requirements. The quality system is assessed by the notified body. A quality system
6140 implemented on the basis of the EN ISO 9001 standard gives a presumption of conformity
6141 with the respective modules with regard to the provisions in the modules that these standards
6142 cover, provided that the quality system takes into consideration the specificities of the
6143 concerned products. However, the manufacturer is free to apply other quality system models
6144 than those based on EN ISO 9001 for the purpose of complying with these modules. In any
6145 case the manufacturer must specifically address all regulatory provisions while applying its
6146 quality system, in particular:

- 6147 • The quality objectives, quality planning and quality manual must fully take on board
6148 the objective of delivering products that conform to the essential requirements;
- 6149 • The manufacturer must identify and document the essential requirements that are
6150 relevant for the product and the harmonised standards or other technical solutions that
6151 will ensure fulfilment of these requirements;

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- The identified standards or other technical solutions must be used as design input, and as verification that design output ensures that the essential requirements will be met.
 - The measures taken to control manufacturing must ensure that the products conform to the identified essential requirements;
 - Quality records, such as inspection reports and test data, calibration data, qualification reports of the personnel concerned, must be suitable to ensure the fulfilment of the applicable essential requirements.

DRAFT - WORK IN PROGRESS

6161 5.7.2 Additional elements of the quality management system and auditing

6162 The elements of module D1 for application in the revised Fertiliser Regulation have been laid
6163 down in the proposal of 17 March 2016. This proposal is largely based on the "default"
6164 module D1 as laid down in Decision (EC) 768/2008, but includes sections of text that have
6165 been **modified**. The adapted module D1 in the proposal for the revised Fertiliser Regulation
6166 **includes additional provisions that account for the specificity of techniques applied in**
6167 **manufacturing processes of fertilising products and the treatment of animal by-**
6168 **products** pursuant Regulation (EC) No 1069/2009.

6169

6170 It is **proposed to further develop the conformity assessment procedure D1, and to**
6171 **incorporate:**

6172 (1) **provisions that relate to the testing of the technical requirements for production**
6173 **process conditions laid down in the STRUBIAS recovery rules.** The STRUBIAS
6174 recovery rules have, nonetheless, been developed with a focus on the testing of the
6175 CMC material that will be incorporated in the CE marked fertilising product.
6176 Therefore, the technical requirements for production process conditions are minimal.
6177 As a matter of fact, the single element that requires further description in the
6178 conformity assessment procedure is the mass balance approach to demonstrate the
6179 removal of contaminants to levels below the limit values established in this
6180 Regulation during post-combustion manufacturing processes of hazardous ashes.

6181 (2) **additional elements in the quality assurance procedure that are specific for the**
6182 **handling and treatment of specific input material.** The production processes for
6183 the STRUBIAS CMCs may involve the transport and handling of waste as input
6184 materials, and possibly multi-operator installations/sites. Also, aspects related to
6185 certification, training and auditing in the adapted D1 module will be reviewed and
6186 updated with new proposals, if deemed appropriate.

6187

6188 To present the adapted D1 module included in the proposal for the Revised Fertiliser
6189 Regulation and the proposals for additions resulting from the addition of the STRUBIAS
6190 CMC, colour codes will be used. The adapted D1 module will be presented in green, whereas
6191 the proposals for further additions will be highlighted in pink, as follows:

6192

6193 **MODULE D1: QUALITY ASSURANCE OF THE PRODUCTION PROCESS**

6194 **1. Description of the module**

6195 1. Quality assurance of the production process is the conformity assessment procedure whereby the
6196 manufacturer of the CE marked fertilising product fulfils the obligations laid down under Headings 2,
6197 4, and 7, and ensures and declares on his or her sole responsibility that the CE marked fertilising
6198 products concerned satisfy the requirements of this Regulation that apply to them.

6199

6200 **2. Technical documentation**

6201 2. The manufacturer of the CE marked fertilising product shall establish the technical documentation.
6202 The documentation shall make it possible to assess the product's conformity with the relevant
6203 requirements, and shall include an adequate analysis and assessment of the risk(s). The technical
6204 documentation shall specify the applicable requirements and cover, as far as relevant for the
6205 assessment, the design, manufacture and use of the product. The technical documentation shall,
6206 wherever applicable, contain at least the following elements:

- 6207 (a) a general description of the product,
 6208 (b) conceptual design and manufacturing drawings and schemes, including a written description and a
 6209 diagram of the production process, where each treatment, storage vessel and area is clearly identified,
 6210 (c) descriptions and explanations necessary for the understanding of those drawings and schemes and
 6211 of the use of the CE marked fertilising product,
 6212 (d) a list of the harmonised standards applied in full or in part the references of which have been
 6213 published in the *Official Journal of the European Union* and, where those harmonised standards have
 6214 not been applied, descriptions of the solutions adopted to meet the essential requirements of this
 6215 Regulation, including a list of common specifications or other relevant technical specifications
 6216 applied. In the event of partly applied harmonised standards, the technical documentation shall specify
 6217 the parts which have been applied,
 6218 (e) results of design calculations made, examinations carried out, *etc.*,
 6219 (e -bis) hazardous waste calculations

6220 The testing referred to in paragraph 5 under CMC "Thermal oxidation materials & derivatives" in
 6221 Annex II to demonstrate the removal or transformation of the contaminants to levels below the limit
 6222 values as defined in Annex III of Directive 2008/98/EC for slags and ashes that display one or more
 6223 hazardous properties, shall be carried out at least every year, or sooner than scheduled if triggered by
 6224 any significant change that may affect the quality of the CE marked fertilising product (e.g.
 6225 processing of input material batches of different composition, modification of process conditions). For
 6226 a representative input material batch that is processed at the plant, the hazardous property identified
 6227 (cfr. heading 5.1.3.1 (b – bis)) and the total mass shall be measured on the different input materials (1,
 6228 ..., n) and on the output material that will be incorporated in the CE market fertilising product. The
 6229 incorporation rate of the hazardous property into the output material shall then be calculated as:

6230
 6231
$$\text{incorporation rate (\%)} = \frac{HPC_{\text{output material}} \times M_{\text{output material}}}{\sum_{i=1}^n (HPC_{\text{input material, } i} \times M_{\text{input material, } i})}$$

6232
 6233 With: HPC the concentration of the hazardous property (mg kg⁻¹), M the total mass (kg), and i (1-n)
 6234 the different input materials used in the production process.

6235 The removal of the hazardous property during the production process shall be such that the
 6236 incorporation rate multiplied by the concentration of the hazardous property of each individual input
 6237 material below the limit values as defined in Annex III of Directive 2008/98/EC for that hazardous
 6238 property.

- 6239 (f) test reports, and
 6240 (g) where the product contains or consists of animal by-products within the meaning of Regulation
 6241 (EC) No 1069/2009, the commercial documents or health certificates required pursuant to that
 6242 Regulation, and evidence that the animal by-products have reached the end point in the manufacturing
 6243 chain within the meaning of that Regulation.

6244
 6245 **3. Availability of technical documentation**

6246 3. The manufacturer shall keep the technical documentation at the disposal of the relevant national
 6247 authorities for 10 years after the CE marked fertilising product has been placed on the market.

6248
 6249 **4. Manufacturing**

6250 4. The manufacturer shall operate an approved quality system for production, final product inspection
 6251 and testing of the products concerned as specified in point 5, and shall be subject to surveillance as
 6252 specified in point 6.

6253
 6254 **5. Quality system**

6255 5.1. The manufacturer shall implement a quality system which shall ensure compliance of the CE
 6256 marked fertilising product with the requirements of this Regulation that apply to them.

6257 5.1.1. The quality system shall include quality objectives and an organisational structure with
 6258 responsibilities and powers of the management with regard to product quality.

6259 5.1.1.1. For compost belonging to component material category ('CMC') 3 ~~and~~, digestate belonging to
6260 CMC 5, precipitated phosphate salts & derivates belonging to CMC XX, thermal oxidation materials
6261 & derivates belonging to CMC YY and pyrolysis & gasification materials belonging to CMC ZZ, as
6262 defined in Annex II, senior management of the manufacturer's organisation shall:

6263 (a) Ensure that sufficient resources (people, infrastructure, equipment) are available to create and
6264 implement the quality system;

6265 (b) Appoint a member of the organisation's management who shall be responsible for:

6266 o Ensuring that quality management processes are established, approved, implemented and
6267 maintained;

6268 o Reporting to senior management of the manufacturer on the performance of the quality
6269 management and any need for improvement;

6270 o Ensuring the promotion of awareness of customer needs and legal requirements throughout
6271 the manufacturer's organisation, and for making the personnel aware of the relevance and
6272 importance of the quality management requirements to meet the legal requirements of this
6273 Regulation;

6274 o Ensuring that each person whose duties affect the product quality is sufficiently trained and
6275 instructed; and

6276 o Ensuring the classification of the quality management documents mentioned under paragraph
6277 5.1.4. below;

6278 (c) Conduct an internal audit every year, or sooner than scheduled if triggered by any significant
6279 change that may affect the quality of the CE marked fertilising product; and

6280 (d) Ensure that appropriate communication processes are established within and outside the
6281 organisation and that communication take place regarding the effectiveness of the quality
6282 management.

6283 5.1.2. The quality system shall be implemented through manufacturing, quality control and quality
6284 assurance techniques, processes and systematic actions.

6285 5.1.2.1. For compost belonging to component material category ('CMC') 3 ~~and~~, digestate belonging to
6286 CMC 5, precipitated phosphate salts & derivates belonging to CMC XX, thermal oxidation materials
6287 & derivates belonging to CMC YY and pyrolysis & gasification materials belonging to CMC ZZ, as
6288 defined in Annex II, the system shall ensure compliance with the ~~composting and digestion~~ process
6289 criteria specified in that Annex.

6290 5.1.2.2. Where any of the requirements from Annex II for production processes for CMC XX
6291 (precipitated phosphate salts & derivates), CMC YY (thermal oxidation materials & derivates) or ZZ
6292 (pyrolysis & gasification materials) have been fulfilled by prior holders of the input material, the
6293 manufacturer shall ensure that all such prior holders implement a quality system that complies with
6294 the requirements of this module.

6295 5.1.3. The quality system shall comprise examinations and tests to be carried out before, during and
6296 after manufacture with a specified frequency.

6297 5.1.3.1. For compost belonging to component material category ('CMC') 3 ~~and~~, digestate belonging to
6298 CMC 5, precipitated phosphate salts & derivates belonging to CMC XX, thermal oxidation materials
6299 & derivates belonging to CMC YY and pyrolysis & gasification materials belonging to CMC ZZ, as
6300 defined in Annex II, the examinations and tests shall comprise the following elements:

6301 (a) The following information shall be recorded for each lot of input materials:

6302 (1) Date delivered;

6303 (2) Amount by weight (or estimation based on the volume and density);

6304 (3) Identity of the input material supplier;

6305 (4) Input material type;

6306 (5) Identification of each lot and delivery location on site. A unique identification code shall be
6307 assigned throughout the production process for quality management purposes; and

6308 (6) In case of refusal, the reasons for the rejection of the lot and where it was sent.

6309 (b) Qualified staff shall carry out a visual inspection of each consignment of input materials and
6310 verify compatibility with the specifications of input materials in CMC 3, CMC 5, CMC XX, CMC
6311 YY and CMC ZZ in Annex II. Where any of the requirements from Annex II for production processes
6312 for CMC XX (precipitated phosphate salts & derivates), CMC YY (thermal oxidation materials &
6313 derivates) or ZZ (pyrolysis & gasification materials) have been fulfilled by prior holders of the input

- 6314 material, the manufacturer shall collect the necessary documentation from these prior holders, in order
 6315 to be able to demonstrate full compliance with all requirements in Annex II.
- 6316 (c) The manufacturer shall refuse any consignment of any given input material where ~~visual~~
 6317 inspection raises any suspicion of
- 6318 ○ the presence of hazardous or damageable substances for the composting, digestion,
 6319 precipitation, thermal oxidation or pyrolysis/gasification process or for the quality of the final
 6320 CE marked fertilising product, or of
 - 6321 ○ incompatibility with the specifications of CMC 3 ~~and~~, CMC 5, CMC XX, CMC YY and
 6322 CMC ZZ in Annex II, in particular by presence of plastics leading to exceedance of the limit
 6323 value for macroscopic impurities.
- 6324 (d) The staff shall be trained on
- 6325 ○ potential hazardous properties that may be associated with input materials, and
 - 6326 ○ features that allow hazardous properties and the presence of plastics to be recognised.
- 6327 (e) Samples shall be taken on output materials, to verify that they comply with the component
 6328 material specifications ~~for compost and digestate laid down in CMC 3 and CMC 5 in Annex II~~ for
 6329 compost belonging to component material category ('CMC') 3 ~~and~~, digestate belonging to CMC 5,
 6330 precipitated phosphate salts & derivates belonging to CMC XX, thermal oxidation materials &
 6331 derivates belonging to CMC YY and pyrolysis & gasification materials belonging to CMC ZZ, as
 6332 defined in Annex II, and that the properties of the output material do not jeopardise the CE marked
 6333 fertilising product's compliance with the relevant requirements in Annex I.
- 6334 (f) The output material samples shall be taken with at least the following frequency, or sooner than
 6335 scheduled if triggered by any significant change that may affect the quality of the CE marked
 6336 fertilising product (e.g. processing of input materials listed under dissimilar letter items on the eligible
 6337 input material list, modification of process conditions):

Annual input (tonnes)	Samples / year
≤ 3000	1
3001 – 10000	2
10001 – 20000	3
20001 – 40000	4
40001 – 60000	5
60001 – 80000	6
80001 – 100000	7
100001 – 120000	8
120001 – 140000	9
140001 – 160000	10
160001 – 180000	11
> 180000	12

- 6339 (g) If any tested output material sample fails one or more of the applicable limits specified in the
 6340 relevant sections of Annexes I and II to this Regulation, the person responsible for quality
 6341 management referred to above in point 5.1.1.1(b) shall:
- 6342
- 6343 (1) Clearly identify the non-conforming products and their storage place,
 - 6344 (2) Analyse the reasons of the non-conformity and take any necessary action to avoid its repetition,
 - 6345 (3) Record in the quality records referred to in paragraph 5.1.4 if reprocessing takes place, or if the
 6346 product is eliminated.
- 6347 5.1.4. The manufacturer shall maintain the quality records, such as inspection reports and test data,
 6348 calibration data, qualification reports on the personnel concerned, etc.,
- 6349 5.1.4.1. For compost belonging to component material category ('CMC') 3 ~~and~~, digestate belonging to
 6350 CMC 5, precipitated phosphate salts & derivates belonging to CMC XX, thermal oxidation materials
 6351 & derivates belonging to CMC YY and pyrolysis & gasification materials belonging to CMC ZZ, as
 6352 defined in Annex II, the quality records shall demonstrate effective control of input materials,
 6353 production, storage and compliance of input- and output materials with the relevant requirements of
 6354 this Regulation. Each document shall be legible and available at its relevant place(s) of use, and any

6355 obsolete version shall be promptly removed from all places where it is used, or at least identified as
6356 obsolete. The quality management documentation shall at least contain the following information:

6357 (a) A title,
6358 (b) A version number,
6359 (c) A date of issue,
6360 (d) The name of the person who issued it,
6361 (e) Records about the effective control of input materials,
6362 (f) Records about the effective control of the production process,
6363 (g) Records about the effective control of the output materials,
6364 (h) Records of non-conformities,
6365 (i) Reports on all accidents and incidents that occur to the site, their known or suspected causes and
6366 actions taken,
6367 (j) Records of the complaints expressed by third parties and how they have been addressed,
6368 (k) A record of the date, type and topic of training followed by the persons responsible for the quality
6369 of the product,
6370 (l) Results of internal audit and actions taken, and
6371 (m) Results of external audit review and actions taken.

6372 5.1.5 The achievement of the required product quality and the effective operation of the quality
6373 system shall be monitored.

6374 5.1.5.1. For compost belonging to component material category ('CMC') 3 and, digestate belonging to
6375 CMC 5, precipitated phosphate salts & derivates belonging to CMC XX, thermal oxidation materials
6376 & derivates belonging to CMC YY and pyrolysis & gasification materials belonging to CMC ZZ, as
6377 defined in Annex II, the manufacturer shall establish an annual internal audit program in order to
6378 verify the compliance to the quality system, with the following components:

6379 (1) A procedure that defines the responsibilities and requirements for planning and conducting
6380 internal audits, establishing records and reporting results shall be established and documented. A
6381 report identifying the non-conformities to the quality scheme shall be prepared and all corrective
6382 actions shall be reported. The records of the internal audit shall be annexed to the quality management
6383 documentation.

6384 (2) Priority shall be given to non-conformities identified by external audits.

6385 (3) Each auditor shall not audit his or her own work.

6386 (4) The management responsible for the area audited shall ensure that the necessary corrective actions
6387 are taken without undue delay.

6388 (5) Internal audit realised in the frame of another quality management system can be taken into
6389 account provided that it is completed by an audit of the requirements to this quality system.

6390 5.2. The manufacturer shall lodge an application for assessment of his or her quality system with the
6391 accredited notified body of his or her choice, for the products concerned. The application shall
6392 include:

6393 - the name and address of the manufacturer and, if the application is lodged by the authorised
6394 representative, his or her name and address as well,
6395 - a written declaration that the same application has not been lodged with any other notified body,
6396 - all relevant information for the product category envisaged,
6397 - the documentation concerning the quality system,
6398 - technical documentation of all the quality system elements set out in paragraphs 5.1 and
6399 subparagraphs.

6400 5.3. All the elements, requirements and provisions adopted by the manufacturer shall be documented
6401 in a systematic and orderly manner in the form of written policies, procedures and instructions. The
6402 quality system documentation shall permit a consistent interpretation of the quality programmes,
6403 plans, manuals and records. It shall, in particular, contain an adequate description of all the quality
6404 management elements mentioned above in paragraph 5.1 and subparagraphs.

6405 5.4.1. The notified body shall assess the quality system to determine whether it satisfies the
6406 requirements referred to in paragraph 5.1 and subparagraphs.

6407 5.4.2. It shall presume conformity with those requirements in respect of the elements of the quality
6408 system that comply with the corresponding specifications of the relevant harmonised standard.

6409 5.4.3. In addition to experience in quality management systems, the auditing team shall have at least
6410 one member with experience of evaluation in the relevant product field and product technology
6411 concerned, and knowledge of the applicable requirements of this Regulation. The audit shall include
6412 an assessment visit to the manufacturer's premises. The auditing team shall review the technical
6413 documentation referred to in point 2 in order to verify the manufacturer's ability to identify the
6414 relevant requirements of this Regulation and to carry out the necessary examinations with a view to
6415 ensuring compliance of the CE marked fertilising product with those requirements.

6416 5.4.4. The decision shall be notified to the manufacturer. The notification shall contain the
6417 conclusions of the audit and the reasoned assessment decision.

6418 5.5. The manufacturer shall undertake to fulfil the obligations arising out of the quality system as
6419 approved and to maintain it so that it remains adequate and efficient

6420 5.6.1. The manufacturer shall keep the notified body that has approved the quality system informed of
6421 any intended change to the quality system.

6422 5.6.2. The notified body shall evaluate any proposed changes and decide whether the modified quality
6423 system will continue to satisfy the requirements referred to in point 5.2 or whether reassessment is
6424 necessary.

6425 5.6.3. It shall notify the manufacturer of its decision. The notification shall contain the conclusions of
6426 the examination and the reasoned assessment decision.

6427

6428 **6. Surveillance under the responsibility of the notified body**

6429 6.1 The purpose of surveillance is to make sure that the manufacturer duly fulfils the obligations
6430 arising out of the approved quality system.

6431 6.2. The manufacturer shall, for assessment purposes, allow the notified body access to the
6432 manufacture, inspection, testing and storage sites and shall provide it with all necessary information,
6433 in particular:

6434 - the quality system documentation,

6435 - the technical documentation referred to in paragraph 2,

6436 - the quality records, such as inspection reports and test data, calibration data, qualification reports on
6437 the personnel concerned.

6438 6.3.1 The notified body shall carry out periodic audits to make sure that the manufacturer maintains
6439 and applies the quality system and shall provide the manufacturer with an audit report.

6440 6.3.2 For compost belonging to component material category ('CMC') 3 ~~and~~, digestate belonging to
6441 CMC 5, precipitated phosphate salts & derivatives belonging to CMC XX, thermal oxidation materials
6442 & derivatives belonging to CMC YY and pyrolysis & gasification materials belonging to CMC ZZ, as
6443 defined in Annex II, the notified body shall take and analyse output material samples during each
6444 audit, and the audits shall be carried out with the following frequency:

6445 (a) During the notified body's first year of surveillance of the plant in question: The same frequency
6446 as the sampling frequency indicated in the table included in paragraph 5.1.3.1(f); and

6447 (b) During the following years of surveillance: Half the sampling frequency indicated in the table
6448 included in paragraph 5.1.3.1(f).

6449 6.4 In addition, the notified body may pay unexpected visits to the manufacturer. During such visits
6450 the notified body may, if necessary, carry out product tests, or have them carried out, in order to
6451 verify that the quality system is functioning correctly. The notified body shall provide the
6452 manufacturer with a visit report and, if tests have been carried out, with a test report.

6453

6454 **7. Conformity marking and EU declaration of conformity**

6455 7.1. The manufacturer shall affix the CE marking and, under the responsibility of the notified body
6456 referred to in paragraph 5.2, the latter's identification number to each individual product that satisfies
6457 the applicable requirements of this Regulation.

6458 7.2.1 The manufacturer shall draw up a written EU declaration of conformity for each CE marked
6459 fertilising product lot and keep it at the disposal of the national authorities for 10 years after the CE
6460 marked fertilising product has been placed on the market.

6461 The EU declaration of conformity shall identify the product lot for which it has been drawn up.

6462 7.2.2. A copy of the EU declaration of conformity shall be made available to the relevant authorities
6463 upon request.

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8. Availability of quality system documentation

8. The manufacturer shall, for a period ending at least 10 years after the product has been placed on the market, keep at the disposal of the national authorities:

- the documentation referred to in paragraph 5.3,
- the change referred to in paragraph 5.6 and subparagraphs, as approved,
- the decisions and reports of the notified body referred to in paragraph 5.6.1-5.6.3, paragraph 6.3 and paragraph 6.4.

9. Notified bodies' information obligation

9.1. Each notified body shall inform its notifying authorities of quality system approvals issued or withdrawn, and shall, periodically or upon request, make available to its notifying authorities the list of quality system approvals refused, suspended or otherwise restricted.

9.2. Each notified body shall inform the other notified bodies of quality system approvals which it has refused, suspended or withdrawn, and, upon request, of quality system approvals which it has issued.

10. Authorised representative

The manufacturer's obligations set out in paragraph 3, paragraph 5.2, paragraphs 5.6.1-5.6.3, Heading 7 and Heading 8 may be fulfilled by his or her authorised representative, on his or her behalf and under his or her responsibility, provided that they are specified in the mandate.

DRAFT - WORK IN PROGRESS

6485 5.7.3 Standards

6486 The presumption of conformity to a legal provision conferred by conformity to a harmonised
6487 standard should enhance recourse to compliance with harmonised standards.

6488

6489 Regulation (EU) No 1025/2012 provides definitions for the terms ‘standard’, ‘national
6490 standard’, ‘European standard’, ‘harmonised standard’, and ‘international standard’.

6491 • ‘Standards’ are defined as technical specifications, adopted by a recognised
6492 standardisation body, for repeated or continuous application, with which compliance is
6493 not compulsory.

6494 • ‘European standards’ are ‘standards’ adopted by the European standardisation
6495 organisations (ESOs) listed in Annex I to Regulation (EU) No 1025/2012 (155).
6496 CENELEC is a European regional standards organisation that together with its sister
6497 organisations CEN, the European Committee for Standardization, and ETSI, the
6498 European Telecommunications Standards Institute, compose the so-called and known
6499 European Standards Organizations (ESOs) that are officially recognised by the European
6500 Commission and act as a European platform through which European Standards are
6501 developed. In the European Union, only standards developed by CEN, CENELEC and
6502 ETSI are recognised as 'European Standards'. CEN and CENELEC are the regional mirror
6503 bodies to their international counterparts, i.e. ISO (the International Organization for
6504 Standardization).

6505 • Taking into account the first two definitions mentioned above, ‘harmonised standards’ are
6506 ‘European standards’ adopted, upon a request made by the Commission, for the
6507 application of Union harmonisation legislation. Harmonised standards maintain their
6508 status of voluntary application. The definition for a ‘harmonised standard’, within the
6509 context of Regulation (EU) No 1025/2012, is not restricted to harmonised standards
6510 supporting harmonised product legislation as the Regulation mainstreams the use of
6511 harmonised standards in harmonisation legislation for services in similar way as in Union
6512 harmonisation legislation for products.

6513

6514 Following standards and measurement methods are available for the parameters that are
6515 included in the proposals for the technical requirements (note: the list is non-exhaustive):

6516

6517 • Sampling

6518 EN 1482-1: Fertilizers and liming materials – sampling and sample preparation – part 1:
6519 sampling and part 2: sample preparation

6520 EN ISO 10249: fluid fertilizers – preliminary visual inspection and preparation of
6521 samples for physical testing

6522 2. pr EN 1482-3 : Fertilizers and liming materials – sampling and sample preparation –
6523 Part 3: sampling of static heaps

- 6524 CEN/TR 17040: Fertilizers and liming materials - Sampling of static heaps - Technical
6525 report on experimental sampling trials performed under mandate M/454
6526
- 6527 • Total phosphorus
 - 6528 EN 15956: Extraction of phosphorus soluble in mineral acids and,
 - 6529 EN 15959: Fertilizers - Determination of extracted phosphorus
 - 6530 EN 16173: Sludge, treated bio-waste and soil - Digestion of nitric acid soluble fractions
 - 6531 of elements
 - 6532 EN 16174: Sludge, treated bio-waste and soil - Digestion of aqua regia soluble fractions
 - 6533 of elements
 - 6534 CEN/TS 16170: Sludge, treated bio-waste and soil – Determination of elements using
 - 6535 inductively coupled plasma optical emission spectroscopy (ICP-OES)
 - 6536 CEN/TS 16171: Sludge, treated bio-waste and soil – Determination of elements using
 - 6537 inductively coupled plasma mass spectroscopy (ICP-MS)
 - 6538
 - 6539 • Macroscopic impurities
 - 6540 CEN/TS 16202: Sludge, treated bio-waste and soil - Determination of impurities and
 - 6541 stones
 - 6542
 - 6543 • Biological pathogens
 - 6544 CEN/TR 16193: Sludge, treated bio-waste and soil – detection and enumeration of E.
 - 6545 Coli
 - 6546 CEN/TR 15214-1: Characterization of sludges - Detection and enumeration of
 - 6547 Escherichia coli in sludges, soils, soil improvers, growing media and bio-wastes - Part 1:
 - 6548 Membrane filtration method for quantification
 - 6549 CEN/TR 15214-2: Characterization of sludges - Detection and enumeration of
 - 6550 Escherichia coli in sludges, soils, soil improvers, growing media and bio-wastes - Part 2:
 - 6551 Miniaturised method (Most Probable Number) by inoculation in liquid medium
 - 6552 CEN/TR 15214-3: Characterization of sludges - Detection and enumeration of
 - 6553 Escherichia coli in sludges, soils, soil improvers, growing media and bio-wastes - Part 3:
 - 6554 Macromethod (Most Probable Number) in liquid medium
 - 6555 EN 15788:2009: Animal feeding stuffs - Isolation and enumeration of Enterococcus (E.
 - 6556 faecium) spp.
 - 6557 prEN 15788 rev: Animal feeding stuffs: Methods of sampling and analysis - Isolation and
 - 6558 enumeration of Enterococcus (E. faecium) spp.
 - 6559 EN ISO 7899-2:2000: Water quality - Detection and enumeration of intestinal enterococci
 - 6560 - Part 2: Membrane filtration method (ISO 7899-2:2000)
 - 6561 CEN/TR 15215-1: Characterization of sludges - Detection and enumeration of Salmonella
 - 6562 spp. in sludges, soils, soil improvers, growing media and bio-wastes - Part 1: Membrane
 - 6563 filtration method for quantitative resuscitation of sub-lethally stressed bacteria (to confirm
 - 6564 efficacy of log drop treatment procedures)
 - 6565 CEN/TR 15215-2: Characterization of sludges - Detection and enumeration of Salmonella
 - 6566 spp. in sludges, soils, soil improvers, growing media and bio-wastes - Part 2: Liquid

- 6567 enrichment method in selenite-cystine medium followed by Rapport-Vassiliadis for semi-
6568 quantitative Most Probable Number (MPN) determination.
- 6569 CEN/TC 308 CEN/TR 15215-3: Characterization of sludges - Detection and
6570 enumeration of Salmonella spp. in sludges, soils, soil improvers, growing media and bio-
6571 wastes - Part 3: Presence/absence method by liquid enrichment in peptone-novobiocin
6572 medium followed by Rapport-Vassiliadis
- 6573 EN ISO 14189:2016: Water quality - Enumeration of Clostridium perfringens - Method
6574 using membrane filtration (ISO 14189:2013)
- 6575 EN ISO 7937:2004: Microbiology of food and animal feeding stuffs - Horizontal method
6576 for the enumeration of Clostridium perfringens - Colony-count technique (ISO
6577 7937:2004)
- 6578 USEPA. Test Method for Detecting, Enumerating, and Determining the Viability of
6579 Ascaris Ova in Sludge. 1999. pp. 616–622. (*Note: not an international standard*)
- 6580
- 6581 • Total organic carbon and hydrogen
- 6582 EN 15936: Sludge, treated bio-waste, soil and waste - Determination of total organic
6583 carbon (TOC) by dry combustion
- 6584 ISO 29541: Determination of total carbon, hydrogen and nitrogen in coal and coke by
6585 instrumental methods.
- 6586 ISO 925: Determination of carbonate carbon content -- Gravimetric method (*Note:*
6587 *determination of inorganic carbon; total organic carbon can then be calculated as the*
6588 *difference between total carbon minus total inorganic carbon*).
- 6589
- 6590 • Moisture content and dry matter content
- 6591 EN 12048:1996: Solid fertilizers and liming materials - Determination of moisture
6592 content - Gravimetric method by drying at (105 +/- 2)°C (ISO 8190:1992 modified)
- 6593 ISO/DIS 19745: Fertilizers and soil conditioners -- Determination of crude (free) water
6594 content of ammoniated phosphate products -- DAP, MAP -- by gravimetric vacuum oven
6595 at 50 °C.
- 6596 EN 13466-1: Fertilizers - Determination of water content (Karl Fischer methods) - Part 1:
6597 Methanol as extracting medium
- 6598 EN 14787: Fertilizers and liming materials - Determination of water content - Guidelines
6599 and recommendations
- 6600 EN 13040: Soil improvers and growing media - Sample preparation for chemical and
6601 physical tests, determination of dry matter content, moisture content and laboratory
6602 compacted bulk density
- 6603 EN 15934: Sludge, treated bio-waste, soil and waste - calculation of dry matter fraction
6604 after determination of dry residue or water content
- 6605
- 6606 • Persistent organic pollutants
- 6607 CEN/TS 16181: Sludge, treated bio-waste and soil - Determination of polycyclic aromatic
6608 hydrocarbons (PAH) by gas chromatography (GC) and high performance liquid

- 6609 EN 15527: Characterization of waste - Determination of polycyclic aromatic
6610 hydrocarbons (PAH) in waste using gas chromatography mass spectrometry (GC/MS)
6611 ISO 13877: Soil quality -- Determination of polynuclear aromatic hydrocarbons --
6612 Method using high -performance liquid chromatography
6613 EN 16181: Soil, treated bio-waste and sludge - Determination of polycyclic aromatic
6614 hydrocarbons (PAH) by gas chromatography (GC) and high performance liquid
6615 chromatography (HPLC)
6616 CEN/TS 16190: Sludge, treated bio-waste and soil - Determination of dioxins and furans
6617 and dioxin-like polychlorinated biphenyls by gas chromatography with high resolution
6618 mass selective detection (HR GC-MS)
6619 prEN 16190: Soil, treated bio-waste and sludge - Determination of dioxins and furans and
6620 dioxin-like polychlorinated biphenyls by gas chromatography with high resolution mass
6621 selective detection (HR GC-MS)
6622
- 6623 • Metals and metalloids
 - 6624 EN 16173: Sludge, treated bio-waste and soil - Digestion of nitric acid soluble fractions
6625 of elements
 - 6626 EN 16170: Sludge, treated bio-waste and soil - Determination of elements using
6627 inductively coupled plasma optical emission spectrometry (ICP-OES)
 - 6628 EN 16171: Sludge, treated bio-waste and soil - Determination of elements using
6629 inductively coupled plasma mass spectrometry (ICP-MS)
 - 6630 EN ISO 16968: Solid biofuels - Determination of minor elements
 - 6631 EN 16319: Fertilizers – Determination of trace elements – determination of cadmium,
6632 chromium, lead and nickel by inductively coupled plasma-atomic emission spectrometry
6633 (ICP-AES) after aqua regia dissolution
 - 6634
 - 6635 • Chlorine
 - 6636 EN 16195: Fertilizers - Determination of chlorides in the absence of organic material
6637 ISO 587: Solid mineral fuels – Determination of chlorine, Eschka method
6638
 - 6639 • Neutralising value
 - 6640 EN 12945: Determination of neutralizing value
6641
 - 6642 • Determination of the pH value
 - 6643 EN 13037: Soil improvers and growing media – determination of pH
6644 EN 15933: Sludge- treated biowaste and soil – determination of pH
6645
6646

6647 **5.8 Other EU legislation of interest**

6648 A list of relevant EU legislation in relation with fertilising products is available in Annex V
6649 of the proposal for the Revised Fertiliser Regulation. STRUBIAS materials that are in line
6650 with the recovery rules may become CMCs in the Revised Fertiliser Regulation and thus be
6651 used as ingredients for fertilising products. Additionally, the producers of the STRUBIAS
6652 materials may have to comply, amongst other, with EU legislation related to **waste**
6653 **management and shipment** (e.g. Waste Framework Directive - 2008/98/EC; Waste
6654 Shipment Regulation - 96/61/EC), **animal by-products and derived materials** (e.g.
6655 Regulation (EC) No 1069/2009, Regulation (EU) 142/2011, see also section 5.3.5),
6656 **containment of emissions to the environment** (e.g. Industrial Emissions Directive -
6657 2010/75/EU, Surface Water Directive 75/440/EEC, Air Quality Directive – 2008/50/EC,
6658 Nitrates Directives - 91/676/EEC), **control of hazards** (e.g. council Directive 96/82/EC on
6659 the control of major-accident hazards involving dangerous substances), **safety of workers**
6660 during production processes (e.g. Council Directive 2013/59/Euratom of 5 December 2013
6661 laying down basic safety standards for protection against the dangers arising from exposure
6662 to ionising radiation) and **transport** (e.g. Directive 2006/94/EC of the European Parliament
6663 and of the Council of 12 December 2006 on the establishment of common rules for certain
6664 types of carriage of goods by road).

6665 STRUBIAS materials will likely **become products** when used as substances on their own or
6666 in mixtures with other CMCs when compliant with all requirements laid down for the
6667 corresponding PFC, and their placing on the market, application and use shall then have to
6668 comply with the legal framework of the **CLP Regulation** ("Classification, Labelling and
6669 Packaging", Regulation (EC) No 1272/2008) and **REACH Regulation (EC) No 1907/2006**.

6670 Finally, any STRUBIAS materials applied on land will have to comply with all legislation
6671 related to **nutrient use and management in crop and livestock production** (e.g. CAP –
6672 Common Agricultural Policy), **biodiversity** (e.g. Habitats Directive (92/43/EEC)), and
6673 **containment of water pollution** (e.g. Water Framework Directive, 2000/60/EC).

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PART B: MARKET STUDY

DRAFT - WORK IN PROGRESS

6676 6 Agronomic efficiency

6677 6.1 Introduction

6678 Knowledge of the agronomic efficiency of STRUBIAS materials is critical to evaluate the
6679 added value of STRUBIAS materials in the revised Fertiliser Regulation. Moreover, it is also
6680 the key starting point in any assessment of the following impacts:

- 6681 • environment & human health impacts: the application rates for STRUBIAS fertilisers
6682 needed to achieve the same agronomic yields relative to typical present-day fertilising
6683 products will depend on the fertiliser efficiency. The contaminant load associated to
6684 the use of STRUBIAS materials is thus not only depend on the concentration of the
6685 contaminants in the material, but also on the agronomic efficiency;
- 6686 • market impact: the price setting and development of the market share of any
6687 STRUBIAS materials will depend on what agronomic value they provide to the user,
6688 compared to alternative fertilising materials on the market.

6689
6690 In this section, the agronomic value of fertilising products containing recovered materials is
6691 evaluated for **different soils and plant types prevalent in the European context**. For this
6692 purpose, meta-analyses were performed that assessed the **fertiliser efficiency** of fertilisers
6693 derived from STRUBIAS materials. The term meta-analysis refers to **a statistical analysis of**
6694 **combined data from a series of well-conducted primary studies, in order to obtain a**
6695 **more precise estimate that reduces the size of the confidence interval of the underlying**
6696 **“true effect” in comparison to any individual study** (Pogue and Yusuf, 1998; Garg et al.,
6697 2008). Meta-analysis techniques enable establishing whether the scientific findings are
6698 **consistent and generalisable** across settings and facilitate understanding the reasons why
6699 some studies differ in their results. For these reasons, a meta-analysis of similar, well-
6700 conducted, randomized, controlled trials has been considered one of the highest levels of
6701 evidence (Garg et al., 2008).

6702

6703 6.2 P-fertilisers containing STRUBIAS materials

6704 6.2.1 Meta-analysis approach

6705 In the proposal for the Revised EU Fertiliser Regulation, **mined and synthetic inorganic**
6706 **fertilisers are considered in the PFC 1**. The overall share of these materials is included in
6707 the category "Straight solid inorganic macronutrient fertiliser" and "Compound solid
6708 inorganic macronutrient fertiliser". A P₂O₅ lower limit value of 12% is considered for the first
6709 category, whereas the second category requires a minimum P₂O₅ content of 3% P₂O₅ plus the
6710 presence of one of the other considered plant macronutrients (K₂O, MgO, N, CaO, SO₃, or
6711 Na₂O). Solid organic (> 15% organic C) and organo-mineral (> 7.5% organic C) P-fertilisers
6712 require a minimum P₂O₅ content of 2% (0.9% P). Therefore, **this assessment focuses on**
6713 **STRUBIAS materials that have a minimum P₂O₅ content of > 2%**.

6714

6715 The agronomic efficiency of fertilisers was assessed using two different **plant response**
6716 **variables** (Figure 6):

- 6717 i. **The plant dry matter yield (DMY):** This is the most common response parameter
 6718 documented in studies. Comparing the absolute values for DMY from F_{prim} and F_{sec}
 6719 (referring to P fertilisers derived from primary and secondary raw materials,
 6720 respectively), provides precise information on the different plant biomass responses in
 6721 function of the fertiliser type.
- 6722 ii. **The phosphorus use efficiency (PUE):** Plant P uptake efficiency is calculated as the
 6723 difference in P uptake between fertilised (PU_F) and unfertilised plants (PU_C),
 6724 expressed relative to the amount of fertiliser P applied (P_{applied}):

$$PUE = (PU_F - PU_C) / P_{\text{applied}} = \Delta PU / P_{\text{applied}}$$

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 6726
 6727
 6728 This parameter takes into account that the consumer valuation of P-fertilisers equals
 6729 the marginal yield increase relative to an unfertilised treatment. The disadvantage of
 6730 this parameter is, however, a higher degree of uncertainty due to error propagation
 6731 because unfertilised treatments have to be subtracted during parameter calculation.
 6732 Therefore, only results of pairwise that documented a significant increase in plant
 6733 uptake relative to control for P-fertilisers derived from phosphate rock were taken into
 6734 consideration (see box 2). The exclusion rate, determined as the number of cases that
 6735 were excluded from the original database, is equal for fertilisers derived from primary
 6736 and secondary raw materials, safeguarding an unbiased assessment (see box 2 for
 6737 methodological details).

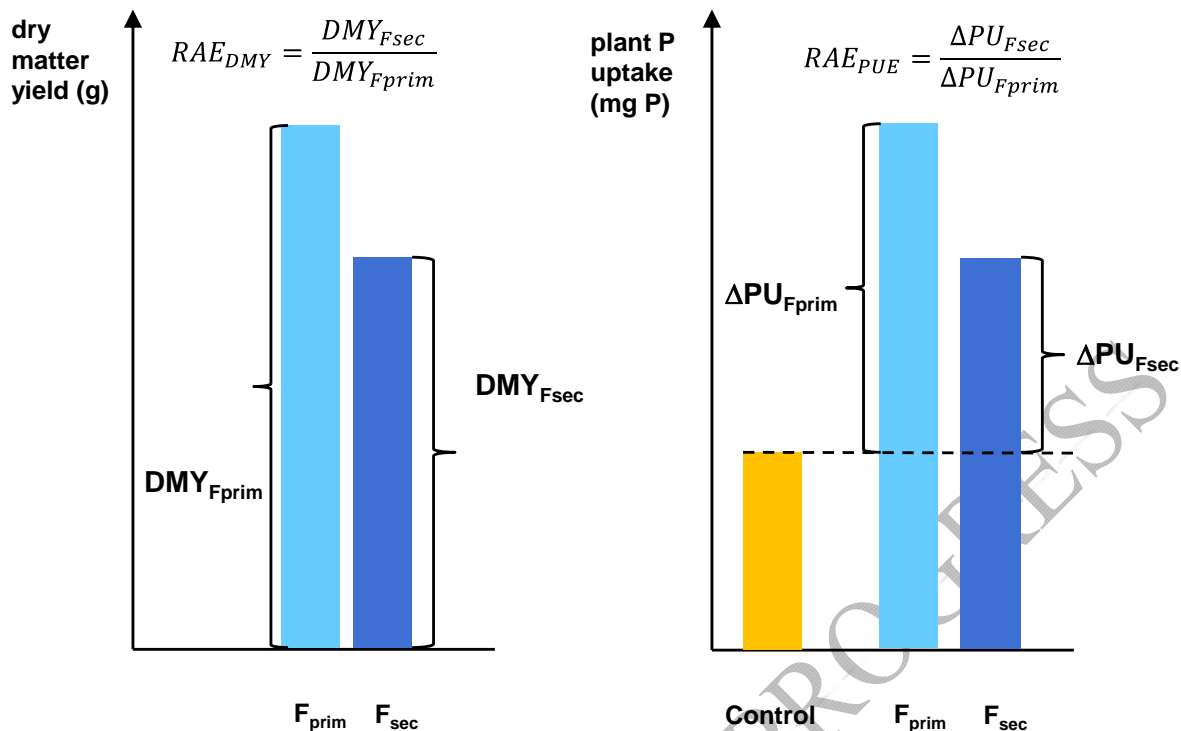
6738
 6739 This study compares plant responses to P fertilisers derived from primary and secondary raw
 6740 materials (F_{prim} and F_{sec}). For F_{sec} , an assessment has been made for each of the three
 6741 STRUBIAS materials. The agronomic efficiency of fertilisers containing STRUBIAS
 6742 materials is expressed relative to mineral P-fertilisers; the resulting ratio is referred to as
 6743 "**relative agronomic efficiency (RAE)**" (Figure 6):

$$RAE_{\text{DMY}} = \text{DMY}_{F_{\text{sec}}} / \text{DMY}_{F_{\text{prim}}}$$

6744
 6745
 6746
 6747
 6748 and

$$RAE_{\text{PUE}} = PUE_{F_{\text{sec}}} / PUE_{F_{\text{prim}}} = \Delta PU_{F_{\text{sec}}} / \Delta PU_{F_{\text{prim}}}$$

6749
 6750
 6751
 6752 Note that the P application rate (P_{applied}) is levelled by dividing $PUE_{F_{\text{sec}}}$ by $PUE_{F_{\text{prim}}}$ to
 6753 calculate RAE_{PUE} .



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Figure 6: Schematic outline of the plant response variables used to calculate the relative agronomic efficiencies RAE_{DMY} and RAE_{PUE} , following treatment with fertilisers from primary materials (F_{prim}) or secondary materials (F_{sec})

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A relative agronomic efficiency value below 1 indicates that that the fertiliser derived from STRUBIAS materials is a less effective plant P-source than a synthetic P-fertiliser derived from mined phosphate rock, and vice versa.

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Data were grouped prior to meta-analysis to enable a broad ranging assessment of fertilising effectiveness of F_{sec} as a function of soil type, plant group, feedstock used for F_{sec} production, and variables related to the experimental design of the study (e.g. fertiliser regime, pot versus field trial, etc.). These parameters that discern groups were referred to as **grouping variables**. The relative agronomic efficiency for both response variables (RAE_{DMY} and RAE_{PUE}) was then calculated for a number of "cases" where all grouping variables (such as soil type and crop grown, crop harvest time, P application rate, etc.) are identical for both fertiliser treatments. Hence, the sole divergent variable for each case is the type of P-fertiliser.

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Results were collected from the information provided by the STRUBIAS sub-group and from scientific literature. The number of studies and "cases" for precipitated phosphate salts, thermal oxidation materials & derivatives and pyrolysis & gasification materials is indicated in Table 8. A significant number of studies were available for precipitated phosphate salts & derivatives and thermal oxidation materials & derivatives, whereas data coverage for pyrolysis & gasification materials was poor. Therefore, no hard conclusions on the agronomic efficiency of pyrolysis & gasification materials could be made. Hence, the **results for pyrolysis & gasification materials provide only a preliminary assessment and should be interpreted**

6782 **with the necessary caution.** The complete methodology and the references to the original
 6783 works used for this study is given in section 17.2 in Annex.

6784

6785 **Table 8: Number of studies and cases included for the meta-analyses on the relative agronomic**
 6786 **efficiency of P-fertilisers derived from precipitated phosphate salts & derivates, thermal**
 6787 **oxidation materials & derivates and pyrolysis & gasification materials.**

	recovered phosphate salts		thermal oxidation materials & derivates		pyrolysis & gasification materials	
	RAE _{DMY}	RAE _{PUE}	RAE _{DMY}	RAE _{PUE}	RAE _{DMY}	RAE _{PUE}
studies	26	19	17	14	8	6
cases	173	104	117	94	31	16

6788

6789

6790 Results are represented as "forest plots" that graphically indicate the RAE_{DMY} (left Figure)
 6791 and RAE_{PUE} (right Figure). The bars cover the 95% confidence interval, so error bars that
 6792 cross the vertical 1 line indicate that F_{sec} is not significantly different from F_{prim} ."

6793

6794 6.2.2 Precipitated phosphate salts & derivates

6795 The overall results indicated a similar agronomic efficiency for precipitated phosphate salts &
 6796 derivates to mined rock phosphate and processed P-fertilisers. The mean values of RAE_{DMY}
 6797 and RAE_{PUE} equal 0.99 and 1.05, respectively (Figure 7), with the corresponding 95%
 6798 confidence intervals overlapping the 1 value for both parameters. Regardless of soil pH, soil
 6799 texture, feedstock, application form, plant type, soil P status, assessment time, and
 6800 experimental design and setting, RAE_{DMY} and RAE_{PUE} values for precipitated phosphate salts
 6801 & derivates were not significantly different from 1. The RAE_{DMY} and RAE_{PUE} for struvite
 6802 and dittmarite were not significantly different from 1, but the 95% confidence interval for
 6803 RAE_{DMY} of calcium phosphates (grouping variable fertiliser) extended to a value marginally
 6804 below 1 (0.995; Figure 7). No significant differences across selected groups were observed at
 6805 the 95% level, albeit the effect of plant type was marginally significant (P: 0.06; data not
 6806 shown) for RAE_{DMY}.

6807

6808 The analysis indicated that the **agronomic efficiency of precipitated phosphate salts is**
 6809 **equal to that of mined and synthetic fertilisers. These results are consistent and**
 6810 **generalisable across different settings, including soil and crop types, relevant for the**
 6811 **European agricultural sector.** Although multi-year assessments fall beyond the scope of
 6812 this meta-analysis, the results of Thompson (2013) and Wilken et al (2015) confirm the
 6813 sustained long-term efficiency of precipitated phosphate salts as a P-fertiliser.

6814

6815 Struvite is the most common precipitated phosphate salt, but some P-recovery processes
 6816 target a **different end-material** such as dittmarite or dicalcium phosphates. The
 6817 crystallization of calcium phosphates may involve the formation of metastable precursor
 6818 phases, such as octocalcium phosphate and hydroxyapatite, which are less available to plants,

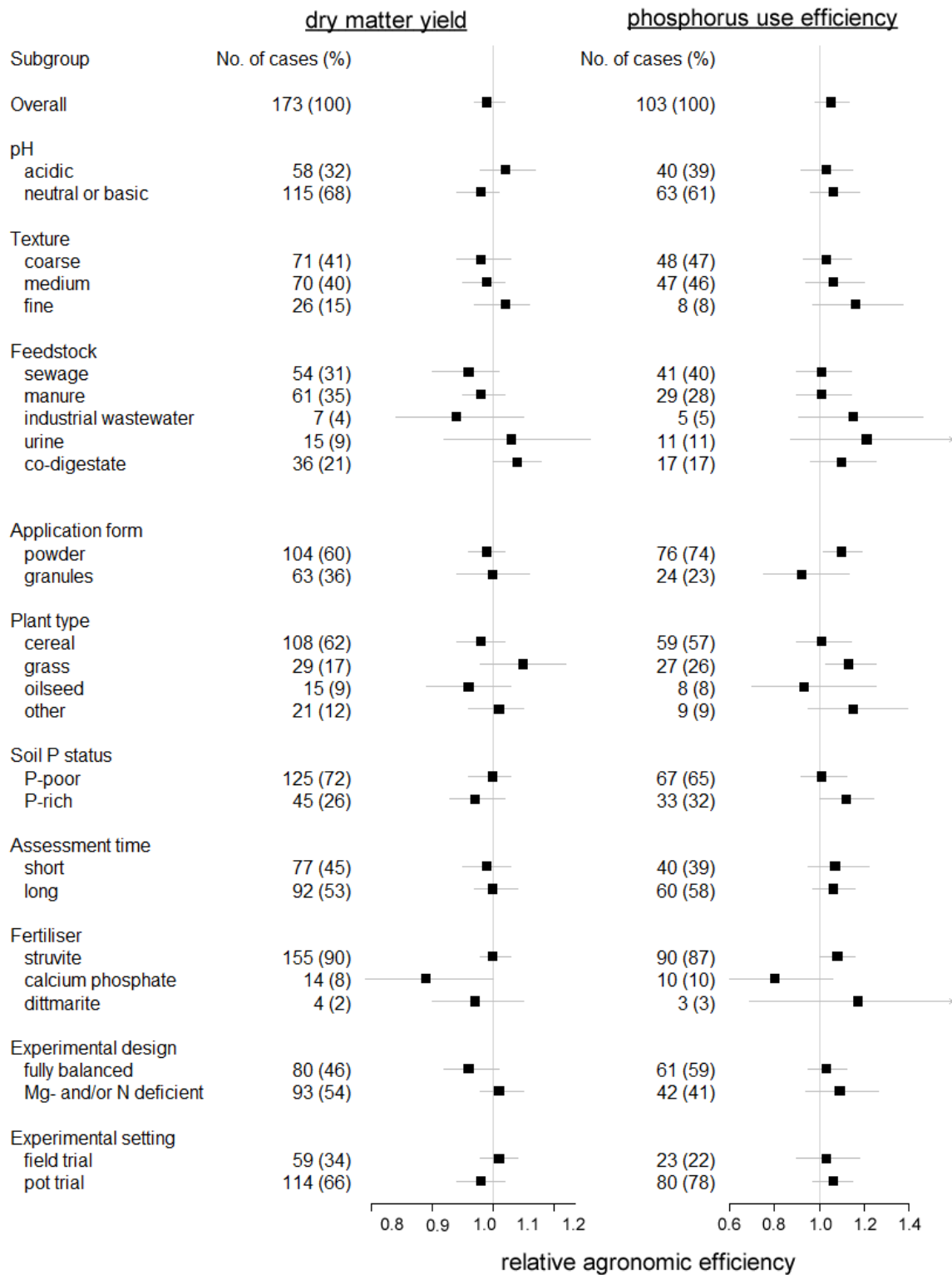
6819 especially at alkaline pH (Wang and Nancollas, 2008). Hence, the RAE of calcium
6820 phosphates can vary depending on the exact composition of the calcium phosphate phases
6821 included in the end-material. After application to the soil, calcium phosphates can also
6822 transform into more stable forms (Arai and Sparks, 2007), potentially further contributing to
6823 the wider RAE ranges observed for calcium phosphates than for struvite and dittmarite.

6824
6825 Unlike most mined and synthetic P-fertilisers, precipitated phosphate salts are water
6826 insoluble, but their solubility is increased in acid solutions (Wilken et al., 2015). Nonetheless,
6827 our results indicated that **soil pH had no significant effect on the relative agronomic**
6828 **efficiency**. Achat et al. (2014a) indicated that isotopically exchangeable P was similar for
6829 finely ground struvite as for triple superphosphate, irrespective of pH in the range 5.2 -8.1.
6830 Talboys et al. (2016) indicated that the short term (<42 days) dissolution of granulated
6831 struvite, the most common precipitated phosphate salt, shows similar dynamics across a
6832 wider soil pH range of 5.0 – 8.0. Degryse et al. (2017) indicated a 60-day granulated struvite
6833 dissolution rate of >80% in an acid soil (pH 5.9), but <10% dissolution in a basic soil (pH
6834 8.5). Hence, as most European soils have a pH between 5 and 8 (Reuter et al., 2008), soil pH
6835 is not expected to exert a major influence over the dissolution patterns of precipitated
6836 phosphate salts and the relative agronomic efficiency. Plants also modify the rhizosphere pH
6837 as they exudate organic acids from their root biomass in significant quantities that can
6838 drastically lower pH in the plant root microenvironment.

6839
6840 Talboys et al. (2016) indicated that organic acids have a major impact on the rate of
6841 dissolution of P from struvite, and that plants with root systems that exude large quantities of
6842 organic acids are more effective at taking up P from struvite granules. The exudates cause the
6843 dissolution of the precipitated phosphate salts in the vicinity of the plant root. Grasses
6844 exudate significantly more organic acids than common crops; estimates for the total
6845 allocation of photosynthates – a proxy for rhizodeposition - to roots are 50-70% higher for
6846 grasses than for cereals such as wheat and barley (Kuzyakov and Domanski, 2000). Hence,
6847 species-specific patterns of root exudation may explain the variations in relative agronomic
6848 efficiencies observed, but the effect of plant type is overall not significant (Fig. 2).

6849

6850



6851

6852 **Figure 7: The relative agronomic efficiency of precipitated phosphate salts & derivatives for the**
 6853 **plant response variables DMY (dry matter yield) and PUE (phosphorus use efficiency) as a**
 6854 **function of grouping variables. Results are presented as weighted mean (square) and 95%**
 6855 **confidence intervals (error bars).**

6856

6857 No significant effect of **assessment time and application form** on the relative agronomic
 6858 efficiency along a single plant growing season was observed for precipitated phosphate salts

6859 (Fig. 2). Although the slower initial P release rate from the granulated fertiliser could
6860 possibly reduce plant uptake of P during the very initial plant growth stages (<36 days;
6861 Degryse et al. 2017; Talboys et al. 2016), studies that applied an assessment time between 36
6862 and 65 days showed good performance when precipitated phosphate salts were applied. For
6863 crops subject to struvite fertilisation, it has been suggested that a reduction in number of
6864 grain heads due to short-term P deficiency is counterbalanced by the crop root system's
6865 capacity to take up P in the later plant growth stages (Talboys et al. 2016). Hence, even for
6866 studies with an assessment time < 65 days, the sustained P release from precipitated
6867 phosphate salts could possibly compensate their lower initial P-availability and their lower P-
6868 dissolution rate relative to water-soluble P-fertilisers (Talboys et al., 2016; Degryse et al.,
6869 2017). The relative agronomic efficiencies for dry matter yield and P use efficiency were not
6870 significantly different from 1 for struvite and dittmarite, but the 95% confidence interval for
6871 calcium phosphates (grouping variable fertiliser) extended to a value marginally below 1 for
6872 dry matter yield (0.995; Fig. 2). Struvite is the most common precipitated phosphate salt, but
6873 some P-recovery processes target a different end-material such as dittmarite or dicalcium
6874 phosphates. The crystallization of calcium phosphates may involve the formation of
6875 metastable precursor phases, such as octocalcium phosphate and hydroxyapatite, which are
6876 less available to plants, especially at alkaline pH (Wang and Nancollas, 2008). Hence, the
6877 relative agronomic efficiency of calcium phosphates can vary depending on the exact
6878 composition of the calcium phosphate phases included in the end-material. After application
6879 to the soil, calcium phosphates can also transform into more stable forms (Arai and Sparks,
6880 2007), potentially further contributing to the wider relative agronomic efficiency ranges
6881 observed for calcium phosphates than for struvite and dittmarite.

6882
6883 In line with the observation that **feedstock** does not have a major impact on the chemical
6884 composition of the precipitated phosphate salts & derivatives, no input material-specific
6885 impacts on RAE were observed.

6886

6887 6.2.3 Thermal oxidation materials & derivatives

6888 **The overall mean effects for thermal oxidation materials & derivatives were 0.92 and 0.81**
6889 **for RAE_{DMY} and RAE_{PUE} , respectively** (Figure 8). The 95% confidence intervals for both
6890 response variables indicated that the agronomic efficiency for thermal oxidation materials &
6891 derivatives was overall lower than for mined and synthetic fertilisers (Figure 8; 95%
6892 confidence intervals do not cross RAE value of 1). The analyses for the different grouping
6893 variables indicated significant effects of feedstock, post-processing groups and assessment
6894 time for RAE_{DMY} and RAE_{PUE} ($P < 0.001$; data not shown). Thermal oxidation materials &
6895 derivatives derived from sewage sludge showed a significantly lower RAE_{DMY} and RAE_{PUE}
6896 than for thermal oxidation materials & derivatives derived from crop residues and poultry litter
6897 (Figure 8), but it should be deliberated that sewage sludge derived thermal oxidation
6898 materials & derivatives include both raw ashes and ashes that have been post-processed. Ashes
6899 that have been post-processed using wet-digestion and thermal manufacturing steps to
6900 improve their plant P-availability and reduce inorganic contaminants showed significantly

6901 greater RAE_{DMY} and RAE_{PUE} than raw sewage sludge ashes (Figure 8). The RAE_{DMY} values
6902 were 1.03 and 0.93 for materials subjected to wet-digestion and thermal post-processing steps
6903 (Figure 8). The RAE of F_{sec} derived from crop residues, poultry litter and pig manure did not
6904 differ from F_{prim} (Figure 8). Thermal oxidation materials & derivatives derived from wood and
6905 steel slags showed a low RAE_{DMY} and RAE_{PUE} , but the results should be interpreted with
6906 precaution because of the low number of cases (Figure 8). A significant effect of assessment
6907 time on RAE_{DMY} and RAE_{PUE} was observed ($P < 0.001$; Figure 8), with values that are 20%
6908 (RAE_{DMY}) and 40% (RAE_{PUE}) lower in the long-term (>65 days) than in the short-term (<65
6909 days). A significant effect of experimental design ($P: 0.04$) and experimental setting ($P:$
6910 0.003) was observed for RAE_{PUE} (Figure 8). No significant effects of soil pH, soil texture,
6911 plant type and soil P status were observed, albeit the effect of soil pH on RAE_{PUE} was
6912 marginally significant ($P: 0.08$) (Figure 8).

6913
6914 Significant differences in the relative agronomic efficiency of thermal oxidation materials &
6915 derivatives were observed, primarily **dependent on the feedstock applied and the possible**
6916 **post-processing steps that were performed**. Thermal oxidation materials & derivatives
6917 consist of P-fertilisers with heterogeneous properties that control their behaviour and
6918 agronomic impacts in soils. Moreover, it should be taken into consideration that this study did
6919 not include fertilising products that are F_{sec} ash-derivates (e.g. Ecophos® process, ICL
6920 RecoPhos® process, acidulation process; see Huygens et al. (2016) and Egle et al. (2016))
6921 of equal chemical composition to that of F_{prim} . For such F_{sec} , an RAE value of 1 can
6922 reasonably be expected. The observed RAE results are not affected by soil pH, soil texture,
6923 application form, or soil P status, and different F_{sec} groups produced from a variety of
6924 feedstocks have an agronomic efficiency that is not significantly different from F_{prim} . Hence,
6925 **these observations validate that thermal oxidation materials & derivatives can deliver an**
6926 **effective alternative for mined rock phosphate and processed P-fertilisers in the**
6927 **European agriculture, but that the RAE is dependent on the properties of the produced**
6928 **end-material**.

6929
6930 The impact of pH on the P-dissolution depends on the elemental composition of the P-
6931 fertiliser because P is strongly bonded to Ca at high pH and to Fe and Al at low pH (Hinsinger,
6932 2001; Tóth et al., 2014). Nonetheless, the high basic cation contents of some thermal
6933 oxidation materials might **buffer the acidity effect of the soil micro-environment, thus**
6934 **obscuring the effect of the soil pH**. Also, no consistent differences were observed in relative
6935 agronomic efficiency across plant types for the response variables, indicating that possible
6936 differences in root exudation patterns of organic acids are not meaningfully impacting the P-
6937 release patterns from thermal oxidation materials & derivatives.

6938
6939 The RAE varies considerably as a function of **feedstock, but these results require a**
6940 **cautionary interpretation as sample sizes are low for most groups, other than sewage**
6941 **sludge**. Crop residues show a high RAE value, but it should be considered that most results
6942 are derived from three studies that used a similar soil type (Schiemenz and Eichler-
6943 Löbermann, 2010; Schiemenz et al., 2011; Delin, 2016). For sewage sludge ashes, a post-
6944 processing step is often applied to increase P-availability, and to comply with legislative limit

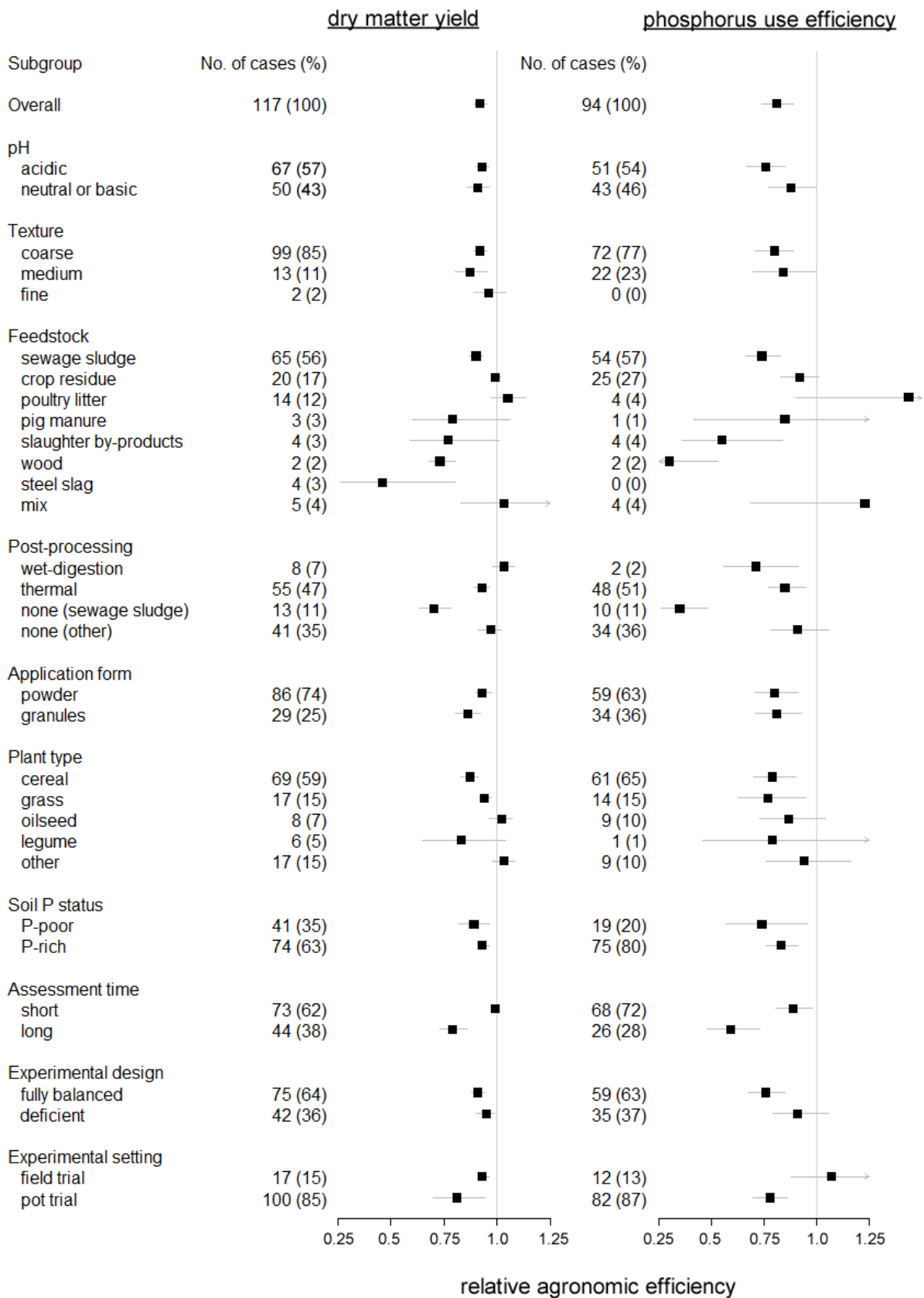
6945 values for metals and metalloids. This analysis confirms that such **manufacturing processes**
6946 **starting from sewage sludge mono-incineration ashes clearly improve the plant**
6947 **availability relative to unprocessed sewage sludge ashes, and enable the transformation**
6948 **of sewage sludge ashes into efficient P-fertilisers.** Relative agronomic efficiencies close to
6949 1 can reasonably be expected materials resulting from wet-digestion post-processing,
6950 especially for these that have an equal chemical composition to that of mined rock phosphate
6951 and processed P-fertilisers. Thermal post-processing steps aim at separating P from other
6952 elements and to influence the crystal structure of the materials by isomorphic substitution of
6953 the PO_4^{3-} ionic group (by for example SiO_4^{2-} or CO_3^{2-}) affecting the reactivity of the final
6954 product and therefore plant P availability. The final products show similar characteristics as
6955 Thomasphosphate and Rhenaniaphosphate, and show overall good fertiliser efficiency.

6956
6957 Thermal oxidation materials and derivatives **perform better in short-term experiments than**
6958 **in long-term studies** (> 65 days) (Figure 8). The plant-availability of the P in P-fertilisers is
6959 likely controlled by the coordinated cations of Ca, Mg Al and Fe to which PO_4^{3-} is bound. All
6960 these different ions are abundantly present in thermal oxidation materials & derivatives,
6961 although their relative abundance varies across end-materials. Complexes between phosphate
6962 and K, Ca, Mg, and S ions are relatively easily decomposed (Hinsinger, 2001; Tóth et al.,
6963 2014), and this more labile P-fraction is therefore likely to be released in the short term.
6964 Phosphate may, however, be unavailable to plants when strongly bound to particular trivalent
6965 cations in a stable matrix (Barrow, 1984; Hinsinger, 2001). The release of P from this more
6966 stable fraction could be limited, effectively decreasing the long-term P supply from thermal
6967 oxidation materials & derivatives. This contrasts with mined and synthetic fertilisers that are of
6968 a uniform chemical composition; such fertilisers can be expected to release P readily upon
6969 physical disintegration. The released P that is not readily taken up by plants can be adsorbed
6970 to soil minerals, with the nature of such reactions dependent on the pH and on the
6971 concentration of metal cations such as Ca, Fe and Al as well as organic and inorganic ligands
6972 (Hinsinger, 2001; Tóth et al., 2014). At a later time in the plant growing season, desorption of
6973 sorbed P can occur via ligand exchange reactions, especially if the P was bound in more
6974 labile soil P-complexes (Hinsinger, 2001). Such desorption processes could effectively
6975 contribute to a better long-term effect of mined rock phosphate and processed P-fertilisers
6976 compared to thermal oxidation materials & derivatives rich in trivalent cations.

6977
6978 Studies that supply primary and secondary macronutrients together with mined rock
6979 phosphate and processed P-fertilisers to ensure the equal supply of all different plant nutrients
6980 across treatments show a somewhat reduced relative agronomic efficiency, especially when
6981 PUE is considered as a response variable. On the other hand, results for the field studies
6982 performed in more realistic settings than those of pot experiments show better results. Both
6983 effects are potentially related, as field studies often apply a deficient experimental design
6984 where the broad range of secondary macronutrients and micronutrients present in thermal
6985 oxidation materials & derivatives are not added in the mined and synthetic P-fertiliser
6986 treatment. Hence, **these results indicate the importance of secondary macronutrients and**
6987 **micronutrients in achieving optimal agricultural yields.** It is often challenging to evaluate
6988 the supplementary fertiliser need for particular plant-limiting elements within the broad

6989 spectrum of secondary macronutrients and micronutrients. On condition that the excess
6990 application of micronutrients is avoided, the application of thermal oxidation materials &
6991 derivatives as P-fertilisers could provide the complementary benefit of supplying secondary
6992 macronutrients and micronutrients to enhance agronomic yields.
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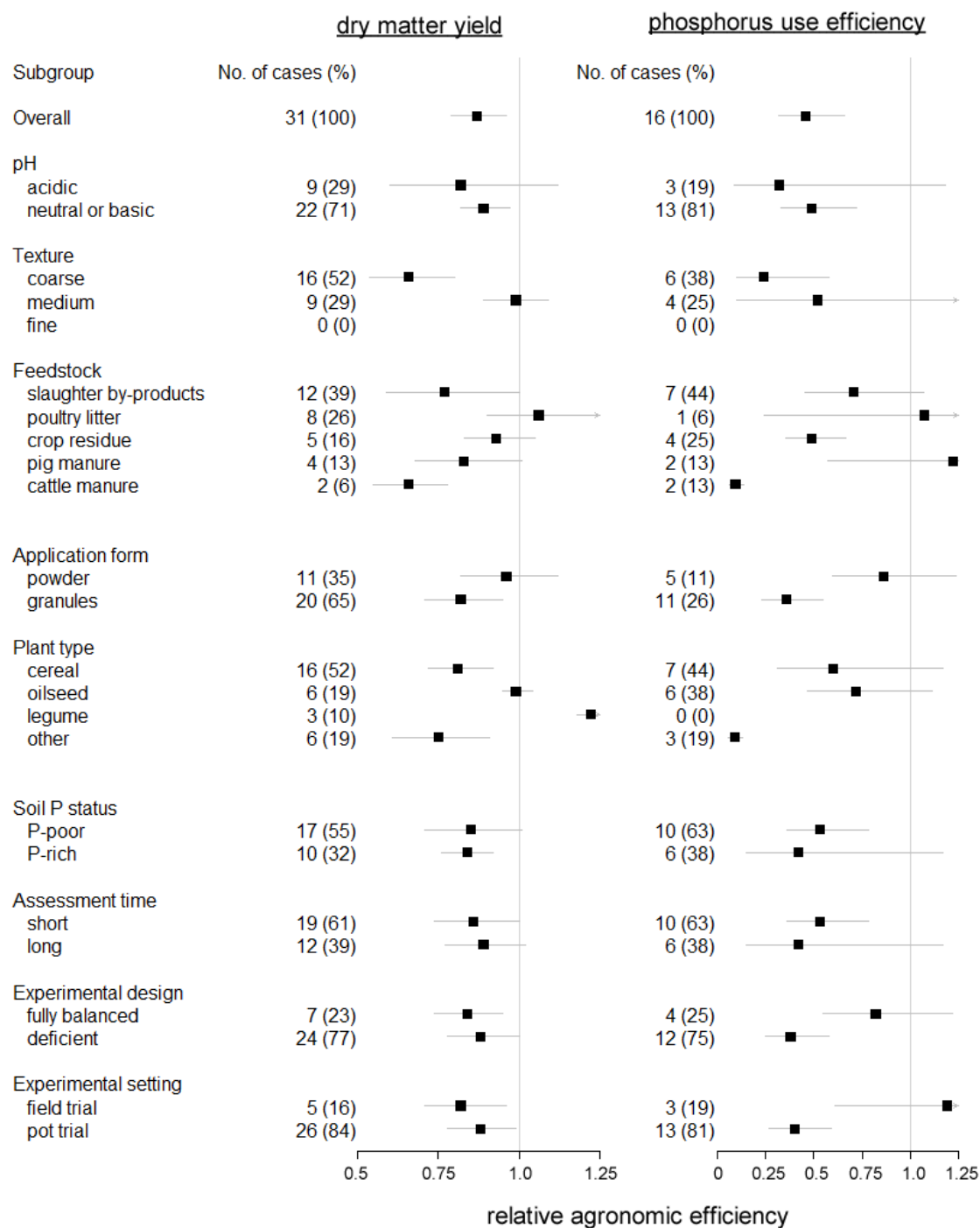
Figure 8: The relative agronomic efficiency of thermal oxidation materials & derivatives for the plant response variables DMY (dry matter yield) and PUE (phosphorus use efficiency) as a function of grouping variables. Results are presented as weighted mean (square) and 95% confidence intervals (error bars).

6999 6.2.4 Pyrolysis & gasification materials

7000 **The overall mean effects for pyrolysis & gasification materials were 0.87 and 0.46 for**
7001 **RAE_{DMY} and RAE_{PUE}, respectively** (Figure 9). The analyses for each of the grouping
7002 variables was constrained by the number of studies available; only the RAE values for neutral
7003 and basic soils and for pyrolysis & gasification materials that were applied in granulated form
7004 were derived from a minimum of 4 different studies and a number of cases greater than 10 for
7005 both response variables (RAE_{DMY} and RAE_{PUE}; Figure 9). For these groups, the RAE_{DMY} and
7006 RAE_{PUE} values pointed towards a significantly lower agronomic efficiency than for mined
7007 rock phosphate and processed P-fertilisers. The significant differences of specific groups such
7008 as those varying in soil texture (RAE_{DMY}), feedstock (RAE_{PUE}), application form (RAE_{PUE}),
7009 plant type (RAE_{DMY} and RAE_{PUE}), experimental design and setting (RAE_{PUE}) should be
7010 interpreted with caution because some of the contrasting groups have a low number of cases,
7011 often originating from a few studies. Therefore, only a marginal reduction of the size of the
7012 confidence interval of the underlying “true effect” across groups could be achieved,
7013 compared to the results from individual studies by applying the meta-analysis techniques.
7014 Hence, no conclusions can be drawn on RAE across pyrolysis & gasification materials
7015 applied to different soil types, feedstocks, application form and plant types. Figure 9 enables,
7016 nevertheless, a standardised visual assessment of the RAE ranges observed across selected
7017 studies.

7018
7019 **Given the small sample size for pyrolysis & gasification materials, it is not pertinent to**
7020 **draw overarching conclusions for pyrolysis & gasification materials from the available**
7021 **data.** The properties of pyrolysis & gasification materials can vary widely, depending on the
7022 interactive effects between production process conditions and feedstock applied. Many
7023 groups, including pyrolysis & gasification materials derived from slaughter by-products,
7024 poultry litter, crop residues and pig manure, display an agronomic efficiency that is not
7025 significantly different from F_{prim} . The sole groups for which a relatively large number of data
7026 are available (at least 4 different studies and > 10 cases) are neutral and basic soils and
7027 pyrolysis & gasification materials that have been applied in granulated form. For these
7028 groups, a lower agronomic efficiency than for mined rock phosphate and processed P-
7029 fertilisers is observed. Potentially, some of the documented high agronomic efficiencies after
7030 PY addition could be the result of a liming effect that increases soil P availability (Hass et al.,
7031 2012), or the result of the milling of the pyrolysis material that increases the P solubility in
7032 the otherwise stable pyrolysis matrix (Ma and Matsunaka, 2013). Therefore, future studies
7033 should focus on assessing the mechanisms that underlie documented potential positive plant
7034 responses, and evaluate the agronomic efficiency of pyrolysis & gasification materials in the
7035 same physical form as it will be applied under actual settings in agriculture. It is concluded
7036 that the current available data does not enable a comprehensive assessment of the agricultural
7037 efficiency of P-rich pyrolysis & gasification materials in relevant European agricultural
7038 settings, and that plant responses for P-rich pyrolysis & gasification materials can vary
7039 widely depending on the feedstock and production conditions of the pyrolysis & gasification
7040 materials, as well as on the soil and plant type under fertilisation.

7041



7043

7044 **Figure 9: The relative agronomic efficiency of pyrolysis & gasification materials for the plant**
 7045 **response variables DMY (dry matter yield) and PUE (phosphorus use efficiency) as a function**
 7046 **of grouping variables. Results are presented as weighted mean (square) and 95% confidence**
 7047 **intervals (error bars).**

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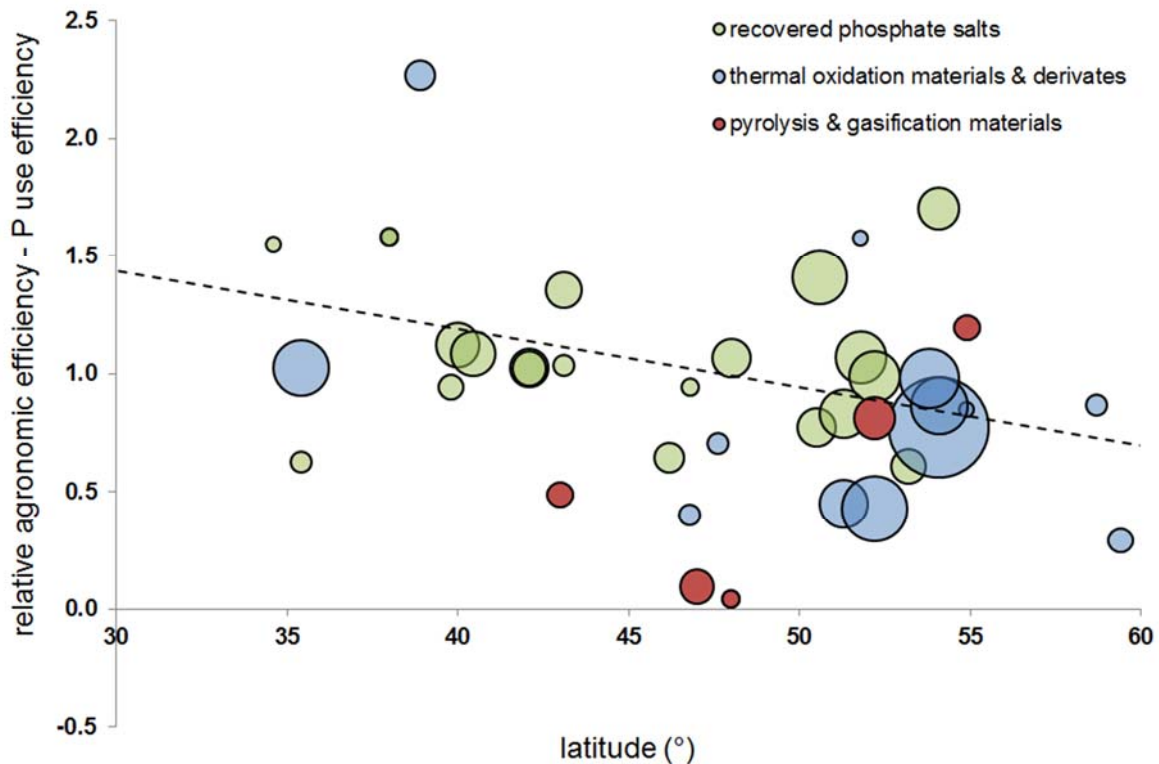
7049 6.2.5 Geographic scattering

7050 The results provided give an overview of the relative agronomic efficiency as a function of
 7051 soil and plant type, but fail to take into consideration the interactions and combinations of
 7052 those variables that occur in different geographic regions in Europe. Especially the effect of

7053 the north–south position (i.e. latitude of the geographic coordinates) is relevant to consider,
7054 given that climate conditions (colder and drier soils at higher latitudes), soil texture (sandier
7055 at higher latitudes), and soil pH (more basic at lower latitudes) vary significantly across this
7056 gradient (Panagos et al., 2012; Ballabio et al., 2016). **A significant negative correlation**
7057 **between geographic latitude on RAE_{PUE} was indicated ($P: 0.02$), with greater RAE_{PUE}**
7058 **values observed in sites of lower latitudes than in higher latitudes** (Figure 10). Latitude
7059 explained, nonetheless, only a minor share of the total variance observed ($R^2_{adj}: 0.14$). It
7060 should, however, be noted that the assessment includes both pot and field studies, and that
7061 some variables, especially climate conditions, may not be accurately represented in pot
7062 experiments. Therefore, the results should be interpreted with the necessary precaution.

7063
7064 Concerns related to the effectiveness of water insoluble P-fertilisers in semi-arid and
7065 Mediterranean regions may exist because some slow release P-fertilisers, such as phosphate
7066 rock and meat and bone meal, do not dissolve readily in such soils (Bolland and Gilkes, 1990;
7067 Elliott et al., 2007). The results of our work, however, reject such expectations for P-
7068 fertilisers containing STRUBIAS materials in European settings as the RAE_{PUE} correlated
7069 negatively to latitude (Figure 10). Therefore, **the effectiveness of F_{sec} for semi-arid and**
7070 **Mediterranean European regions is suggested**. The soil moisture patterns probably have a
7071 negligible impact on the solubility of P-fertilisers containing STRUBIAS materials, as these
7072 have a low water-soluble P fraction. Their solubility is mainly determined by the extent of
7073 root exudation of the plants grown on the agricultural field. It can, however, be expected that
7074 the solubility of water-soluble P-fertilisers is increased in the more northern latitudes
7075 characterised by more moist soils due to the increased precipitation. Therefore, the agronomic
7076 efficiency of mined rock phosphate and processed P-fertilisers could be higher for the higher
7077 latitudes, resulting in decreased RAE ratios in the more northern regions. Other soil
7078 properties that vary across latitude, such as soil texture and soil pH, did not have a significant
7079 effect on the RAE for the STRUBIAS materials under study.

7080



7081

7082 **Figure 10: Bubble plot indicating the relationship between RAE_{PUE} and latitude. The size of the**
 7083 **bubbles represents the number of cases and relative weight for each data pair.**

7084

7085 6.3 C-rich pyrolysis & gasification materials

7086 The addition of pyrolysis & gasification materials to soils induces a series of changes in the
 7087 plant mycorrhizosphere that can promote (e.g. augmented soil fertility, increased soil water
 7088 holding capacity, physical protection for plant-growth promoting microorganisms) or reduce
 7089 (e.g. addition phytotoxic volatile organic compounds, nutrient immobilisation, water
 7090 retention) plant growth and nutrient uptake. The interaction between positive and negative
 7091 effects determines the effect on plant yield and plant nutrient uptake, and thus the possible
 7092 benefit to the farmer. Meta-analysis results have summarised the effect of the application of
 7093 pyrolysis materials relative to control soils that were unamended. A recent meta-analysis for
 7094 C-rich pyrolysis & gasification materials indicated that, on average, C-rich pyrolysis &
 7095 gasification materials did not increase plant yields relative to unfertilised control sites (Jeffery
 7096 et al., 2017). The study was based on 598 cases documented in 44 different studies from
 7097 temperate regions. It was observed that **C-rich biochar amendment to soils in temperate**
 7098 **regions significantly decreased crop yield relative to controls (i.e. soils that did not**
 7099 **receive any fertilising materials)**, averaging approximately 3% at a median biochar
 7100 application rate of 30 t ha⁻¹. For temperate regions, only positive effects for pyrolysis &
 7101 gasification materials were observed at an application rate of 31-50 tonne ha⁻¹. Lower
 7102 application rates (312 pairwise comparison; 52% of all data) did not show any significant
 7103 differences relative to control soils, whereas higher application rates (224 pairwise
 7104 comparisons, 37% of the data) showed at times even negative impacts on plant yields. These
 7105 results of Jeffery et al. (2017) are in line with the results found for temperate regions by

7106 Biederman and Harpole (2013). Jeffery et al. (2017) indicated that many arable soils in
7107 temperate regions are moderate in pH, high in fertility, and generally receive high fertiliser
7108 inputs, leaving little room for additional benefits from C-rich pyrolysis & gasification
7109 materials. Their work indicated positive impacts of the application of pyrolysis & gasification
7110 materials for soils with an organic C level <1%. Although such soils are mostly absent in
7111 Europe (de Brogniez et al., 2015), this observation may point towards the possible added
7112 value of pyrolysis & gasification materials in soilless growing media.
7113

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7114 **7 Market aspects and outlook for the year 2030**

7115 This section gives an overview of the current (section 7.1) and projected future market
7116 (section 7.3) for STRUBIAS materials, as well as for mined phosphate rock and processed P-
7117 fertilisers (section 7.2). In the proposal for the Revised EU Fertiliser Regulation, fertilising
7118 products are classified in product function categories (PFCs) that are in line with their
7119 intended function. Given the different intended uses for these STRUBIAS materials, this
7120 document is structured into different **sub-sections that cover uses of such materials in P-**
7121 **fertilisers (section 7.2 and 7.3) or in liming materials, soils improvers, growing media**
7122 **and plant biostimulants (section 7.4)**. The sections 0 and 7.3 on P-fertilisers cover materials
7123 with a minimum P-content of 3% and 2% P₂O₅, the P-threshold values for inorganic and
7124 organic/organo-mineral P-fertilisers, respectively. Market aspects for materials with a lower
7125 P-content are covered in section 7.4.

7126

7127 **7.1 Current STRUBIAS market**

7128 7.1.1 Precipitated phosphate salts

7129 Currently, best estimates summing production volumes of the different plants suggest that
7130 **about 15 000 tonnes of struvite** are produced each year in Europe. Existing facilities mainly
7131 use municipal waste waters as input material, although also industrial waste waters (potato
7132 industry, pharmaceutical industry, dairy industry) and manure and livestock stable slurries are
7133 used as input materials (Kabbe et al., 2017; Ehlert et al., 2016a). Additionally, substantial
7134 amounts of struvite are produced outside Europe (USA, Japan, China) (Kabbe, 2017).

7135
7136

Table 9: Overview of facilities that produce precipitated phosphate salts in the European Union (data adopted from Kabbe, 2017 and Ehlert et al., 2016a)

Technology	recovered P-salt	input material	Location and operator	year of initiation
AirPrex®	struvite	municipal waste water	MG-Neuwerk (DE), Niersverband	2009
AirPrex®	struvite	municipal waste water	Wassmannsdorf (DE), Berliner Wasserbetriebe	2010
AirPrex®	struvite	municipal waste water	Echten (NL), Drents Overijsselse Delta	2013
AirPrex®	struvite	municipal waste water	Amsterdam-West (NL), Waternet	2014
AirPrex®	struvite	municipal waste water	Uelzen (DE), SE Uelzen	2015
AirPrex®	struvite	municipal waste water	Salzgitter Nord (DE), ASG	2015
AirPrex®	struvite	municipal waste water	Wolfsburg (DE), SE Wolfsburg	2016
ANPHOS	struvite	municipal waste water	Land van Cuijk (NL), Aa en Maas	2011
EloPhos®	struvite	municipal waste water	Lingen (DE), SE Lingen	2016
EXTRAPHOS (Budenheim)	DCP	municipal waste water	MZ-Mombach (DE), Wirtschaftsbetrieb Mainz	2017
Gifhorn	struvite/CaP	municipal waste water	Gifhorn (DE), ASG	2007
NASKEO	struvite	municipal waste water	Castres (FR)	2015
NuReSys®	struvite	waste water (potato industry)	Harelbeke (BE), Agristo	2008
NuReSys®	struvite	waste water (potato industry)	2x Niewkerke (BE), Clarebout Potatoes	2009/12
NuReSys®	struvite	waste water (potato industry)	Waasten (BE), Clarebout Potatoes	2012
NuReSys®	struvite	waste water (pharmaceutical industry)	Geel (BE), Genzyme	2014
REPHOS® (NuReSys)	struvite	waste water (dairy industry)	Altentreptow, DE, Remondis Aqua	2006
NuReSys®	struvite	municipal waste water	Leuven (BE), Aquafin	2013
NuReSys®	struvite	municipal waste water	Schiphol Airport (NL), Evides	2014-2015
NuReSys®	struvite	municipal waste water	Land van Cuijk (NL), Logisticon	2015
NuReSys® - ELIQUO	struvite	municipal waste water	Apeldoorn (NL), Vallei & Veluwe	2016
NuReSys®	struvite	municipal waste water	Braunschweig Steinhof (DE), SE BS / AVB	2018/19
PEARL® (OSTARA)	struvite	municipal waste water	Slough (UK), Thames Water	2013
PEARL® (OSTARA)	struvite	municipal waste water	Amersfoort (NL), Vallei & Veluwe	2015
PEARL® (OSTARA)	struvite	municipal waste water	Madrid (ES), Canal de Isabel II	2016
PHORWater	struvite	municipal waste water	Calahorra (ES), El Cidacos	2015 (demo)
PHOSPAQ™	struvite	municipal waste water	Olburgen (NL), Waterstromen	2006
PHOSPAQ™	struvite	municipal waste water	Lomm (NL), Waterstromen	2008
PHOSPAQ™	struvite	municipal waste water	Nottingham (UK), Severn Trent Water	2014
PHOSPAQ™	struvite	municipal waste water	Tilburg (NL), Waterchap de Dommel	2016
PhosphoGREEN (SUEZ)	struvite	municipal waste water	Aaby (DK), Aarhus Water	2013
PhosphoGREEN (SUEZ)	struvite	municipal waste water	Marselisborg (DK), Aarhus Water	2018
PhosphoGREEN (SUEZ)	struvite	municipal waste water	Herning (DK), Herning Water	2016
STRUVIA™	struvite	municipal waste water	Helsingør Southcoast (DK), Forsyning Helsingør	2015
Stuttgart	struvite	municipal waste water	Offenburg (DE), AZV	2011 (demo)
Stuttgart	struvite	municipal waste water	MSE Mobile Schlammwässerungs GmbH	2015 (pilot)
Unknown	K-struvite	manure and livestock stable slurries	4 x Stichting Mestverwerking Gelderland (NL)	2010

7137

7138 The current market for P-salt recovery materials is mainly driven by the increased needs to
7139 remove P from waste streams (e.g. urban wastewaters, manure, waste from food-processing
7140 industry) to reduce and prevent the leaching of P to water bodies. Given the national and EU
7141 legislation and guidance on nutrient management and water quality (Common Agricultural
7142 Policy, Water Framework Directive, Nitrates Directive, etc.), tertiary treatment with
7143 enhanced P removal is becoming a more common practice in many European municipal and
7144 industrial waste water treatment facilities (European Environment Agency, 2013b).
7145 Basically, there are two options to prevent P from ending up in the effluents of waste water
7146 treatment plants: (1) **enhanced biological phosphorus removal (EBPR)**, and (2) **chemical
7147 precipitation with metal salts (ChemP)** or a combination of both. In EBPR,
7148 microorganisms (P accumulating organisms) incorporate P in a cell biomass compound called
7149 polyphosphate and the P is removed from the process by sludge wasting. Chemical
7150 precipitation with metal salts can remove the P to low levels in the effluent. The commonly
7151 used chemicals are aluminium (Al(III)), ferric (Fe(III)) and ferrous Fe(II), and calcium
7152 (Ca(II)) salts. Phosphorus nutrient removal initially relied entirely on chemical precipitation,
7153 which remains a leading technology today (Wilfert et al., 2015). Nonetheless, EBPR has
7154 become firmly established in some European Member States (Wilfert et al., 2015).

7155 Struvite production provides important operational **benefits for the operation of municipal**
7156 **wastewater treatment plants** that apply enhanced biological phosphorus removal, even
7157 without retailing struvite as a fertiliser.

7158 ○ Costs for biological waste water treatment plants are reduced by the lower
7159 maintenance costs due to the **avoided pipe clogging and abrasion of**
7160 **centrifuges**.

7161 ○ Struvite producing processes that precipitate **P from (activated) digested**
7162 **sludges increase the dewaterability** of the sludge, in turn lowering the
7163 associated costs for dewatering chemicals (e.g. flocculation agents) and
7164 sludge disposal. At present, operating costs for sludge dewatering usually
7165 account for up to 25–50% of the total expenses of the entire wastewater
7166 treatment process (Mahmoud et al., 2011). The divalent cation bridging
7167 theory states that flocculation, which is strongly linked to dewaterability, is
7168 driven by the ratio of divalent cation concentrations (Ca^{2+} , Mg^{2+}) over
7169 monovalent cations (Na^+ , K^+ , NH_4^+ , etc.). Divalent cations create bridges
7170 between particles whereas monovalent cations tend to deteriorate floc
7171 structures. Therefore, an improved dewaterability can be expected if the
7172 addition of magnesium divalent cations surpasses the effect of sodium
7173 hydroxide dosing. Marchi et al. (2015) indicated the importance of a proper
7174 tuning of chemical additions in order to achieve progressive dewatering.

7175 ○ The **reduction of the N load of the sludge liquor** has a direct effect on the
7176 overall treatment capacity of the waste water treatment plant as well as on its
7177 operational costs, since the removal of N from wastewater requires energy,
7178 chemicals and tank volume (Ewert et al., 2014).

7179 In most EU Member States, **struvite is not yet legally recognised as a fertiliser**, meaning a
7180 special permission from the national government is needed to be relieved of the waste status.
7181 This situation may cause a bottleneck in the distribution of the produced struvite as fertiliser
7182 to agriculture. Of the full-scale techniques mentioned, only the struvite products of Pearl and
7183 NuReSys (respectively Crystal Green and BioSTRU) are certified as fertilisers in the United
7184 States/United Kingdom and Belgium, respectively. The struvite obtained by the Seaborne
7185 process is only used locally. It can be concluded that the produced outputs are mostly used in
7186 the countries where production takes place and that **in most cases the existing market and**
7187 **production volumes are very small**.

7188 The installation of P-precipitation recovery processes is a service that is typically carried out
7189 by **industrial partners** of the municipalities that operate the plant. The improved operability
7190 and the reduced maintenance costs associated with controlled struvite precipitation and
7191 removal enable municipalities to justify expenditure for the installation of the recovery
7192 facility. The industrial partner can be in charge of the sales of the recovered P-precipitate, or
7193 P-precipitates can be sold directly by the wastewater treatment operators to the fertiliser
7194 industry (for further processing) and to farmers (for direct use on the field).

7195 7.1.2 Thermal oxidation materials & derivatives

7196 Significant amounts of ashes are produced as **production residues from the biomass energy**
7197 **and paper industry**. In addition, the incineration of **poultry litter** and **meat and bone meal**
7198 is an established practice that combines the purposes of energy generation and nutrient
7199 recovery. The ashes of those combustion and incineration facilities can be applied as
7200 fertilising materials directly on land (**raw ashes**), without post-treatment. A second group of
7201 ash-based materials are P-concentrated fertilisers that have been derived from manufacturing
7202 processes on ashes obtained from the combustion/incineration of P-rich input materials with
7203 the specific intention to produce P-fertilisers.

7204

7205 7.1.2.1 Raw ashes and slags

7206 Biomass ashes from the wood and paper industry

7207 The demand for biomass-based heat and electricity is increasing because of targets for
7208 generating **energy from renewables** and decreasing the emission of fossil CO₂. **Thus, there**
7209 **is increased interest in biomass ash utilisation**. Also for the waste generated by the wood
7210 pulp and paper industry, incineration with energy recovery is becoming the main waste
7211 recovery method because landfills are increasingly being reduced as a final destination for
7212 wastes in Europe (Monte et al., 2009). Data on the exact amount of ashes produced are
7213 limited; according to the report of the International Energy Agency (van Eijk et al., 2012),
7214 about 600 kt of ashes per year are produced from clean wood summing the contributions
7215 from Austria, Denmark, Finland, Germany, the Netherlands, and Sweden alone. Additionally,
7216 substantial amounts of ashes are produced from waste wood (e.g. 270 kt yr⁻¹ in Germany) and
7217 black liquor (i.e. the waste materials from the kraft process when digesting pulpwood into
7218 paper pulp; e.g. 135 kt yr⁻¹ in Austria). Hence, the volumes of ash produced are substantial.

7219

7220 Nevertheless, direct use as fertiliser on agricultural or forest soils of ashes is primarily
7221 possible for bottom ashes or mixtures of bottom and coarse fly ashes that have lower amounts
7222 of contaminants, and only when clean biomass fuels are used. Moreover, it should be
7223 considered that plant-based ashes have a low P-content (see section 5.5.4.1 and 16.2.1; on
7224 average about 0.7% P for bottom ashes), making the potential for P-recovery from such
7225 materials intrinsically low. Based on the data by Van Dijk et al. (2016), the combined P
7226 losses from the wood and paper industry are about 79 kt P yr⁻¹. Nonetheless, considering the
7227 contamination of a substantial fraction of ashes by chemicals (paper industry, waste wood
7228 from households, etc.), the existing alternative uses of ashes (e.g. cement industry), and the
7229 quality requirements for their use as a fertilising product, **only a relatively small**
7230 **contribution is expected for raw ash materials from the wood and paper industry for P-**
7231 **recycling in Europe**. These ashes may, however, also contribute to the recycling of other
7232 nutrients, such as Ca and K.

7233

7234 Poultry litter and meat and bone meal raw ashes

7235 About 80% of the **non-edible animal by-products from abattoirs** are processed to meal
7236 (bone meal, meat meal, feather meal, blood meal, carcass meal and combinations thereof).
7237 Animal meal production is a process that includes bulk slaughterhouse waste mincing and
7238 coagulation, followed by the separation of the solid and liquid material by pressing. The solid
7239 fraction is then dried, while the wet fraction is heated for the extraction of fats. For processed
7240 meat and bone meals (MBM; ~5% P), pet food and combustion with energy recovery are the
7241 most common fates, and only a small share of the available and sterilised meals are used for
7242 direct use as a fertiliser, often in organic farming (Franke-Whittle and Insam, 2013; Moller,
7243 2015). Especially in the UK, MBM are increasingly being processed to fertilisers of high P-
7244 content (6% - 19%) (ESPP, 2016). EPR (UK) produces more than 2.8 kt P yr⁻¹ of their “P-
7245 grow” MBM fertiliser, while Saria (UK) processes around 45 kt of MBM to produce ~2 kt P
7246 yr⁻¹ MBM as the P-fertiliser product "Kalfos" (mainly calcium phosphate mineral fertiliser,
7247 ~21% P₂O₅ plus potassium and sulphur). Also companies like Fibrophos (UK), ACL/Wykes
7248 Engineering (UK), COOPERL (FR), Elosato (FI), ITS SA (PT) process inedible animal by-
7249 products and meat and bone meal to straight P-fertilisers or compound PK Fertilisers (ESPP,
7250 2016). Van Dijk et al. (2016) estimated the total P-recovery through the production of
7251 fertilisers from slaughterhouse waste at 16 kt P yr⁻¹.

7252

7253 The incineration of **poultry litter** with energy recovery is currently being performed by
7254 commercial companies such as BMC Moerdijk (NL), Fibrophos (UK), and BHSL (IE) and
7255 others. Those companies alone process yearly > 1500 kt of poultry litter leading to an
7256 estimated recovery of about 30 kt P yr⁻¹ (and similar quantities of K). The poultry litter ash
7257 end-material has a P content of about 7-10% (16 – 23% P₂O₅).

7258

7259 *7.1.2.2 Thermal oxidation material derivatives*

7260 Raw ashes can only be applied on land as fertilisers when derived from input materials with a
7261 low content of inorganic metals and metalloids. **The post-processing techniques can**
7262 **remove the inorganic contaminants present in ashes, enabling the use of more**
7263 **contaminated input materials, and simultaneously increase the plant-availability of the**
7264 **nutrients in the ashes.**

7265

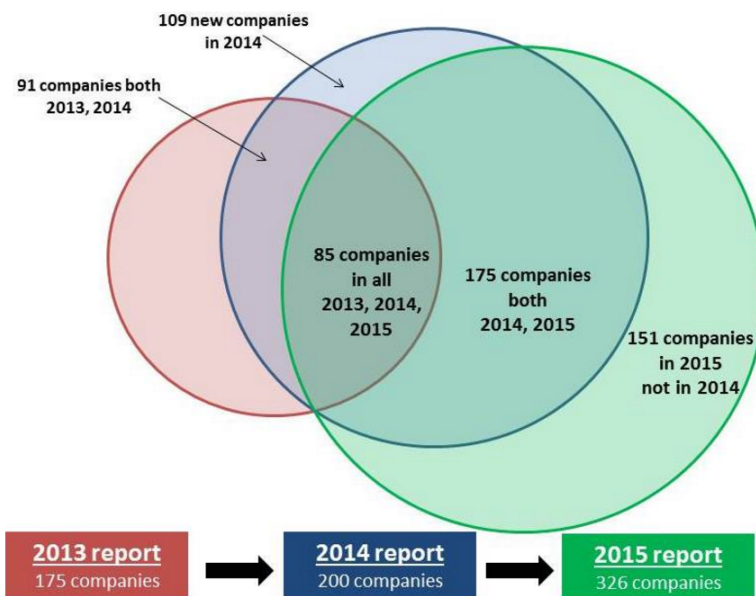
7266 Both thermochemical and wet-digestion techniques are applied in piloting and operational
7267 facilities in Europe (see section 15.2). Most suitable input materials for these processes are
7268 ashes that have been produced from **P-rich input materials** (e.g. mono-incinerated sewage
7269 sludge ashes from EBPR and Chem-P plants, animal bones, meat and bone meal, possibly
7270 poultry litter). These facilities are recently establishing in Europe, and some operators have
7271 the ambition to replace a large share of their phosphate rock by secondary phosphates in the
7272 near future (see section 15.2.2 for a non-exhaustive list of such processes).

7273

7274 7.1.3 Pyrolysis & gasification materials

7275 The **International Biochar Initiative (IBI)**, a trade and advocacy group for the nascent
 7276 industry that focuses exclusively on for-profit pyrolysis production enterprises, made a
 7277 conservative estimation of 827 tonnes of pyrolysis & gasification materials produced
 7278 worldwide in 2013, by a total of 175 companies. The 2015 IBI report highlights that the
 7279 number of active pyrolysis companies rose from **200 in 2014 to 326 companies in 2015**. The
 7280 steady increase is most likely indicative of both new companies entering the marketplace as
 7281 well as more information being readily available regarding pyrolysis companies around the
 7282 world (International Biochar Initiative, 2016b).

7283



7284

7285 **Figure 11: Evolution in the worldwide number of active companies producing pyrolysis &**
 7286 **gasification materials (adopted from the International Biochar Initiative (2016b))**
 7287

7288 According to IBI, the industry of pyrolysis & gasification materials is in a fledgling state,
 7289 comprised largely of enterprises selling relatively **small volumes** of pyrolysis & gasification
 7290 materials with a limited package size **locally for end uses such as gardening and tree care**.
 7291 Pyrolysis has yet to make a substantial entry into large-scale agricultural operations
 7292 (International Biochar Initiative, 2016b).

7293 An **overall assessment of the specific situation for Europe is not available**. Nevertheless,
 7294 based on the information available for specific pyrolysis facilities and retailers in the EU, it is
 7295 concluded that the current market is relatively small (actual production volumes < 10 000 t
 7296 material yr⁻¹). It should be noted that most manufacturers and producers focus on the
 7297 production of plant-based pyrolysis & gasification materials of low P-content, for which
 7298 reason the current contribution of pyrolysis to the market of P-fertilisers derived from
 7299 secondary raw materials is low:

- 7300 ○ The **developed 3R technology** integrates pyrolysis, catalytic and
 7301 biotechnological process to produce plant-based and animal bone pyrolysis
 7302 facilities and materials (3R AgroCarbon, 2016). The technology is owned by

7303 the company **Terra Humana Ltd.**, with a staff of 12 people, and is the only
7304 medium pyrolysis facility that produces materials intended for agricultural use
7305 with a $> 1000 \text{ t yr}^{-1}$ throughput capacity. Recently the company also received
7306 authority permits for the full-scale industrial installation and operation of a
7307 pyrolysis plant in Kajászó, Hungary. For 2017/2018 a **production (output)**
7308 **capacity of 12500 t material yr⁻¹ is targeted.** The current state of technology
7309 readiness level is high (TRL 8-9).

7310 ○ The German company **Pyreg (PYREG, 2016)** sells pyrolysis plants, but does
7311 not operate any plant.

7312 ○ **Carbon Terra** has a production capacity of about 1000 t yr^{-1} and relies on the
7313 Schottdorf Technology (under patent) and is also based in Germany. The input
7314 materials are not specified, but it is stated the company only relies on surplus
7315 biomass, and that the technology can process over 100 different kinds of
7316 biomass. The process is certified according to the EBC, and the quality
7317 management of Carbon Terra is based on the DIN ISO 9001 standard. The
7318 pricing ranges from 25 € for a 30 L package to 900 € for 1400 L.

7319 ○ The German company **Regenis GmbH** has a pyrolysis plant with an annual
7320 production capacity of 500 tonnes, but no further information is currently
7321 available on pricing (Regenis - Bio Energie Technologie, 2016).

7322 ○ **Biomaccon GmbH (Germany) and Black Carbon (Denmark)** are producers
7323 of pyrolysis plants. Biomaccon produces machineries with production
7324 capacities ranging from 6.2 to 34.2 kg hour⁻¹ ($540 - 3000 \text{ t yr}^{-1}$), while an
7325 annual production capacity of 300 tonnes is planned for Black Carbon
7326 (BIOMACON, 2016; Black Carbon, 2016).

7327 ○ Moreover, there are a number of companies based in the EU that produce or
7328 sell small volumes of pyrolysis & gasification materials: Biogreen/EDT (FR),
7329 EM-Chiemgau (Germany), Sonnenerde (Austria), AWN
7330 Abfallwirtschaftsgesellschaft des Neckar-Odenwald-Kreises mbH (Germany),
7331 Geiger Pflanzenkohle und Energie UG (Germany), FETZER Rohstoffe +
7332 Recycling GmbH (Germany), Lixhe Compost SA (Belgium) and Carmagnola
7333 Energie SRL (Italy)

7334

7335

7336 **7.2 Market aspects and outlook for P-fertilisers**

7337 7.2.1 Phosphate rock as the major source for P-fertilisers

7338 The current market of P-fertilisers other than manure is **dominated by processed mineral**
7339 **materials that have been derived from phosphate rock**. Specific materials such as
7340 unprocessed phosphate rock, meat and bone meal, and guano can be used as alternative P-
7341 fertilisers, but their use is limited in quantities applied and agricultural sectors covered. The
7342 future outlook of P-fertilisers is based on the evolution of supply and demand of mined
7343 fertilising products that currently dominate the market of P-fertilisers.

7344
7345 There are three classical routes for the **production process of P-fertiliser from phosphate**
7346 **rock** (European Phosphate Fertilizer Alliance, 2017):

- 7347
- 7348 • The first route treats phosphate rock with sulfuric acid to create phosphoric acid, which is
7349 then used to produce **Diammonium phosphate (DAP) or Monoammonium phosphate**
7350 **(MAP)**. DAP is typically 18-46-0 (i.e. contains 18% N, 46% P₂O₅ and 0% K₂O), whereas
7351 MAP can be between 10-50-0 and 11-55-0. MAP and DAP can be used as the final
7352 fertiliser or as input for NPKs. The main downside of this process is that some
7353 phosphogypsum is created as a residue, which raises environmental concerns and also
7354 leads to some P being lost. About two-thirds of the phosphate fertilisers' production is
7355 currently performed through this route.
 - 7356 • The second route also uses sulfuric acid, but in smaller quantities in relation to phosphate
7357 rock, which results in superphosphate (**SSP**, typically between 0-16-0 and 0-22-0) or
7358 triple phosphate (**TSP**, typically ranging between 0-44-0 and 0-48-0). These can be used
7359 as final fertilisers, or as inputs for NPK fertilisers.
 - 7360 • The third route is the so-called **nitrophosphate** route, which consists of treating
7361 phosphate rock with nitric acid to obtain compound fertilisers. Phosphoric acid and
7362 calcium nitrate are formed as intermediary products, which then react. There are generally
7363 two variations of this process (“Odda” process or mixed-acid process).

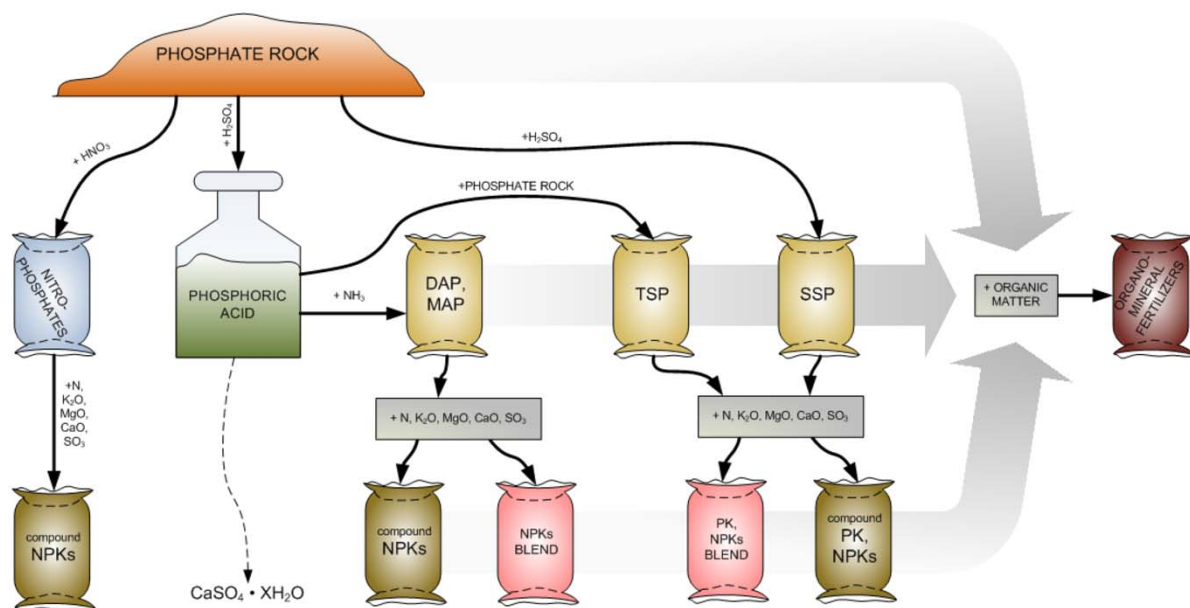
7364
7365 The resulting materials from these three routes can then be used for the production of NPK
7366 fertilisers:

- 7367 ○ **Complex NPK fertilisers** are produced by a chemical reaction in a chemical plant.
7368 For example, an NPK fertiliser can be made by reacting nitric acid with phosphate
7369 rock to make an ammoniated phosphate, and adding potassium chloride (KCl) and
7370 granulating. The resulting product will have the same proportions of N, P and K in
7371 each granule. Complex plants are expensive to build, but can produce the lowest cost
7372 NPK products. They are relatively inflexible, being best operated making a small
7373 number of large volume grades.

- 7374 ○ **Compound NPK fertilisers** are physical mixes. Ingredients such as ammonium
7375 nitrate (AN), monoammonium phosphate (MAP) and KCl can be mixed in the correct
7376 proportions for the amounts of N, P and K required. This mix is then ground down to

7377 a fine powder, thoroughly mixed, and usually granulated using e.g. steam granulation.
 7378 This ensures that the desired N, P and K proportions are present in each granule, but
 7379 without involvement of wet chemistry. Compound plants require moderate
 7380 investment, and whilst still benefiting from economies of scale, are generally smaller
 7381 and more flexible than complex plants, making a wider variety of products.

7382 ○ **NPK Blends** are physical mixes of different fertilisers, such that the proportions of N,
 7383 P and K correspond to the desired value in each bag, but each pellet will be of e.g.
 7384 AN, or MAP, or KCl. Blending plants are the least expensive, requiring only storage,
 7385 physical mixing and bagging operations, and have the highest flexibility in terms of
 7386 products offered.



7387
 7388 **Figure 12: Production routes for P-fertilisers that are derived from mined phosphate rock**
 7389 **(DAP: diammonium phosphate; MAP: monoammonium phosphate; TSP: triple**
 7390 **superphosphate; SSP: single superphosphate; NPK: Fertiliser containing nitrogen, phosphorus**
 7391 **and potassium) (source: European Phosphate Fertilizer Alliance (2017))**
 7392

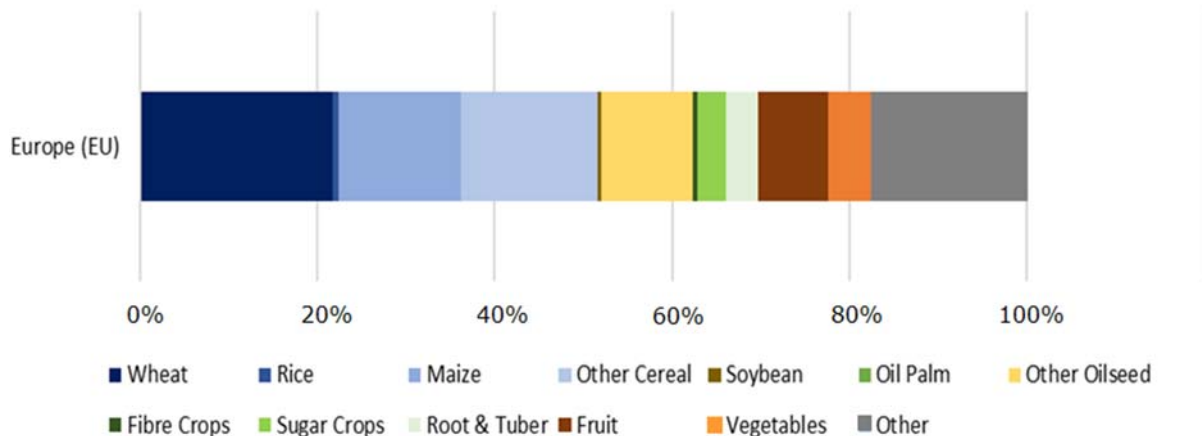
7393 7.2.2 Market drivers for P-fertiliser demand

7394 The main **long-term macro-economic drivers** for P-fertilisers are **population growth**,
 7395 changing diets, determining how many people need to be fed, and **per capita income**,
 7396 determining how much that population has to spend on food and therefore the quantity and
 7397 quality of food they can afford.

7398
 7399 In addition to the macro-economic drivers, both annual and regional demand for P-fertilisers
 7400 will vary according to the influences of a range of factors, with crop plantings as the most
 7401 important one (in turn influenced by crop prices). The price of fertilisers can also have an
 7402 influence, as – increasingly - does the weather. Government policy also plays a significant
 7403 role in the demand for fertiliser, as can local agricultural practices.

7404

7405 Different crops require differing quantities of N, P and K to produce optimum yields. IFA has
 7406 been collecting and monitoring fertiliser use by crop at the global level for a number of years.
 7407 In its most recent report (IFA, 2013), a breakdown of P-fertiliser demand by crop was given
 7408 for Europe (Figure 13). More than 50% of the P fertilisers were applied to arable farmed land
 7409 planted with cereals in 2010-11.
 7410



7411
 7412 **Figure 13: P-fertiliser use by crop (%) in Europe for the year 2010/2011 (Source: Fertilisers**
 7413 **Europe & IFA)**
 7414

7415 **The main driver of the reduction in apparent P-fertiliser consumption in Europe has**
 7416 **been the significant change to agricultural policy implemented from 2003.** The most
 7417 relevant of these has been the decoupling of subsidies from production, which was agreed in
 7418 June 2003, for implementation from May 2005. Prior to 2005 the more farmers produced in
 7419 volume terms the more subsidies they received. **Since 2005, the subsidy has been as a**
 7420 **single farm payment, which is subject to meeting a number of conditions relating to**
 7421 **factors such as environmental compliance and quality, food safety and animal welfare.**
 7422 There is discretion across the EU in terms of implementation but over time the reform, by
 7423 promoting factors other than production has caused that production and fertiliser use
 7424 declined, or at best stabilised, in the period to 2008. **Since then, as the impact of the revised**
 7425 **subsidy faded, production has grown modestly: based on rolling 5-year averages for**
 7426 **2008 and 2015 production has grown at 1.04% p.a. through the period.**

7427 The impact of **climate change and the weather** will probably play an increasing role in
 7428 affecting annual volumes. Although the full impacts of climate change on the weather are not
 7429 yet clear, it does seem that more extreme weather patterns are emerging – bigger storms,
 7430 more severe droughts and floods etc (climate variability). The impact of this will be an
 7431 increased volatility of demand – if there is a significant risk of losing a crop farmers will
 7432 either not apply P, or reduce the amount added to mitigate the risk.

7433 **In conclusion, the main long-term global drivers for phosphate demand will be**
 7434 **population growth and the continued economic prosperity of each country. At a**
 7435 **regional and national level, and on an annual basis, the mix of crop plantings, crop**

7436 **prices, the weather, government policy and fertiliser prices will all influence how**
7437 **demand develops.**

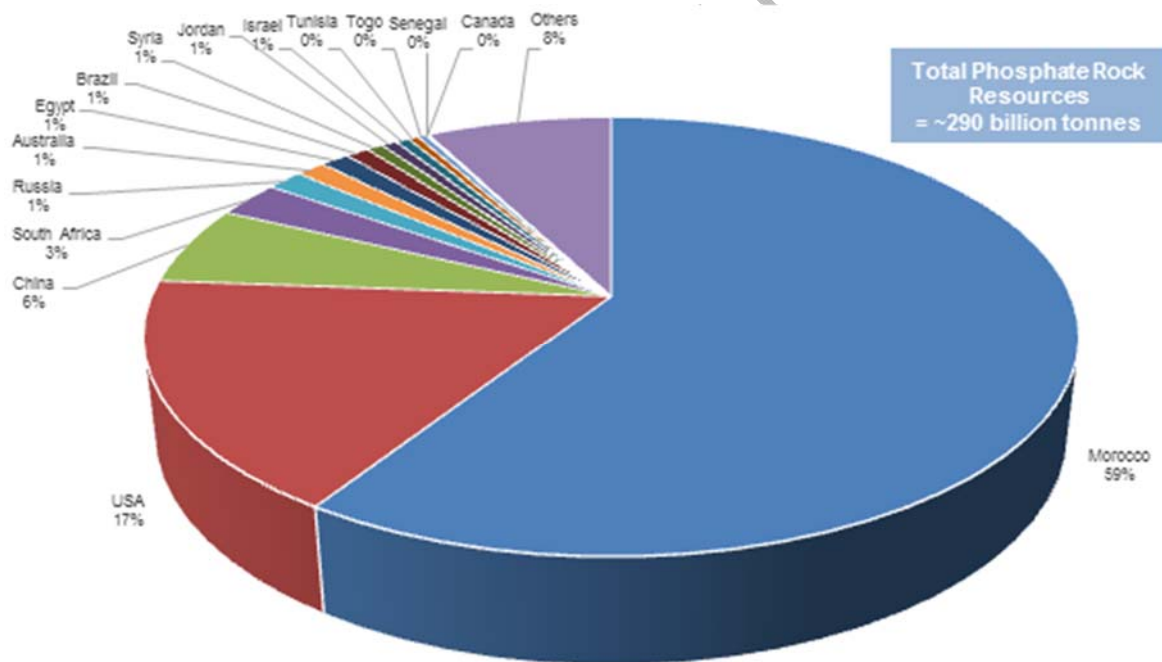
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7439 7.2.3 Production and consumption volumes

7440 7.2.3.1 Raw materials for P-fertiliser production

7441 The primary raw material for the P-fertiliser industry is **phosphate rock**. Phosphate rocks can
7442 be igneous (volcanic – e.g. the rock deposits in the Kola Peninsula in Russia, at Phalaborwa
7443 in South Africa, and in a number of locations in Brazil amongst others), but most commonly
7444 are sedimentary, being made up from the bones (calcium phosphate) laid down in shallow
7445 seas over millions of years. Most sedimentary rocks contain some phosphate, but economic
7446 deposit of phosphate rock occur where there are one or more seams of rock containing
7447 generally more than 15% P₂O₅, which have uniform texture and composition. Morocco has
7448 the largest proven reserves of phosphate, but the International Fertilizer Association (IFA)
7449 noted that **commercial production of phosphate rock took place in 29 countries in 2015**.
7450 The most important commercial resources are given in Figure 14.

7451



7452

7453 **Figure 14: Global Phosphate Rock Sources (Source: IFDC, 2010)**

7454

7455 Europe has only one active phosphate rock mine, owned and operated by Yara, and located at
7456 Siilinjärvi in Finland (Davidson and Sheldon, 1986). Most of this rock is used by Yara at its
7457 manufacturing sites in Finland, or elsewhere in the Nordic region. It therefore follows that
7458 most of the rock used in Europe is imported from outside the region. There are other
7459 phosphate resources in Europe, including:

- 7460
- Igneous carbonatite outcrops in Sweden, Norway, Scotland and Spain

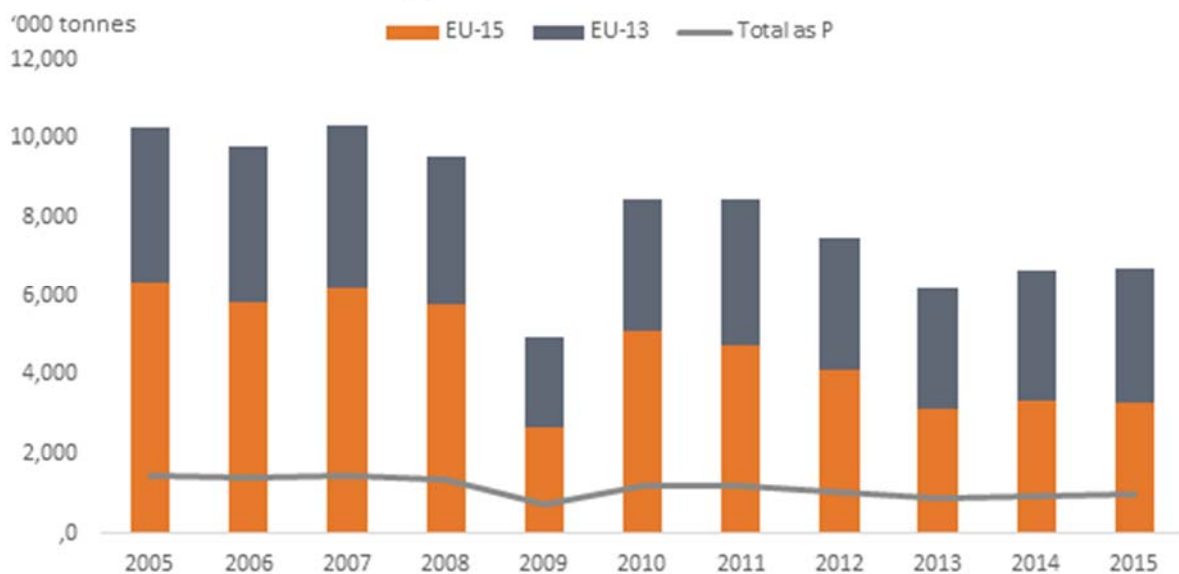
- 7461 • Sedimentary deposits in Belgium, France, Germany
- 7462 • Metamorphic deposit in Serbia

7463 None of these are currently deemed to be commercially viable. Yara has a project to develop
 7464 a second resource in Finland at Sokli, north of the Arctic Circle, but the project is currently
 7465 stalled as there may be alternative long-term sources for the company that are more
 7466 commercially attractive.

7467 **Phosphate rock is thus mined mostly outside of the European Union** and either imported
 7468 into the European Union **as rock**, or further **processed abroad and brought into the**
 7469 **European Union as a semi-product or product**: phosphoric acid, diammonium phosphate
 7470 (DAP), monoammonium phosphate (MAP), triple superphosphate (SSP), single
 7471 superphosphate (SSP). The main phosphate rock importing countries in the EU are Lithuania,
 7472 Poland, Belgium, Bulgaria, Romania and Spain. Most of EU imports come from Morocco
 7473 (1.6 Mt), Russia (1.4 Mt), Algeria (702 kt), Israel (506 kt), and South Africa (429 kt).

7474 **Imports of rock** into Europe have declined from around 9.6 million tonnes to 6.0 million
 7475 tonnes in the 10 years between 2005 and 2015. The phosphate content of the rock imported
 7476 has remained fairly constant at between 31.9% and 32.9% P₂O₅ (13.9% to 14.3% P). Imports
 7477 have declined in both the original EU countries (EU-15) and the more recent accession
 7478 countries (EU-13), but much more so in the former than the latter. The compound average
 7479 decline in imports between 2005 and 2015 in the EU-15 is 7.9% p.a., whereas in the EU-13 it
 7480 is a much more modest 1.2% p.a. decline. With only very modest extraction of rock in
 7481 Europe (0.7 Mt phosphate rock from Finland), apparent consumption follows the same
 7482 pattern as imports. For the year 2015, Fertecon estimated that **the total apparent P-**
 7483 **consumption as phosphate rock in the EU-28 equal ~936 kt P** (6.7 Mt material x 0.32 kg
 7484 P₂O₅ / kg phosphate rock x 0.437 kg P/ kg P₂O₅).

7485



7486

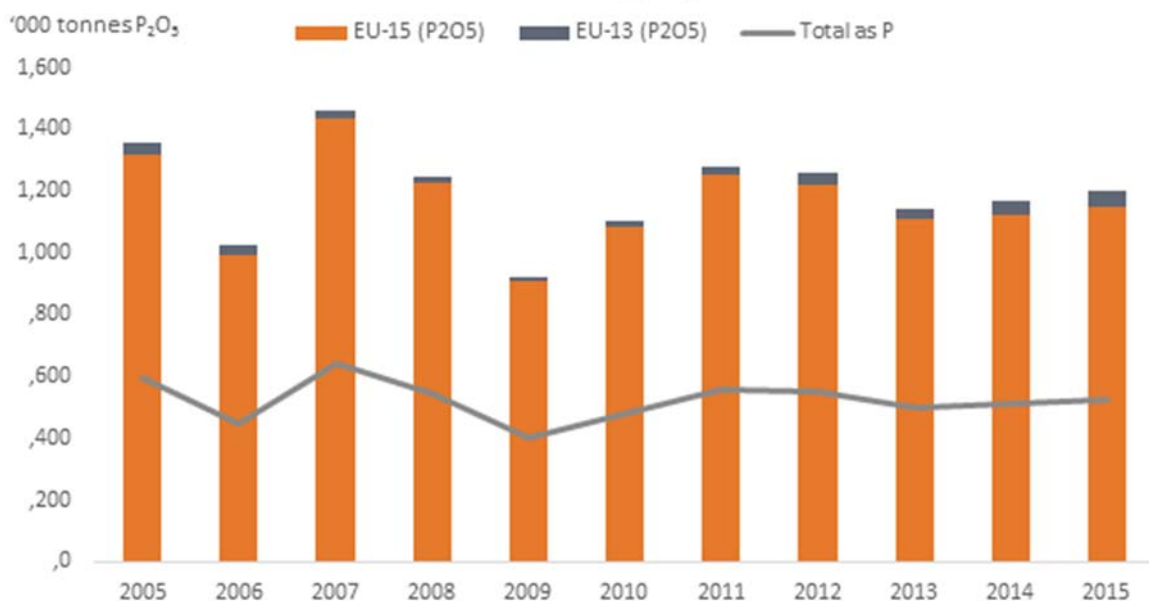
7487 **Figure 15: Phosphate rock apparent consumption for all applications in Europe, 2005 – 2015-**
 7488 **(Sources: IFA, GTIS, Fertecon)**

7489

7490 Since 2005 apparent phosphate rock **consumption** in the EU-15 countries has declined by
 7491 6.3% p.a., compared with a more modest 1.4% p.a. in the EU-13 countries (Figure 15). Since
 7492 2010 apparent consumption for the EU-13, when seasonal fluctuations are removed, seems
 7493 stable, whereas in the EU-15 countries it has reduced from levels typically above 5.0M
 7494 tonnes product to levels below 3.5M tonnes product (Figure 15).

7495 The other main source of phosphate raw material for Europe is **phosphoric acid**. Acid is
 7496 imported in two main forms, Merchant Grade Acid (MGA, otherwise known as green acid or
 7497 fertiliser acid), which is an impure acid containing around 54% P₂O₅, and purified phosphoric
 7498 acid (PPA, otherwise known as white acid), typically containing around 61% P₂O₅. MGA is
 7499 used as a feedstock for fertiliser and animal feed products, purified acid is used for industrial
 7500 applications including some speciality fertilisers (frequently, but not exclusively fully soluble
 7501 products). **For the year 2015, it is estimated that the total P-imports as phosphoric acid**
 7502 **in the EU-28 equal ~ 524 kt P** (Figure 16). The EU-15 accounts for over 95% of all
 7503 phosphoric acid imports in the EU (Figure 16). This might overstate reality, depending on the
 7504 accuracy of data on re-exports from key import-ports in e.g. the Netherlands and Belgium,
 7505 but there is no doubt at all that the EU-15 will account for the majority of the use of imports.
 7506 Imports to the EU-15 have declined by 1.3% p.a. in the 2005 – 2015 timeframe, whereas
 7507 imports have grown at 1.8% p.a. in the EU-13 region.

7508



7509

7510 **Figure 16: Imports of phosphoric acid into Europe by region (Source: GTIS, IFA)**

7511

7512 **7.2.3.2 Finished P-fertilisers**

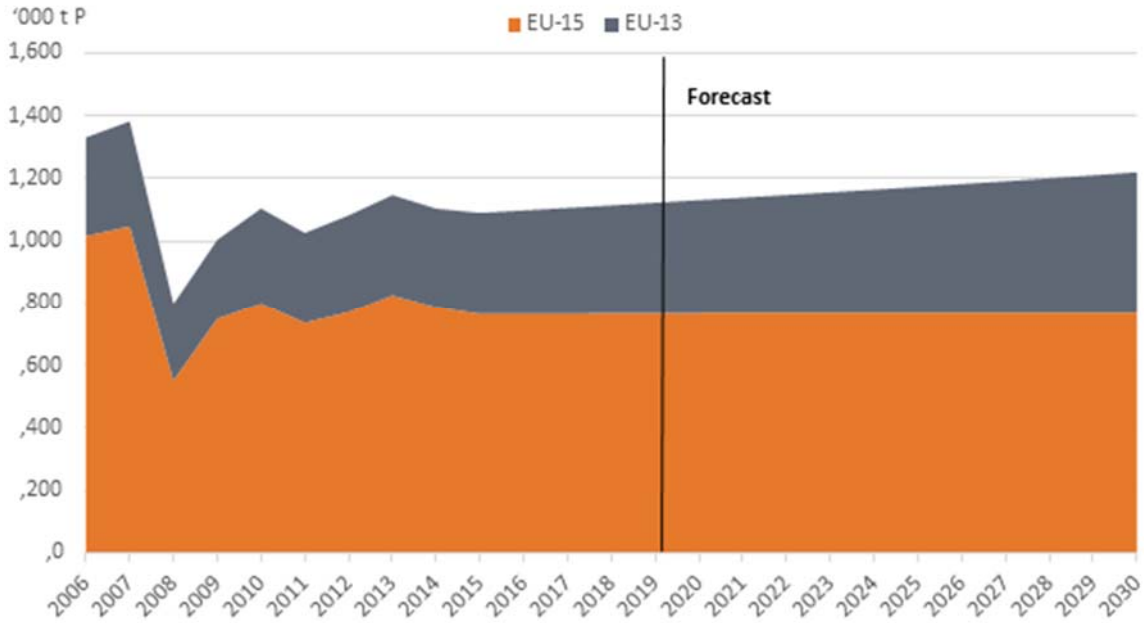
7513 Eurostat publishes two data sets on inorganic fertilisers use. The first one is collected from
 7514 Member States and is an estimate of the N and P use in agriculture. However, data on
 7515 fertiliser consumption is available in many countries from country specific data sources
 7516 (surveys, trade/production statistics) that are not always trustworthy. **As indicated by**
 7517 **Eurostat itself, the quality of data cannot be sufficiently verified** due to different data

7518 sources used (farmer surveys vs trade/production statistics) and inherent problems of data
7519 sources used (for instance inclusion of non-agricultural use in statistics based on trade and
7520 production). This involves significant limitations as, for instance, the reliability and accuracy
7521 of farmer surveys depend amongst others on the sampling design and size.
7522

7523 The other data set is estimated consumption based on the sales of mineral fertiliser in the EU-
7524 28 from **Fertilizers Europe**. The figures estimated by the trade association Fertilizers Europe
7525 based on sales of mineral fertiliser mostly correspond with the estimates of N and P use
7526 reported by countries although they cannot be directly compared due to methodological
7527 differences. This is a harmonized data source. Data are available at NUTS0 for EU-27 (i.e.
7528 does not include Croatia). Data from Fertilizers Europe relate to crop years (t-1/t) which are
7529 reported under year t-1. These data have been used in this assessment, also because they are
7530 in between the Member State data documented by Eurostat and the FAO.
7531

7532 **Fertilizers Europe assessed the apparent P-consumption for fertilisers in the EU-28 at**
7533 **1090 kt P in 2015** (Figure 17). Eurostat estimated the total P-consumption as mineral
7534 fertilisers at 1133 kt P for the year 2015, whereas FAOSTAT documents 1070 kt P for the
7535 EU-28 in 2015. The data from Fertilizers Europe indicate that mineral P-fertiliser
7536 consumption was larger in the EU-15 (70%, 765 kt P yr⁻¹) than in the EU-13 (30%, 325 P yr⁻¹)
7537 (Figure 17).
7538

7539 Looking forward, Fertecon forecasts phosphate consumption for fertilisers to grow across the
7540 EU-28 at a CAGR (Compound Annual Growth Rate) of 0.8% p.a. for the next decade.
7541 Growth in the EU-15 is stable within any reasonable margin of error (0.09% p.a.). Fertecon,
7542 however, forecasts a growth in the EU-13 countries at a CAGR of 2.2% (Figure 17). Future
7543 estimates on mineral P-fertiliser consumption were obtained by projecting these CAPR
7544 growth rates, resulting in a 2030 estimate of 1220 kt P yr⁻¹. The EU-13 still had a dominant
7545 share of the total mineral P-consumption (63%; 769 kt P yr⁻¹), but the contribution of the EU-
7546 13 increased to a total value of 37% (450 kt P yr⁻¹). Fertilisers Europe forecasts total P-
7547 fertiliser consumption at 1178 kt P yr⁻¹, thus reasonably in line with the FerteCon estimate for
7548 the year 2030.
7549



7550

7551 **Figure 17: Apparent Consumption of mineral P-fertiliser in the EU-28 (kt P yr⁻¹) (Source:**
 7552 **Fertilizers Europe; forecasts based on projected Fertecon's Compound Annual Growth Rates)**

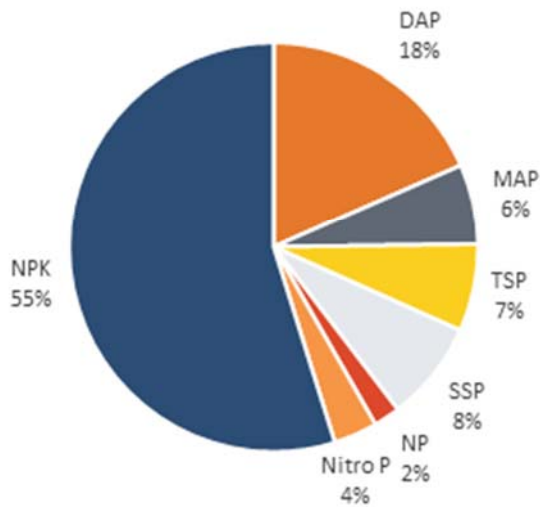
7553

7554 Although traditionally P-fertiliser and NPK fertiliser producers purchase phosphate rock to
 7555 produce fertilisers within Europe, in recent years some of the producers have – for numerous
 7556 reasons (price, environmental or others) – **suspended or abandoned purchases of**
 7557 **phosphate rock and have chosen instead to purchase phosphoric acid.** Some of them
 7558 have even temporarily decided to move even further downstream and purchase MAP or DAP.
 7559 instead (European Phosphate Fertilizer Alliance, 2017).

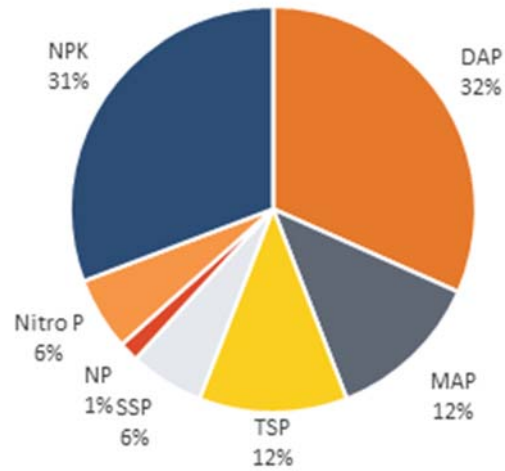
7560 The apparent consumption of phosphate in the EU-15 both in terms of the physical tonnes of
 7561 products containing P, and the total P-content delivered through those products is given in
 7562 Figure 18. The analysis shows that in terms of product types, NPKs accounted for 55% of P-
 7563 containing tonnes consumed, followed by DAP (18%) and SSP (8%) (Figure 18). In terms of
 7564 **actual P delivered** however, because NPKs contain less P than as MAP, DAP or TSP, the
 7565 proportions change. **DAP has the largest share at 32%, followed by NPKs at 31%, and**
 7566 **MAP with 12%** (Figure 18).

7567

Phosphate Consumption in Physical Tonnes



Nutrient Consumption by Fertiliser Type



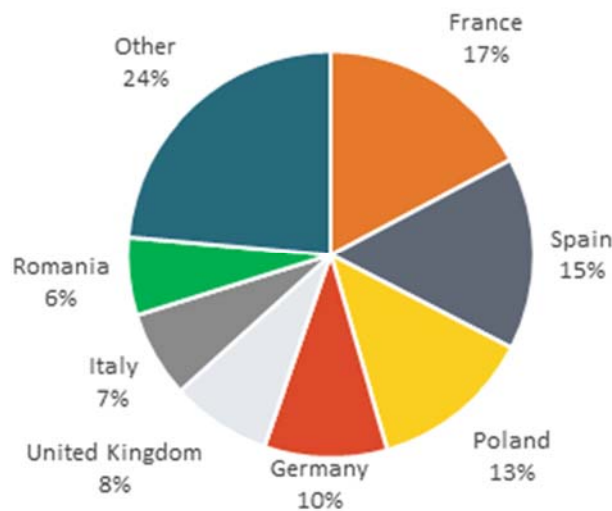
7568

7569 **Figure 18: Apparent consumption of P-fertilisers in the EU-28 for the year 2015. The left Figure**
 7570 **indicates the actual tonnes of material; the right Figure indicates the same data expressed on a**
 7571 **P-basis (Source: Fertecon)**

7572

7573 The data from Fertilizers Europe indicate that France is the largest consumer of phosphates
 7574 for fertilisers, with a share assessed at 17% of the EU-28 in 2015. Spain is the second largest
 7575 market (15%) followed by Poland (13%). The top 7 markets accounted for just over 76% of
 7576 apparent consumption of phosphate for fertilisers, with the balance spread over the remaining
 7577 EU countries (Figure 19).

7578



7579

7580 **Figure 19: EU-28 Top 10 markets for apparent consumption of mineral phosphate fertilisers for**
 7581 **the year 2015 (Source: Fertilizers Europe)**

7582

7583

7584 **Box 3: Production of DAP, MAP, TSP, SSP and NPK in the EU (AEEP, 2017; Fertecon):**

- 7585
- 7586
- 7587
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- 7596
- 7597
- 7598
- 7599
- 7600
- **Diammonium phosphate (DAP, $(\text{NH}_4)_2\text{HPO}_4$):** DAP is typically 18-46-0 (i.e. contains 18% N, 46% P_2O_5 and 0% K_2O). It was one of the first fertilisers to have a standardised content, which in part explains why it is the largest selling phosphate fertiliser. Annual production of DAP in the EU-28 is just under 1.0 Mt or 200 kt P, with Lithuania by far the largest producer, followed by Poland, Spain, and Belgium.
 - **Monoammonium phosphate (MAP, $\text{NH}_4\text{H}_2\text{PO}_4$):** MAP can be between 10-50-0 and 11-55-0. Annual production of MAP in the EU-28 production is a modest 78 kt (18 kt P), with Belgium, Poland, Bulgaria and Spain as the main producers.
 - **Single Superphosphate (SSP; $\text{Ca}(\text{H}_2\text{PO}_4)_2 + \text{CaSO}_4$):** SSP is typically between 0-16-0 and 0-22-0. Annual production is of SSP in the EU-28 accounts for just over 1.0 Mt or 88 kt P. No information is available on imports/exports.
 - **Triple Superphosphate (TSP; $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$):** TSP is the highest analysis straight phosphate fertiliser, typically ranging between 0-44-0 and 0-48-0. Annual production of TSP in the EU-28 accounts for just over 250 kt or 53 kt P, mostly in Bulgaria.
 - **NPK Fertilisers:** No direct data are available on the total production of NPK fertilisers in Europe.

7601

7602

7603 **7.3 Market outlook for P fertilisers derived from STRUBIAS materials for the year**

7604 **2030**

7605 7.3.1 General considerations

7606 **The market potential of STRUBIAS materials is based on estimates of plant-available P.**

7607 The agronomic efficiency of fertilisers containing STRUBIAS materials is expressed relative

7608 to mineral P-fertilisers based on the so-called "relative agronomic efficiency" (see section

7609 6.2.1). A relative agronomic efficiency value below 100% indicates that that the fertiliser

7610 derived from STRUBIAS materials is a less effective plant P-source than a mineral P-

7611 fertiliser derived from mined phosphate rock, and vice versa.

7612

7613 The market for P-fertilisers derived from STRUBIAS materials is dependent on the

7614 **technological readiness** and potential production limitations of the production processes,

7615 **market and consumer readiness**, and the **impacts** along the STRUBIAS material life cycle

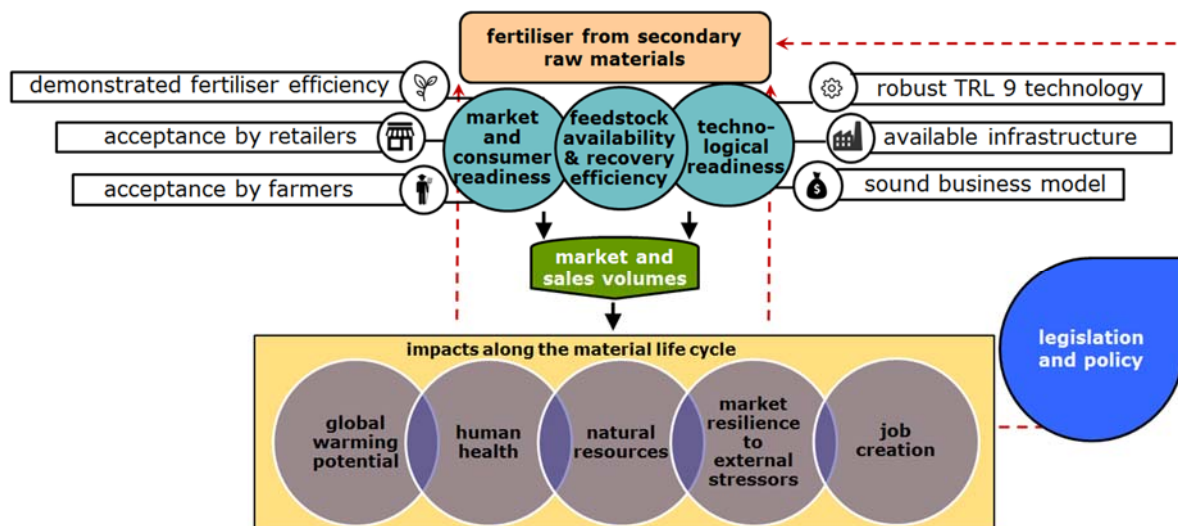
7616 (Figure 20). Legislative and policy impacts due to the possible beneficial impacts of

7617 STRUBIAS materials relative to alternative fertilising products that are available on the

7618 internal market are considered.

7619

7620



7621

7622 **Figure 20: Schematic overview of the market drivers for P-fertilisers derived from secondary**
 7623 **raw materials**

7624

7625 The market for STRUBIAS materials will not only depend on the nutrient recovery rules as
 7626 laid down in the fertiliser product legislation, but also on national and EU legislation related
 7627 to specific **eligible input materials** (e.g. Directive 2008/98/EC on waste and by-products,
 7628 Regulation (EC) No 1069/2009 as regards animal by-products, Regulation (EC) 86/278 as
 7629 regards sewage sludge, etc.), **nutrient use and management** in crop and livestock
 7630 production, and **prevention and reduction of water pollution** (Buckwell and Nadeu, 2016).
 7631 Moreover, links exist with the **bioeconomy initiatives and related legislation**, and more
 7632 specifically Directive 2009/28/EC on the promotion of the use of energy from renewable
 7633 sources. The existing legal framework and policy incentives vary considerable as a function
 7634 of eligible input materials. When relevant, the relation of existing EU legislation to
 7635 STRUBIAS market aspects will be discussed for the eligible materials. **In case STRUBIAS**
 7636 **materials are associated to a positive impact on the environment, human health, or the**
 7637 **circular economy in general, positive feedback loops due to legislative and policy**
 7638 **initiatives could possibly further stimulate the market** (see section 7.3.8.2).

7639 The sections 7.3.4 - 7.3.8 discuss market estimates under the anticipatable EU and national
 7640 legislation for all process pathways of high technological readiness level (TRL 7-9). A broad
 7641 spectrum of new STRUBIAS production processes are emerging and developing, some of
 7642 them being present at TRL 6 level ("System/subsystem model or prototype demonstration in
 7643 a relevant environment"). **It is, nonetheless, challenging to predict a 2030 market for**
 7644 **production pathways that might still face technological and market failures during the**
 7645 **remaining TRL stages ahead.** Therefore, the market assessment TRL 6 processes are
 7646 discussed together with possible legislative drivers in section 7.3.8.2.

7647

7648 7.3.2 Market and consumer readiness

7649 7.3.2.1 *Conventional agriculture*

7650 STRUBIAS materials are used to produce a variety of fertilising products (see section 15).
7651 On the hand one, **STRUBIAS materials can be used for the production of traditional P-**
7652 **fertilisers of well-known chemical composition such as DAP, MAP, TSP, SSP**, etc. On the
7653 other hand, STRUBIAS production processes may expand the variety of P-fertilising
7654 products on the market by producing P-fertilising products **of a different chemical**
7655 **composition**, with P present in a water-insoluble form. Development of new fertiliser
7656 products requires determining key properties of the materials that affect storage and
7657 spreading, soil behaviour, and agronomic efficiency. **Knowledge of these properties is of**
7658 **prime importance to increase market and consumer readiness for new fertilisers** (Antille
7659 et al., 2013).

7660
7661 STRUBIAS materials should preferentially be **available in a physical form that enables**
7662 **their homogeneous distribution across the agricultural field and their application using**
7663 **conventional application equipment**. With the increased need and readiness of the sector to
7664 increase nutrient-use efficiency, it is important that the fertiliser characteristics enable the
7665 accurate distribution of fertilisers within the field. At the same time, there is a strong
7666 preference to use existing machineries that apply fertilisers in a time and energy-efficient
7667 manner, for which reason the physical form of the fertilisers should be compatible with
7668 existing machineries. This implies, for instance, that fertilisers that will be broadcasted
7669 should preferentially comply with physical characteristics such as bulk density, grain size
7670 distribution, sphericity, hardness, brittleness, dust rate, resistance to humidity, resistance to
7671 weight increase, etc. (Antille et al., 2013). Fertiliser materials which have moderately high
7672 crushing strength can better resist handling, storage, and spreading without significant
7673 shattering, dust formation, or caking. Density properties are related to the volume needed for
7674 storage and transport, and are required to calibrate fertiliser spreading equipment. Particle
7675 size and size distribution affect uniformity of distribution during field application, and it is
7676 well documented that uneven spreading of fertilisers can increase nutrient losses to the
7677 environment, reduce fertiliser use efficiency and crop profit margins (e.g. Horrel et al., 1999).
7678 Alternatively, materials could be applied using lime spreaders that homogeneously distribute
7679 fertiliser materials on the field, albeit in a more labour-intensive manner due to the reduced
7680 distribution width relative to modern fertiliser broadcasters.

7681
7682 Fertiliser blending companies could incorporate STRUBIAS materials as part of a physical or
7683 chemical blend together with traditional mineral fertilisers on condition that they meet certain
7684 characteristics (e.g. with respect to material purity and granulometry (Formisani, 2003)).
7685 Also, certain combinations of molecules should be avoided due to possibly occurring
7686 chemical reactions in the granulator that cause nutrient loss or reduce the water solubility of
7687 specific elements in the blend. Certain fertiliser companies are in the process of **testing**
7688 **and/or partially including struvite and poultry litter as part of compound mineral P-**
7689 **fertilisers**. ICL Fertilisers has successfully tested partial struvite incorporation in their
7690 compounding process (20% of the total P in the blend). Given that the P in good-quality
7691 precipitated phosphate salts & derivates is already in plant-available form, there is no need

7692 for acidulation; ICL tests indicated that in quantities <20%, precipitated phosphate salts &
7693 derivates can be placed directly in a granulator with acidulated phosphate rocks (Six et al.,
7694 2014). In such a process, struvite is physically mixed or blended with phosphorus fertilisers
7695 and possibly with N, K and other nutrient sources. It is not chemically converted. Struvite
7696 will in this case be used as a P, N and Mg source and will require identical application
7697 machinery as for traditional P-fertilisers. Some fertiliser blending companies formulate
7698 poultry litter ashes as powder with KCl or TSP.

7699
7700 There is an increased acceptance for innovative fertilisers within the European agricultural
7701 sector, but market and consumer readiness is enhanced for products with a **proven**
7702 **agronomic benefits and comparable fertiliser efficiencies relative to traditional P-**
7703 **fertilisers expressed on a monetary basis**. Such evidence would recently be available after
7704 **comprehensive agronomic testing** under different climate and soil conditions are complete,
7705 which will require a minimum of 3 or 4 years of field trials, and probably more. With the
7706 exception of struvite and poultry litter ashes, such assessments have not yet started for most
7707 recovered products that have a different chemical composition than those products currently
7708 dominating the market (DAP, MAP, TSP, SSP, nitrophosphate, etc.).

7709
7710 In conventional European agriculture, the P-fertilisers MAP and DAP (with a P₂O₅-content of
7711 48-61% and 46%, respectively) or physical blends (NPK) make up more than 75% of the
7712 total mineral P-fertilisers applied, expressed on a P-basis (see section 7.2.3.2). The straight P-
7713 fertiliser TSP (45% P₂O₅) and SSP (16-20% P₂O₅) only make up 18% of the total share of all
7714 P-fertilisers, expressed on a P-basis (see section 7.2.3.2). A major reason for this observation
7715 is the ease and efficiency of fertiliser application and distribution logistics. **The nutrient**
7716 **content of the fertiliser directly impacts upon the logistic cost for the transport,**
7717 **distribution and application of fertilisers**. Therefore, nutrient-dense fertilisers will provide
7718 clear benefits for the downstream transport, distribution, and application by retailers and
7719 farmers.

7720
7721 Some recovered fertiliser products could also enter the market in **specific segments that**
7722 **deliver the highest margins**. Struvite and poultry litter ashes are, for instance, currently
7723 already sold in specific niche segments of the fertiliser market. In the early stages of market
7724 development, it may lead fertiliser producers to choose physical and chemical forms that are
7725 specifically adapted to these markets. The STRUBIAS application potential in niche markets
7726 includes for instance use in **growing media** for greenhouse farming or the fertilisation of
7727 **grasslands** where some STRUBIAS materials show a high potential. Moreover, STRUBIAS
7728 materials could be marketed as alternatives to mined rock phosphate and processed P-
7729 fertilisers, possibly providing market opportunities for customers attentive to alternatives
7730 derived from waste materials within a circular economy framework.

7731
7732 Assuming a similar price setting as for traditional P-fertilisers, it is concluded that fertilisers
7733 derived from STRUBIAS materials should meet numerous conditions in order to provide a
7734 substantial spot-on alternative for mined rock phosphate and processed P-fertilisers in
7735 conventional farming. The fertiliser end-product should preferentially be presented in a

7736 **physical form that enables its efficient application** and its **agronomic efficiency should be**
7737 **well-demonstrated.** Additionally, it is advisable that P-fertilisers derived from STRUBIAS
7738 materials have characteristics that enable the use in fertiliser blends together with other plant
7739 macronutrients to increase nutrient-density. **Therefore, STRUBIAS materials contained in**
7740 **compound P-fertilisers of chemical composition that are already available on the**
7741 **market and acid-soluble P-fertilisers that are well-advanced in the process of agronomic**
7742 **efficiency testing and are compatible for blending are associated to the highest degree of**
7743 **market and consumer readiness, at least for conventional agriculture.** Phosphorous
7744 fertilisers that do not meet these conditions may possibly be relevant for specialised market
7745 niches or be traded at a lower price.

7746

7747 7.3.2.2 *Organic farming*

7748 Depending on the input materials and process pathways employed, certain STRUBIAS
7749 materials could be used as fertilisers in organic farming. Agricultural practices, including
7750 fertiliser management, are regulated under the existing legislation (**Council Regulation (EC)**
7751 **No 834/2007 on organic production and labelling of organic products**). The EU organic
7752 farming sector mainly uses organic fertilising materials, but under specific circumstances also
7753 natural or naturally-derived substances and low-solubility mineral fertilisers can be applied.
7754 **Synthetic resources and inputs may only be permissible if there are no suitable**
7755 **alternatives.** Such products, which must be scrutinised by the Commission and EU countries
7756 (the Expert Group for Technical Advice on Organic Production – EGTOP, see below) before
7757 authorisation, are listed in the annexes to the implementing regulation (Commission
7758 Regulation (EC) No. 889/2008).

7759

7760 **The manufacturing of many STRUBIAS fertilisers from secondary raw materials is in**
7761 **line with the objectives, criteria and principles of organic farming and the responsible**
7762 **use of natural resources.** Given the limited availability of concentrated P-fertilisers that
7763 comply with the principles of organic farming, P-fertilisers derived from STRUBIAS
7764 materials could potentially fulfil an important role as fertilising material for the sector,
7765 especially in organic systems that rely on biological N fixation for N inputs (Seufert and
7766 Ramankutty, 2017). P-fertilisers derived from STRUBIAS materials could provide an
7767 alternative for meat and bone meal, meat and bone meal ashes and lower concentrated P-
7768 fertilising products such as manure and compost that are currently the major P-sources in
7769 organic farming (Nelson and Janke, 2007). In 2015, the percentage of the total utilised
7770 agricultural area within the EU for organic farming was 6.2%, of which 42% was planted
7771 with arable crops. **The expanding organic farming sector could, however, become a more**
7772 **significant agricultural market in the near future.** The Common Agricultural Policy
7773 (CAP) (2014-2020) recognizes the role of organic farming in responding to consumer
7774 demand for more environmentally friendly farming practices: under the first pillar organic
7775 farms will benefit from the green direct payment without fulfilling any further obligations
7776 because of their overall significant contribution to environmental objectives.

7777

7778 The EU’s “**Expert Group for Technical Advice on Organic Production**” (EGTOP) has
7779 evaluated **positively two dossiers** proposing authorisation of recycled phosphate products as
7780 fertilisers in organic agriculture (under EU Organic Farming Regulation 889/2008). The
7781 dossier for struvite was submitted by the UK in 2014 and concerns struvite (magnesium
7782 ammonium phosphate) recovered in sewage works or from animal waste processing. The
7783 dossier for calcined phosphates was submitted by Austria in 2011 and concerns recovery
7784 from ashes of sewage sludge, meat and bone meal, or other biomass ash. **The committee**
7785 **concludes that for Ostara Pearl struvite (the submitted dossier) there is no hygiene risk**
7786 **(organic pollutants or pathogens), but that this is not proven for other struvite**
7787 **production methods and struvite-like end materials.** EGTOP concluded that struvite
7788 recovery is conform to environmental objectives (reduces N and P losses to surface waters,
7789 recycles nutrients, reduces consumption of non-renewable P resources) and that struvite
7790 should be authorised for organic farming “**provided that the method of production ensures**
7791 **hygienic and pollutant safety**”. For calcined phosphates, the committee also concludes that
7792 recovery from ashes is conform to environmental objectives (but with some concerns about
7793 energy consumption) and that calcined phosphates should be authorised for organic farming
7794 subject to being recovered from sewage sludge incineration ash and that heavy metal content
7795 should be limited. The EGTOP also concluded that these two products cannot be authorised
7796 under the Organic Farming Regulation until they are authorised under the EU Fertilisers
7797 Regulation. **Properly formulated nutrient recovery rules integrated into the revised**
7798 **Fertiliser Regulation could address the above considerations from the EGTOP and**
7799 **hence facilitate the market entry of STRUBIAS materials into the organic farming**
7800 **market.**

7801
7802 It should be noted, however, that STRUBIAS materials for organic farming are most likely to
7803 replace currently used (organic) P-fertilising materials as the use of mined rock phosphate
7804 and processed P-fertilisers is negligible in this agricultural sector. Regardless of their
7805 volumes used in organic farming, **the use of STRUBIAS materials as P-sources in organic**
7806 **farming is unlikely to contribute significantly to the substitution of mined rock**
7807 **phosphate and processed P-fertilisers** unless a significant expansion of organic farming
7808 occurs prior to the year 2030 at the expense of traditional farming.

7809

7810 7.3.3 Technological readiness level and potential production limitations

7811 Due to the combination of diverse input materials and output materials that can be produced,
7812 STRUBIAS production processes span a broad range of technological readiness levels. For
7813 the assessment of the market outlook for P-fertilisers derived from STRUBIAS materials for
7814 the year 2030, only STRUBIAS production processes of **technological readiness levels**
7815 **(TRLs) 6-9 are considered:**

- 7816 • TRL 6 – technology demonstrated in relevant environment (industrially relevant
7817 environment in the case of key enabling technologies);
- 7818 • TRL 7 – system prototype demonstration in operational environment;
- 7819 • TRL 8 – system complete and qualified;

- 7820 • TRL 9 – actual system proven in operational environment (competitive manufacturing
7821 in the case of key enabling technologies; or in space).

7822

7823 TRL 6 processes are covered in section 7.3.8.2 whereas TRL 7-9 processes are split up as a
7824 function of eligible input material (see section 7.3.4 - 7.3.7).

7825 The underlying justification for excluding TRL 1-5 processes is the unlikelihood of
7826 technologies of a lower technological readiness level to

- 7827 • surpass TRLs 6-9;
7828 • comply with administrative arrangements (e.g. obtain waste treatment permit,
7829 REACH registration of CE fertilising product containing STRUBIAS materials,
7830 arrangements with downstream distributors and retailers, etc.);
7831 • build the necessary infrastructure; and
7832 • perform extensive product testing on agronomic efficiency.

7833 in order to ensure market and consumer confidence (see section 7.3.2) prior to the year 2030.
7834 Although TRL 1-5 STRUBIAS materials are not covered in this section, the possibility of
7835 such emerging process pathways to contribute to the substitution effect for mined rock
7836 phosphate and processed P-fertilisers in the mid- to long-term is not excluded.

7837 An additional point that should be taken into consideration to derive the substitution potential
7838 for the year 2030 is the **availability of infrastructure** required to produce STRUBIAS
7839 materials. STRUBIAS production processes often include different phases and specific
7840 configurations within the production process: struvite can be precipitated in wastewater
7841 treatment plants that use biological nutrient removal techniques, K-struvite can be
7842 precipitated from manures after anaerobic digestion, DAP can be produced from mono-
7843 incinerated sewage sludge ashes, etc. As a matter of fact, in most occasions, STRUBIAS
7844 production takes place as part of a material cycle that also serves other objectives, for
7845 instance the handling and recycling of wastes and by-products in a bio-economy perspective,
7846 the production of a different primary material (e.g. clean water effluents, steel), etc.
7847 Therefore, the substitution potential will be partially dependent on the trade, market, needs
7848 and infrastructure to deal with co-products that are formed as part of the STRUBIAS material
7849 cascade. An additional aspect related to infrastructure that is especially relevant to consider
7850 for thermal oxidation materials & derivatives is the **configuration of the incinerator** (mono-
7851 versus co-incineration). This choice has a large impact on the suitable further use of the ashes
7852 from sewage sludge and meat and bone meal for nutrient recovery. It is preferable that P-rich
7853 input materials are mono-incinerated because co-incinerated materials are less suitable for P-
7854 recovery due to P-dilution. Even in Member States such as Germany and the Netherlands that
7855 incinerate a dominant share of their sewage sludge, mono-incinerators currently only process
7856 50% or less of the current volumes (STOWA, 2011; Wiechmann et al., 2013a).

7857 A major challenge also lies in increasing the production volumes of P-fertilisers derived from
7858 secondary raw materials. With the exception of manure ashes, struvite producing plants,
7859 EcoPhos and 3R agroc carbon (animal bone biochar), **P-recovery facilities are at present still
7860 piloting or producing minor P-fertiliser volumes compared to the apparent fertiliser P-**

7861 **consumption in Europe.** Other promising technologies, such as RecoPhos and Budenheim,
7862 will start to build full-scale installations in Europe, of which the first will most likely be
7863 operational in 2018. It should be evaluated to what extent current P-fertiliser production
7864 processes through the acidulation route could be adapted to use other P-sources than
7865 phosphate rock (for instance P-rich ashes). Leading P-fertiliser companies aim at decreasing
7866 their reliance on phosphate rock, but further technical process refinements may be required.
7867 Therefore, the recovered P-fertiliser volumes will only gradually become more abundant in
7868 the coming years. ICL Fertilisers has, for instance, expressed the ambition of substituting 25
7869 kt of P yr⁻¹ by the year 2025.

7870 In the following sections, the market potential for STRUBIAS materials derived from
7871 different input materials will be discussed, considering possible limitations on feedstock, P-
7872 recovery efficiency and available infrastructure.

7873

7874 7.3.4 STRUBIAS materials from crop residues, manure, and bio-waste

7875 7.3.4.1 *Introduction*

7876 In Europe, most **agricultural crop residues arise** on farms in the form of straw, maize
7877 stover, residues from sugar beet, oilseeds, grass cuttings, and pruning and cutting materials
7878 from permanent crops, and in the crop processing sector in the form of olive pits, seed husks,
7879 nut shells. By far the largest source of crop residues is the straw and stover from grain crops
7880 (wheat, barley and maize) (Kretschmer et al., 2013). There are essentially two overarching
7881 challenges to mobilising crop residues (Kretschmer et al., 2013). **Transport costs are high**
7882 because the residues are highly dispersed and have high bulk volumes and low value. This
7883 limits the range over which they can economically be collected for processing and makes it
7884 important that processing plants are optimally located. This requires appropriate investment
7885 in machinery and equipment, which may be beyond individual farmers' reach and necessitates
7886 cooperative action or specialised contractors. Harvesting costs can also be high in relation to
7887 the value of the material. Secondly, **many crop residues have existing uses and established**
7888 **practices, particularly for recycling organic materials and nutrients back to the soil.**
7889 There is poor awareness of sustainable extraction rates in relation to local conditions. There
7890 are therefore real risks that overextraction could cause detrimental reduction of soil organic
7891 matter with knock-on effects for wider soil functionality, soil biodiversity and erosion risk.
7892 Together these issues into account, the realistic potential derived from the technical-
7893 sustainable potential for agricultural crop residues – excluding grasslands - to contribute to
7894 renewable energy production has been estimated at 75 million tonnes per year in the EU-28,
7895 with a dominant contribution of the cereals wheat, maize and barley (Iqbal et al., 2016). The
7896 total P content in those crop residues would be around 110 kt P yr⁻¹ (see section 14.2).
7897 Much of the off-land technology for dealing with biomass is well understood and long
7898 established. Generally, the biomass based raw materials will require some physical **pre-**
7899 **treatment**, for example to separate components, dry, chop, and pelletise. Then, the
7900 processing will either follow a **biochemical pathway** (based on digestion, transesterification,
7901 or fractionation, the latter also serving as a type of pre-treatment) or a **thermochemical**
7902 **process** (based on hydrogenation, gasification or pyrolysis). The review of a wide range of

7903 life cycle assessments (LCA) for different treatments for crop residues shows the superiority
7904 of the anaerobic digestion pathway over other pathways for energy recovery and other bio-
7905 based applications from crop residues (Kretschmer et al., 2013). Thermochemical conversion
7906 technologies are less suitable for the direct processing of crop residues, characterised by
7907 relatively high moisture content.

7908
7909 Manure is defined as a Category 2 Animal By-product material according to Regulation (EC)
7910 No 1069/2009. Pursuant to this Regulation, **it can be applied to land without processing.**
7911 Most European countries have similar supplementary regulations regarding livestock farming
7912 including (i) licensing required for housing animals, (ii) storage of manures and slurries to
7913 enable a better agronomic utilization and (iii) prohibited periods for land spreading (usually
7914 the winter months of November to February). There are, however, differences between
7915 countries - and even between regions of the same country - as a consequence of the local
7916 situations and locally defined Nitrate Vulnerable Zones. A common pollution concern is
7917 nitrate contamination of water, but in most countries there are other pollution issues including
7918 ammonia emission (in the Netherlands) and odour nuisance (in the UK and Greece).

7919 In 2010, about **7.8% of the livestock manure production in the EU was processed, equal**
7920 **to a total manure volume of 108 million tonnes/year, and containing 556 kt N and 139 kt**
7921 **P** (Foget et al., 2011; Flotats et al., 2013). At least **45 different manure treatment**
7922 **technologies** are available (Foget et al., 2011). The largest levels of livestock manure
7923 processing were recorded in Italy, Greece and Germany, with 36.8%, 34.6% and 14.8% of the
7924 manure production being processed, respectively. The **objectives** for manure processing
7925 include **increasing the handling and management** for storage and transport of nutrients
7926 (viscosity, greenhouse gas emissions, storage of reduced volumes, etc.), the **selective**
7927 **removal of nutrients** (especially N), and **incentives received for renewable energy**
7928 **production** (biogas).

7929 **A clear tendency identified is that anaerobic digestion is the “door-opener” for the**
7930 **introduction of nutrient recovery technologies for cattle and pig manure of high**
7931 **moisture content (Foget et al., 2011).** Several EU Member States have no other type of
7932 manure processing than anaerobic digestion (Foget et al., 2011). The reason for this is that
7933 most of the manure nutrient processing technologies are complementary to anaerobic
7934 digestion, either as pre-treatment technologies that can enhance the biogas production, or as
7935 post-treatments, which can help to convert the digestate into products with envisaged
7936 properties (Foget et al., 2011). Solid manure fractions, such as poultry manure, can also be
7937 used for direct incineration leading the manufacturing of thermal oxidation materials &
7938 derivatives, as currently already performed in different EU Member States.

7939
7940 **Bio-waste** means biodegradable garden and park waste, food and kitchen waste from
7941 households, restaurants, caterers and retail premises and comparable waste from food
7942 processing plants. Across the European Union, somewhere between 118 and 138 million
7943 tonnes of bio-waste arise annually, of which currently only about 25% is effectively recycled
7944 into high-quality compost and digestate (European Commission, 2010a). The total P content
7945 of this fraction is unknown, but solid residues from the food processing industries (e.g.
7946 brewery, sugar industry) make up at least 36 kt P (see section 14.6).

7947
7948 **Co-digestion of animal manure with solid or slurried bio-waste of high methane**
7949 **potential such as oily residues and by-products, alcohol residues, digestible organic**
7950 **wastes from agri-processing and food industry or food waste, produces more gas from**
7951 **the digester than manure only** (Al Seadi and Lukehurst, 2012). Co-digestion can therefore
7952 improve the profitability of biogas plants, and is a common practice in many biogas facilities
7953 in Europe (Foget et al., 2011). In addition, co-digestion of animal manure and slurry with
7954 suitable organic wastes from food industries utilise the huge amounts of organic wastes that
7955 are produced annually and in many places otherwise dumped into landfills. The liquid
7956 fraction of co-digestates varies in phosphate content depending on the composition of the
7957 input materials; digestates that contain a dominant share of manure and food industry
7958 residues (e.g. sugar production, residues from the brewery industry) typically have phosphate
7959 contents above 500-2000 mg L⁻¹ PO₄³⁻P, whereas liquid digestate fraction produced from
7960 dominantly plant-based materials contain much lower phosphate contents (~0 - 500 mg L⁻¹
7961 PO₄³⁻P) (Akhlar et al., 2017).

7962

7963 7.3.4.2 Policy and legal framework

7964 The field extraction of crop residues and manure for STRUBIAS nutrient recycling processes
7965 manifestly result in the loss of nutrients and other valuable agronomic assets, such as soil
7966 organic matter. Therefore, it is clear that STRUBIAS nutrient recycling processes from these
7967 materials will only take place for reasons other than nutrient recycling close the site of
7968 extraction of manures and crop residues (hygienisation, transport logistics, synergies with
7969 energy recovery, etc.). Fundamentally, it is assumed that **significant materials from the**
7970 **agricultural sector might be used as input materials for STRUBIAS processes bearing**
7971 **in mind two different rationales:**

- 7972 i. **Pollution control:** in case of manure, in European regions characterised by nutrient
7973 excess and the need for the long-distance translocation of fertilising products to
7974 nutrient poor regions or the storage under appropriate conditions.
- 7975 ii. **Synergies with other bio-based materials:** secondary raw materials from the
7976 agricultural sector are used for STRUBIAS production processes as part of a
7977 cascading approach; in this case, the input materials for the STRUBIAS production
7978 processes are the residues of a process aimed at producing a different primary raw
7979 material from crop residues and manure, often renewable energy;

7980 Both rationales are not mutually exclusive and measures related to pollution control are
7981 mostly accompanied by additional benefits obtained through energy recovery.

7982

7983 As outlined in the Waste Framework Directive (Regulation (EC) No 2008/98), Member
7984 States shall take measures to encourage (a) the **separate collection of bio-waste with a view**
7985 **to the composting and digestion** of bio-waste; (b) the treatment of bio-waste in a way that
7986 fulfils a high level of environmental protection; (c) **the use of environmentally safe**
7987 **materials produced from bio-waste.**

7988 Pollution control

7989 **International conventions** of relevance to P use in agriculture include inter alia UNEP/MAP
7990 (**United Nations Environment Programme/Mediterranean Action Plan**), CBD
7991 (**Convention on Biological Diversity**) and OSPAR (**Oslo & Paris Convention to prevent**
7992 **pollution**). Such international treaties often give an impetus to harmonise standards amongst
7993 all Member States of the European Union. Despite the significant off-site impact that diffuse
7994 contamination of P from agricultural land poses, there is no specific legislation that is directly
7995 concerned with the use of P in agriculture at European level. There is an insufficiency of
7996 appropriate institutional arrangements specific to the environmental pollution of P. Aspects of
7997 the P problem are, however, integrated in several policy areas and related legal instruments at
7998 European level. This section provides an overview of existing regulations and directives
7999 dealing with farm-level nutrients, including P, use and production at **European level**.

8000

8001 The **Water Framework Directive** (Directive 0060/2000) is a legal obligation to protect and
8002 restore the quality of waters across Europe. Measures applied under the Water Framework
8003 Directive affecting the use of P in agriculture relate to best environmental practices and
8004 include the reduction of nutrient application, the modification of cultivation techniques, the
8005 proper handling of pesticides and fertilisers, and the prevention of soil erosion through
8006 erosion minimising soil cultivation. The P balance surplus is a commonly used indicator for
8007 identifying areas vulnerable to nutrient pollution in the pressures and impacts analysis.

8008

8009 The **Nitrates Directive** (Directive 0676/1991) established in 1991 aims to reduce water
8010 pollution caused or induced by nitrates from agricultural sources and to prevent further nitrate
8011 pollution. The Water Framework Directive explicitly refers to the Nitrates Directive for
8012 information on diffuse pollution of nitrates from agricultural activities and extends this to
8013 phosphates. Under the Nitrate Directive, Member States had to establish action programmes
8014 for nitrate vulnerable zones with the purpose of meeting the objective of reducing and
8015 preventing nitrate pollution. It is the responsibility of each Member State to set limits
8016 appropriate to their vulnerable zones; there is no specific limits set in the Directive. However,
8017 the action programmes must include measures to ensure that, for each farm or livestock unit,
8018 the amount of livestock manure applied to land each year, including processed forms of
8019 manure and direct excretions by animals, shall not exceed 170 kg N per hectare. The
8020 measures established within the Action Programmes aim to control diffuse and direct water
8021 pollution and also to influence the use of P in farm practice. For instance, by limiting the
8022 annual application of N fertiliser and livestock manure, defining legally binding maximum
8023 concentrations of nitrates in drinking water and designating periods when the application is
8024 prohibited, the directive clearly aims at establishing and maintaining the natural balance of
8025 nutrients in soils. Through these measures a massive influx of nutrients to ground- and
8026 surface water and thus potential eutrophication is prevented, while excess nutrients,
8027 oversaturation and a possible ensuing soil quality degradation is avoided at the same time.
8028 The monitoring of waters for nitrate and the review of the eutrophic state of waters must be
8029 repeated every 4 years.

8030

8031 Pollution by P is also partially covered by the **Directive on Bathing Water** (Directive
8032 0007/2006), which together with the Nitrates Directive and the Industrial Emissions Directive
8033 has been linked since 2000 in the Water Framework Directive.

8034
8035 The **7th Environmental Action Programme** encourages the full implementation of the
8036 Water Framework Directive, in order to achieve levels of water quality that do not give rise
8037 to unacceptable impacts on, and risks to, human health and the environment.

8038
8039 **The Rural Development Programme** has established various agri-environment measures
8040 throughout the European Union directly or indirectly addressing diffuse contamination by P.
8041 Some of these measures are directed at mitigating soil erosion such as crop rotations, mulch
8042 seeding retaining stubble after harvest and ploughing restrictions. Other measures tackle the
8043 problem of excess nutrients through reduced fertiliser use. All measures that impact soil
8044 erosion and nutrient balances ultimately result in a reduction of diffuse contamination by
8045 phosphates from agricultural land.

8046
8047 The **Industrial Emissions Directive (IED, 2010/75/EU)** introduces an integrated cross-
8048 media approach, aiming to prevent or minimise emissions to air, water and land, as well as to
8049 avoid waste production with a view to achieving a high level of environmental protection as a
8050 whole. The IED Directive also concerns potentially polluting industries in the agricultural
8051 sector, among which are intensive pig and poultry farms. A single permit based on the
8052 concept of Best Available Techniques (BAT including limit values) must include all
8053 arrangements made, including emission limit values for pollutants, for water, air and land,
8054 and may, if necessary, contain requirements for the protection of the soil and the groundwater
8055 as well as measures or waste management (Art. 9(3)) in order to continuously prevent and
8056 reduce pollution. The purpose of the IED Directive was to achieve integrated prevention and
8057 control of pollution arising from several categories of industrial activities. The indicative list
8058 of main polluting substances to be taken into account if they are relevant for fixing emission
8059 limit values includes oxides of N and substances which contribute to eutrophication (P and
8060 N).

8061
8062 The main purpose of the **Habitats Directive** (Directive 0043/1992) and **Birds Directive**
8063 (Directive 0147/2009) is to ensure biological diversity through the conservation of natural
8064 habitats and wild flora and fauna within the European territory, while taking into account
8065 economic, social, cultural and regional requirements. Farmers who have agricultural land in
8066 Natura 2000 sites and face restrictions due to the requirements of the Habitat-Directive are
8067 eligible to receive payments for the management of these sites by the Rural Development
8068 Regulation, which helps promote environmental-friendly farming. Depending on the specific
8069 conditions of a certain area, these include measures to reduce the use of pesticides and
8070 fertilisers, measures to mitigate the effects of soil compaction, e.g. limitations on the use of
8071 machinery or the setting of stocking limits, or measures aiming to regulate the irrigation of
8072 agricultural land.

8073

8074 **Specific EU Member States** have set in place **national or regional regulations** to control
8075 for P use on farmland (Buckwell and Nadeu, 2016). Belgium-Flanders, Estonia, Finland,
8076 France-Brittany, Germany, Ireland, Luxembourg, Northern Ireland, Sweden and The
8077 Netherlands apply a regulation system that limits maximum P application rates. Limits are
8078 mostly dependent on crop type, soil P status and yield.

8079

8080 In spite of significant improvement in potential P surpluses within the EU, the **latest**
8081 **progress report on the implementation of the Water Framework Directive** (European
8082 Commission, 2015b) indicated that Member States need to strengthen their basic measures to
8083 tackle diffuse pollution caused by agriculture. Notwithstanding the fact that there is still a
8084 long way to go to achieving ‘good status’ (as defined in the Water Framework Directive)
8085 many Member States rely only on voluntary measures. Moreover, they need to ensure that
8086 their measures target the sources and chemicals that cause water bodies to fail to achieve
8087 ‘good status’. While these can effectively close a fraction of the remaining gap, significant
8088 improvement can only be achieved through compulsory basic measures. Member States
8089 should tackle the sources of pollution by fully implementing the Water Framework Directive
8090 measures and water-related legislation, especially the Nitrates Directive, Industrial Emissions
8091 Directive and Urban Waste Water Treatment Directive. This is much preferable to using end-
8092 of-pipe treatment, for instance to ensure the high quality of drinking water while avoiding
8093 high treatment costs and protecting the environment. Member States are encouraged to
8094 continue extending the establishment of safeguard zones to protect areas used for the
8095 abstraction of drinking water, in particular as regards surface waters.

8096

8097 The **last report on the Nitrates Directive** (European Commission, 2013b) points to a slight
8098 improvement in groundwater nitrate pollution while stressing the need for further action to
8099 reduce and prevent pollution. This is confirmed by the analysis of "Programmes of Measures"
8100 reported by the Member States. Despite the fact that 63% of river basin districts reported that
8101 implementation of the Nitrates Directive is not enough to tackle diffuse pollution to the level
8102 needed to meet Water Framework Directives objectives, necessary measures have not been
8103 added to address the remaining shortcomings. Diffuse pollution still affects 90% of river
8104 basin districts, 50% of surface water bodies and 33% of groundwater bodies across the EU.
8105 The agricultural sector is the primary source of diffuse pollution. **The report indicates that**
8106 **there are still many gaps in the basic measures put in place by Member States to**
8107 **address agricultural pressures, including a lack of measures to control phosphate and**
8108 **nitrate emissions outside nitrate vulnerable zones established under the Nitrates**
8109 **Directive.**

8110

8111 Supplementary measures reported in agriculture are largely voluntary, including advice
8112 schemes and agri-environment measures of the **Common Agriculture Policy (CAP)** such as
8113 **farm extensification** and **organic agriculture**.

8114 **Renewable energy**

8115 Renewable Energy Sources contribute to **climate change mitigation** through the reduction of
8116 greenhouse gas emissions, achieve sustainable development, protect the environment and

8117 improve citizens' health. Moreover, renewable energy is also emerging as a driver of
8118 inclusive economic growth, creating jobs and reinforcing energy security across Europe.

8119

8120 These aspects are enshrined in Article 194 of the Treaty on the Functioning of the EU, which
8121 has conferred Union competences to promote renewable energy. The EU has long been a
8122 world leader in the promotion and development of renewable energy, steering the effort to
8123 combat climate change, encouraging the shift to a low-carbon economy and stimulating high-
8124 potential economic growth.

8125

8126 The current 2020 framework sets an **EU 20% target for energy consumption** which relies
8127 on legally binding national targets until 2020. **National Renewable Energy Action Plans**
8128 **(NREAPs)** and the biennial monitoring provided for by Directive 2009/28/EC on the
8129 promotion of the use of energy from renewable sources have been effective in promoting
8130 transparency for investors and other economic operators. This has favoured the rapid increase
8131 in deployment in the share of renewables from 10.4% in 2007 to 17.0% in 2015.

8132

8133 In October 2014, the European Council agreed the 2030 framework for climate and energy
8134 reaffirming the Union's long-term commitment to the ambitious EU strategy in renewable
8135 energies. **The new framework sets out the European Union target of at least 27% for the**
8136 **share of renewable energy consumed in the EU in 2030.** This target is binding at EU level
8137 and will be fulfilled through individual Member States' contributions guided by the need to
8138 deliver collectively for the EU. In addition, the new framework also enables the collective
8139 delivery to be done without preventing Member States from setting their own, including more
8140 ambitious, national targets. Member States can support renewable energy, subject to State aid
8141 rules.

8142

8143 To qualify for the Renewable energy Directive targets, materials consumed in the EU must
8144 comply with strict **sustainability criteria** provided in Article 17 of the Directive, in order to
8145 be eligible for financial support and to count towards the EU renewable energy target.
8146 Rigorous requirements are set in the Renewable energy Directive on the minimum level of
8147 greenhouse gas savings, appropriate land use, as well as monitoring requirements for any
8148 potentially adverse effects. Agricultural raw materials produced within the EU must be
8149 produced in accordance with the minimum requirements for good agricultural and
8150 environmental practices that are established in the common rules for direct support schemes
8151 under the common agricultural policy. **Using manure and agricultural residues as**
8152 **feedstock is highly advantageous as it does not augment pressure on land and water**
8153 **resources and offers very high greenhouse gas mitigation gains** (European Environment
8154 Agency, 2013a).

8155

8156 **Materials from the agronomic sector can contribute to renewable energy production**
8157 **through the production of biogas and the thermochemical conversion of solid biomass.**

8158 The resulting materials (i.e. digestates and ashes) are suitable intermediate or end materials of
8159 STRUBIAS production processes, including precipitated phosphate salts & derivatives, thermal
8160 oxidation materials & derivatives and pyrolysis & gasification materials.

8161
8162 The application of anaerobic digestion for biogas production remains widespread as a useful
8163 **bioenergy production** route due to the robustness of its main design configurations and
8164 pathways. Anaerobic digestion serves multiple purposes. It provides a treatment platform for
8165 decreasing large amounts of complex organic materials, converting the majority of such
8166 molecules into monomers i.e. methane and carbon dioxide (biogas) utilisable in the energy
8167 sector in multiple pathways. The EU Common Agricultural Policy (CAP, Pillar II - Rural
8168 Development Policy) mechanisms provide support for capital investments on farm or as part
8169 of local renewable energy initiatives, including providing grant aid for the installation of
8170 anaerobic digesters.

8171
8172 The produced digestate can be used as fertiliser for crops without any further processing.
8173 However, the need for efficient nutrient management, required by restrictions on manure
8174 applications in areas with high livestock density, make recovery and recycling from plant
8175 nutrients from manure and bio-based waste streams increasingly important for farmers. **The**
8176 **anaerobic treatment serves to improve the efficiency for nutrient recycling as solid–**
8177 **liquid separation procedures can be applied to separate the solid from the liquid**
8178 **digestate** (Möller and Müller, 2012). The solid phase may be characterized as an organic
8179 fertiliser comparable with solid animal manure with highly available N and P contents, best
8180 suited to application on arable land in order to increase soil humus reproduction and to
8181 substitute P-losses via harvested P-rich biomass such as grains. Separated liquid digestates
8182 are characterised as liquid N–K fertilisers. A digestate solid– liquid separation, with a target-
8183 oriented separate application of the liquid and solid phase, is, therefore, a technique for
8184 further improvement of the nutrient use efficiency upon return to the field (Möller and
8185 Müller, 2012).

8186
8187 The traditional substrates for anaerobic digestion plants in Europe are **agricultural/livestock**
8188 **residues** (manure and slurries), **biogenic waste** (food waste, municipal organic waste, etc.),
8189 **energy crops** (maize whole crop silage, sugar beet, grass silage), as well as **residues from**
8190 **food and agro-industries** (animal by-products from abattoirs, brewers' spent grains and
8191 solubles, etc.) (Drogs et al., 2015). More recently, residues from the **bioethanol** and the
8192 **biodiesel** industries are used. Producing biogas from dedicated energy crops, such as maize,
8193 sugar beet or wheat, requires careful analysis due to their land use implications. The
8194 emissions of greenhouse gases and acidifying gases such as ammonia from these systems are
8195 substantial. The use of specifically grown energy crops for biogas has thus been questioned
8196 due to sustainability concerns. Such energy cropping patterns are not 'environmentally
8197 compatible' according to the criteria of a 2006 EEA study (European Environment Agency,
8198 2006). Where manure or organic residential wastes are used, the greenhouse gas performance
8199 of biogas pathways is far better (European Environment Agency, 2013a). **Wastes and crop**
8200 **residues are currently underused and can contribute significantly to reaching EU**
8201 **bioenergy targets** (European Environment Agency, 2013a). The latter report projects that
8202 agricultural residues and organic waste would contribute 44% of the total supply for meeting
8203 the NREAP bioenergy targets for agriculture. Therefore, introducing new, cost-competitive

8204 and sustainable feedstock such as manure, straw and even grass, will be increasingly
8205 important for the biogas sector to deliver its full potential in the future energy scenario.

8206

8207 Biogas is a diverse energy source, suitable as a flexible and storable energy form. Between
8208 2000 and 2013 the production of biogas in Europe increased six-fold, from 2.2 to 13.5 Mtoe,
8209 with the main producers being Germany, UK and Italy, followed by the Czech Republic,
8210 France and the Netherlands. Germany is the leader in biogas production from biomass with
8211 more than 65% of the EU production in 2013 (Flach et al., 2015). For Germany, it was
8212 estimated that in the year 2011, approximately 20% of the animal wastes and the biomass
8213 harvested from an area of approximately 1.1 million ha were used as feedstock in biogas
8214 plants (Möller and Müller, 2012). Italy, the Czech Republic and the Netherlands followed
8215 with a production share of 14%, 5%, and 2%, respectively (Flach et al., 2015). The incentive
8216 for farmers in Germany to invest in biogas digesters is a guaranteed feed-in price for the
8217 generated electricity, which is considerably higher than that of electricity generated from
8218 fossil fuels, natural gas, coal, or nuclear sources. This feed-in price is guaranteed for 20 years
8219 from the erection of the plants. However, changes to the German renewable energy law in
8220 2012 and 2014 and similar policy changes in Italy, **reduced the attractiveness of investing**
8221 **in new plants (Flach et al., 2015)**. As a result, the further increase in biogas plants will be
8222 minimal. Instead, investments will focus on rejuvenating existing plants. Biogas production is
8223 increasing in the Czech Republic (driven by feed-in tariffs for the derived electricity) and
8224 Denmark (driven by the goal to use 50% of livestock manure for biogas production in 2020)
8225 (Flach et al., 2015). In France, the government seeks to increase the number of biogas
8226 facilities by means of investment support. However, administrative burden and a lack of
8227 profitability for investors limit the expansion. The development is also stagnant in the Slovak
8228 Republic and Hungary. Slovak energy distribution companies announced a blanket stop on
8229 connecting new electricity producing facilities (over 10 kW) to the grid until further notice.
8230 Hungary reports problems with green energy feed-in systems and the complicated non-
8231 harmonised investment licensing. In addition, low electricity purchase prices make further
8232 investments into biogas facilities economically unattractive. In the Netherlands, the low
8233 electricity prices have even led to a decline in biogas production.

8234

8235 Landfilling of biodegradable waste

8236 The **Landfill Directive (1999/31/EC)** obliges Member States to reduce the amount of
8237 biodegradable municipal waste that they landfill to 35% of 1995 levels by 2016 (for some
8238 countries by 2020). On 2 July 2014, the European Commission adopted a legislative proposal
8239 to review waste-related targets in the Landfill Directive as well as recycling and other waste-
8240 related targets in Directive 2008/98/EC on waste and Directive 94/62/EC on Packaging and
8241 Packaging Waste. The proposal aims at phasing out landfilling by 2025 for recyclable waste
8242 (including plastics, paper, metals, glass and bio-waste) in non-hazardous waste landfills,
8243 corresponding to a maximum landfilling rate of 25%.

8244

8245 7.3.4.3 *Anaerobic digestion followed by P-precipitation*

8246 The European Environment Agency that forecast a reduced growth rate for biogas production
8247 in Europe, with a predicted **annual growth rate of 3% for the period 2013-2020 based on**
8248 **the NREAPs** (European Environment Agency, 2016).

8249
8250 The anaerobic digestion process does not affect the content of phosphate in digestate, which
8251 is completely dependent on the content in the substrate. Nonetheless, the technique is a door-
8252 opener for manure solid-liquid separation processes (Foget et al., 2011).

8253
8254 **Box 2: Precipitated phosphate salts & derivatives from the liquid fraction of anaerobically**
8255 **digested materials**

8256
8257 To derive the substitution potential of P-fertilisers containing STRUBIAS materials from the
8258 eligible input materials that have undergone an anaerobic digestion process, following
8259 assumptions and calculations were made:

8260
8261 1) **Digestates from manure and specific food industries** are more suitable for P-recovery
8262 than digestates from crop residues and other biowaste materials due to the higher P content in
8263 the liquid digestate fractions. Although co-digestion of other organic materials (food waste,
8264 crop residues) is common practice, the liquid fraction of such digestates is typically low in
8265 phosphates that can be precipitated (Akhiar et al., 2017). Therefore, this assessment only
8266 takes into account the P present of anaerobically digested manures and solid residues of food
8267 processing industries.

8268
8269 2) In 2010, about 88 million tonnes of **manure**, excluding other organic materials as co-
8270 substrates, were anaerobically digested in the EU (Flotats et al., 2013). Anaerobic digestion is
8271 also a door-opener for separation processes and treatment of the liquid manure fraction
8272 (Foget et al., 2011). Using the average P-contents of Foget et al. (2011), the total manure P
8273 that is subjected to anaerobic digestion was estimated at 114 kT of P for the year 2010. The
8274 European Environment Agency (2016) indicates that biogas production from anaerobic
8275 digestion would roughly double in the period 2010-2020. After 2020, an annual 3% growth,
8276 similar to the period 2013-2020, was assumed. Therefore, it is assumed that the total volume
8277 of materials from the agricultural sector would increase by a factor 2.69 relative to the
8278 amounts processed by anaerobic digestion in the year 2010. Hence, **a total amount of 237**
8279 **million tonnes of manure would be processed through anaerobic digestion, with an**
8280 **estimated P content of 306 kt P**. This number is considered realistic; it equals the excess P
8281 that accumulates in soils from six livestock-dense Member States: Belgium, Denmark,
8282 Germany, France, the Netherlands, and the UK (based on data for the year 2005 by van Dijk
8283 et al., 2016).

8284
8285 3) P-rich residues from the **food processing industry** are taken into account (36 kt P yr⁻¹,
8286 mainly from sugar residues and brewery industries; for the reference year 2005). These P-
8287 estimates are assumed to remain steady for the year 2030.

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5) It is assumed that **precipitated phosphate salts & derivates are recovered from all anaerobic digesters that process manure and solid processing residues**. The possible non-compliance with this assumption is presumed to be counteracted by the fact that liquid manure fractions can also be obtained by solid-liquid separation techniques on raw manures; thus not after anaerobic digestion.

4) At present, the P-recovery process of **Stichting Mestverwerking Gelderland (SMG)** is the only process at TRL level 7-9 processes in Europe that processes P-rich digestate liquids that complies with the draft proposals of the STRUBIAS nutrient recovery rules. In this process, a mineral phase dominantly composed out of K-struvite is precipitated from the liquid digestate fraction. The assessment of the process indicates the business case for the plant in the Netherlands where manure treatment is associated with a gate fee. It is assumed that more operators might emerge in other livestock-dense EU regions in the near future.

5) Following solid/liquid separation of the digestate, between 10-30% of the total P content will end up in the liquid digestate fraction, and about 80-95% of this P in the liquid fraction can be recovered as precipitated phosphate salts & derivates. Therefore, the total P-recovery efficiency from anaerobically digested manure varies between 8% and 28.5%. The exact numbers are highly dependent on the separation technology applied (Drosg et al., 2015). In order to estimate the P-recovery potential, **a P-recovery efficiency of 13.3% as indicated by SMG** is used.

6) The **relative agronomic efficiency (RAE_{PUE})** of precipitated phosphate salts & derivates relative to mined rock phosphate and processed P-fertilisers is assumed to be 1.05 (see section 6.2.2).

7) Considering 1) - 6), **the 2030 P-recovery from anaerobically digested eligible input materials is estimated at 48 kt P yr⁻¹** ((306 kt P yr⁻¹ (manure) + 36 kt P yr⁻¹ (food processing) * 0.133 (recovery efficiency) * 1.05 (RAE)). It is estimated that these materials will be brought on the market directly as P-fertilisers or as part of a physical blend, and that their further processing in recovered phosphate salt derivates (e.g. MAP, DAP, TSP, nitrophosphate, etc.) is unlikely.

7.3.4.4 *Thermochemical conversion processes of solid fractions from the agricultural sector*

The **poultry manure** fractions and other manure fractions that have undergone **a solid-liquid separation process** might be suitable for thermochemical conversion processes due to their relatively low moisture content. Both **thermal oxidation and pyrolysis spectrum techniques** are considered in the STRUBIAS project.

8328 Thermal oxidation

8329 Thermal oxidation processes have been widely used for the production of energy (electricity
8330 and power). **Poultry litter incinerators** in the UK (Fibrophos), IE (BHSL), the Netherlands
8331 (BMC Moerdijk), and some Scandinavian Member States produce approximately **150.000 -**
8332 **200.000 tonnes of poultry litter ash** per year in the year 2015, equalling an estimated
8333 recovery of about **12-16 kt P yr⁻¹** (assuming a P content of 8%). A best estimate of 14 kt P yr⁻¹
8334 is assumed.

8335
8336 The aim of bioenergy technologies is to convert biomass into different forms of energy
8337 including power, heat, combined heat & power (CHP) and liquid biofuels. **The primary aim**
8338 **of poultry litter combustion is the production of renewable energy** (Billen et al., 2015).
8339 The calorific power of poultry litter when used as a fuel is about half that of coal (Moore,
8340 2013). In order to meet NREAP expectations, **a compound annual growth of 7% over the**
8341 **period remaining up to 2020 would be necessary** (European Environment Agency,
8342 **2016**).

8343
8344 The CE Delft research firm established the environmental effects of nine different ways that
8345 poultry litter – from the chicken to the field – can be used (Ehlert and Nelemans, 2015a;
8346 Ehlert and Nelemans, 2015b; De Graaff et al., 2017). The study concluded that the production
8347 of electricity through thermal oxidation is the most **attractive and sustainable manner to**
8348 **process poultry litter from an environmental perspective**.

8349
8350 In section 6.2.3, a relative agronomic efficiency for the response variable phosphorus use
8351 efficiency (RAE_{PUE}) of 1.49 was observed. The accuracy of this value is, however, uncertain,
8352 because this value was based on only 4 cases. Data from a research study performed by
8353 Alterra Wageningen UR, cited in De Graaff et al. (2017) indicated a relative fertiliser
8354 efficiency varying from 37% to 100%. These data were not included in the meta-analyses of
8355 section 6.2.3 due to lack of detailed results. Therefore, the lower end estimate of **0.90 for**
8356 **RAE_{PUE} for poultry litter ashes was retained for further calculations**; this value
8357 corresponds roughly to the weighted mean of the data from section 6.2.3 and the results given
8358 in De Graaff et al. (2017).

8359

8360 Box 3: Thermal oxidation materials & derivatives from solid manure fractions

8361

8362 To derive the substitution potential of P-fertilisers containing STRUBIAS materials from
8363 solid manure fractions from the agricultural sector, following assumptions and calculations
8364 were made:

8365

8366 1) Only poultry litter is considered as input material for thermal oxidation materials &
8367 derivatives as no TRL 7-9 thermal oxidation processes from other solid manure fractions have
8368 been described that produce P-fertilisers.

8369

- 8370 2) In 2015, a total amount of 150.000 – 200.000 tonnes of poultry litter ash was produced,
8371 with an estimated P content of 14 kt P.
8372
- 8373 3) An annual growth rate in energy production from solid biomass of 7%, forecasted by the
8374 European Environment Agency (2016) for the period 2013-2020, has been assumed for
8375 poultry litter and extended until the year 2030. Accumulated over the time period 2015-2030,
8376 this would imply an increase of renewable energy production from poultry litter manure by a
8377 factor 2.76. Expressed on a P basis, the total P recovered as poultry litter ash would equal 39
8378 kt P yr⁻¹ for the year 2030.
8379
- 8380 4) The agronomic efficiency of poultry litter ash (RAE_{PUE}) relative to mined and synthetic
8381 fertilisers is assumed to be 0.90.
8382
- 8383 5) Considering 1) – 4), the estimated P-recovery from solid material from the agricultural
8384 sector is estimated at 35 kT of P.
8385

8386 Pyrolysis spectrum techniques

8387 Gasification and pyrolysis can potentially convert a range of biomass types with high input-
8388 output efficiency and these are **therefore interesting technology options to convert**
8389 **residues and wastes that do not occur in large and geographically concentrated volumes**
8390 (Kretschmer et al., 2013). One of the advantages of pyrolysis spectrum techniques is that
8391 processing facilities can operate at a relative small industrial scale, enabling the establishment
8392 of regional facilities to process high-volume, geographically dispersed materials, such as
8393 excess manure, without excessive transport costs. Moreover, the syngas generated during the
8394 pyrolysis process is mostly used as an energy source to dry the manure input material as
8395 pyrolysis processes of the raw input materials is often not autothermal. Starting from input
8396 materials that have not undergone a solid-liquid separation, this process pathway would
8397 therefore only marginally contribute to the production of renewable energy, but would be
8398 principally performed as a measure for pollution control.
8399

8400 Although no commercial thermochemical technologies using biomass at the time of writing
8401 have been identified in Europe, several commercial plants are close to piloting and
8402 operationalisation, both in Europe and rest of the world. The emerging technologies
8403 especially focus on **the treatment of the solid pig manure fraction**, as obtained after solid-
8404 liquid separation treatment. This issue is particularly relevant given that the highly diluted pig
8405 manure is associated with high transport costs, and most farmers have only a small surface
8406 area to dispose the slurry produced (Foget et al., 2011).
8407

8408 The EU funded **BioEcoSim** project (<https://www.bioecosim.eu/>) projects to process
8409 2.000.000 m³ of pig manure per year, resulting in a production of 62 kt of pyrolysis &
8410 gasification materials derived from pig manure (3 kt P, assuming a 5% P content in the
8411 resulting output material). The Japanese company **Hitachi Zosen Corporation** also aims to
8412 turn pig manure from pig farmers, in particular in the Netherlands and Belgium, into P-rich

8413 pyrolysis & gasification materials. The latter company has gained experience with the
8414 process from their operations in Japan.

8415

8416 The **market outlook for this STRUBIAS pathway is associated to a large degree of**
8417 **uncertainty** as the resulting pyrolysis material is the only output material that will be brought
8418 on the market. In contrast to anaerobic digestion techniques, no energy can be recovered from
8419 pyrolysis and the increase demand for renewable energy will thus not stimulate this
8420 STRUBIAS pathway. The economic valuation of pyrolysis & gasification materials is at
8421 present, however, largely unknown, as well as the degree of consumer confidence associated
8422 to the end-material due the lack of long-term test results on agronomic efficiency for this
8423 material. Pyrolysis & gasification materials from solid manures have a P content of about 4-
8424 6%, organic C (~ 30-60%) and the presence of other nutrients in smaller quantities such as N,
8425 Mg and K. Therefore, the **nutrient density** of the resulting pyrolysis material is much **lower**,
8426 resulting in a higher land application cost for pyrolysis & gasification materials relative to
8427 more concentrated P-fertilisers. **It is assumed that the market potential of pyrolysis**
8428 **material in the conventional agricultural sector is indeterminate in the short-term (<**
8429 **year 2030).** Given the lack of availability of concentrated P-fertilisers for organic farming,
8430 pyrolysis & gasification materials could potentially make an entry into the organic farming
8431 sector. **Due to the limited availability of P-dense fertilisers that meet the principles and**
8432 **requirements for organic farming, it is believed that this STRUBIAS material might be**
8433 **demanded and traded in this sector.** Here, the higher price setting of P-rich pyrolysis &
8434 gasification materials relative to mined rock phosphate and processed P-fertilisers could
8435 potentially be compensated by the higher sales prices of organically-grown food products.
8436 Manure-derived pyrolysis & gasification materials could thus potentially replace current
8437 organic P-inputs such as manure, compost, meat & bone meal and meat & bone meal ashes in
8438 the organic farming sector.

8439

8440 7.3.5 STRUBIAS materials derived from slaughter residues

8441 7.3.5.1 *Introduction*

8442 **Animal by-products activities covered under this section include the by-products**
8443 **obtained from the treatments of entire bodies or parts of animals at slaughterhouses.**
8444 Rendering activities include the treatments of animal by-products both intended for and not
8445 intended for human consumption. The animal by-products industry handles all of the raw
8446 materials that are not directly destined for human consumption. **The use and disposal routes**
8447 **permitted are governed by Regulation (EC) No 1069/2009 laying down health rules as**
8448 **regards animal by-products and derived products not intended for human**
8449 **consumption.** Animal by-products are classified in three different categories of which
8450 category 2 and 3 can be used for the production of fertilisers. **The transformation of**
8451 **category 1 material into fertilisers is effectively prohibited by Regulation (EC) No**
8452 **1069/2009, even after incineration, as any produced ashes should be disposed of as**
8453 **waste.** The ban on the use of processed animal proteins in feed for animals farmed for food
8454 and pet food has led to the diversification of the animal by-products industry.

8455

8456 The **rendering industry** processes most of the **animal by-products not intended for**
8457 **human consumption** as well as a significant fraction of the **catering waste**, also having a
8458 legal status as animal by-product (European Commission, 2005). There appears to be a trend
8459 towards fewer slaughterhouses with increasing average throughputs, favouring the **central**
8460 **collection of the slaughterhouse residues** for possible further processing to STRUBIAS
8461 materials (European Commission, 2005). In the year 2016, the rendering industry processed
8462 about 12.4 million tonnes of animal by-products of category 2 (0.8 million tonnes) and 3
8463 (11.7 million tonnes) (EFPPA, 2017).

8464

8465 *7.3.5.2 Sector outlook for the rendering industry and material use*

8466 **The total meat consumption in the EU is expected to remain stable within the EU for**
8467 **the period 2016-2026** (European Commission, 2016a). After the recent recovery, EU-28 per
8468 capita consumption of meat products is expected to rise only slightly over the projection
8469 period, mainly as a result of the increase in meat consumption in the EU-13. However,
8470 developments in total meat consumption depend both on evolutions in per capita
8471 consumption and in total population numbers. The population in the EU-13 is projected to
8472 decline in the next years at such a rate that the per capita increase in meat consumption is
8473 almost completely flattened out by the shrinking population, resulting in only 35 000 t
8474 additional meat consumed by 2026. In the EU-15, by contrast, the population is still
8475 increasing and therefore, with stable per capita consumption, total meat consumption is
8476 expected to grow by 600 000 t by 2026. Combined, total EU meat production is expected to
8477 expand only slightly in the next 10 years, reaching 47.6 million tonnes. This can be mainly
8478 attributed to an increase in poultry meat production and to a lesser extent to pig meat
8479 production, while beef and veal production will decrease substantially. Production of poultry
8480 is expanding (+ 4.5% for the period 2016-2026, to a total value of about 15 million tonnes of
8481 meat produced), driven by a favourable domestic market. Pig meat production is expected to
8482 increase slightly (+0.1%, to a total value of about 23 million tonnes of meat produced),
8483 despite the environmental concerns. After a few years of increase, beef production is
8484 expected to return to its downward trend in the coming years (-8.6% for the period 2016-
8485 2026, to a total value of about 7.5 million tonnes of meat produced). By contrast, production
8486 of sheep and goat meat is likely to remain relatively stable after years of decline. **As EU**
8487 **consumption will not entirely absorb the moderate increase in production, the EU**
8488 **balance is stable due to somewhat increased export prospects** (European Commission,
8489 2016a).

8490

8491 Based on these meat production numbers, **a 2030 outlook of 11.5 million tonnes and 0.8**
8492 **million tonnes of animal by-product processing is predicted for category 3 and 2,**
8493 **respectively** (i.e. 98.5% of the volumes processed in the year 2016). The degreasing process
8494 then results in the production of ~2.9 million tonnes of protein-rich materials of category 2
8495 and 3 that contain the overall share of the P derived from animal bones, feathers, hairs, blood,
8496 etc. (Dobbelare, 2017). This material is known as meat and bone meal (category 2 materials)
8497 or processed animal proteins (PAP, category 3 materials). The P-concentrated bones (~10.5%
8498 P on a dry matter basis) contain the overall share of the P in the meat and bone meal, because

8499 the other animal fractions are characterised by a low P content (0.1% - 1.7%). Assuming an
8500 average P-content of 5.3% (Moller, 2015), **it is projected that the protein fraction of**
8501 **category 2 and 3 materials contains about 154 kt of P yr⁻¹.**
8502

8503 At present, the meat and bone meal of **category 2 material is already largely used for the**
8504 **production of fertilisers, mostly as meat and bone meal without any significant further**
8505 **processing** (Dobbelare, 2017). Minor amounts of category 2 materials are sent to incineration
8506 (for energy recovery), landfill or composting. Its use in pet food, feed or food materials is not
8507 permitted according to the provisions of Regulation (EC) No 1069/2009. **Category 3**
8508 **materials are used to a smaller extent for the production of fertilisers (~17%). Most of**
8509 **the materials are used in pet food (~65-70%), fish feed (~10%) and fur animal feed (5-**
8510 **10%).** Less than 5% of the category 3 materials are used for the production of terrestrial
8511 animal food, human food (gelatin) or incinerated (Dobbelare, 2017).
8512

8513 The proteins derived from processed animal by-products are thus intensively used for the
8514 production of different materials. As a consequence of the many different competing uses,
8515 **meat and bone meal and processed animal proteins are traded at a price of about 50-70**
8516 **Euro per tonne, or about 943 – 1320 Euro per tonne P.** The bone fraction is even traded at
8517 a higher price, expressed on P-basis.
8518

8519 *7.3.5.3 Thermochemical conversion processes*

8520 Meat and bone meal has a heating value ranging between 13000 and 30000 MJ per tonne
8521 (Conesa et al., 2003). Therefore, a thermal treatment by combustion, gasification or pyrolysis
8522 could potentially be used to generate energy.

8523 *Incineration*

8524 When incinerated, the ashes derive mostly from the bone component and contain high
8525 amounts of Ca and P, mainly hydroxyapatites and tricalcium phosphates. The combustion
8526 induces a wide range of structural modifications, reducing the P-solubility relative to the
8527 unburnt meat and bone meal (Moller, 2015).
8528

8529 **Co-incineration of meat and bone meal is at present the foremost treatment for category**
8530 **1 materials that should be disposed of.** However, according to Article 32 of the Animal By-
8531 Products Regulation (EC No 1069/2009), Category 1 derived materials cannot be placed on
8532 the market as organic fertilisers or soil improvers.
8533

8534 The **fertiliser industry has already successfully tested the use of Category 2 and 3 meat**
8535 **and bone meal ashes in the acidulation process** for the production of mineral P-fertilisers
8536 (Langeveld and Ten Wolde, 2013). Meat and bone meal ashes can effectively substitute
8537 phosphate rock in the process due to their high P content similar to phosphate rock, their
8538 consistency, their low Al and Fe content and their low levels of metals/metalloids (especially
8539 the Cd content is much lower than in phosphate rock). The chemical composition of the
8540 fertilisers (partly) produced from incinerated protein-based animal by-products is equal to
8541 that of fertilisers that are currently on the market (DAP, MAP, TSP, SSP, nitrophosphate, etc;

8542 depending on the choice of the production process). In any case, the contaminant profile of
8543 the fertiliser end-material will be different, with metals/metalloids – especially Cd - being
8544 present in lower contents in P-fertilisers derived from meat and bone meal ashes relative to
8545 most mineral P-fertilisers derived from phosphate rock (Kratz et al., 2016). Also, the
8546 environmental impact of producing fertiliser using these secondary phosphate sources
8547 suggests the emissions of phosphate and fluorine is lower than when using regular phosphate
8548 rock (Langeveld and Ten Wolde, 2013).

8549
8550 From an economic point of view, meat and bone meal and processed animal proteins of
8551 Category 2 and 3 material (943 – 1320 Euro per tonne P, see section 7.3.5.2) are more
8552 expensive than phosphate rock (on average 649 Euro per tonne P; see section 9.1.3).
8553 However, in contrast to phosphate rock, the combustion of meat and bone meal and processed
8554 animal proteins will enable some energy recovery. **Thermochemical P-fertiliser production**
8555 processes such as the Mephrec process, the FEhS/Salzgitter process, and the thermo-
8556 reductive Recophos process (see paragraph 15.2.2) use meat and bone meal as an input
8557 material, **effectively reducing the energy demand of such processes**. Meat and bone meal
8558 is used as a fuel and as a P-source in the above-mentioned STRUBIAS production processes
8559 that produce phosphoric acid and ashes/slugs that can directly be used as a P-fertiliser.
8560 Moreover, benefits for the protection of the environment and human health could be achieved
8561 relative to alternative scenarios (see section 8.8). Nonetheless, mainly due to the strong
8562 competition for value-added category 2 and 3 animal by-products (feed industry, pet food
8563 industry, etc.), **the market potential for STRUBIAS materials produced through this**
8564 **pathway remains indeterminate**.

8565 Pyrolysis of animal bone materials

8566 Animal by-products of Category 2 and 3 could also be processed via pyrolysis spectrum
8567 techniques, **resulting in a P-rich material that is embedded in a matrix of stabilised C**. At
8568 present, the only TRL 7-9 production pathway is the so-called 3R pyrolysis process, where
8569 animal bone materials are heated further up to 850°C. During the pyrolysis process all
8570 volatile and protein based substances are removed from the mineral matrix, and a highly
8571 macro-porous apatite type mineral material is produced, composed of hydroxyapatite (70-
8572 76%), CaCO₃ (7-13%) and carbon (9-11%), with a P content of 13% (30 P₂O₅) (3R
8573 AgroCarbon, 2016). The composition of the bone char material is, however, dependent on the
8574 production process applied; the bone chars produced as in Morshedizad et al. (2018)
8575 contained on average 60% hydroxyapatite, 26% dicalcium phosphate and 14% calcium
8576 phytate.

8577
8578 Similar to the market for pyrolysis & gasification materials derived from manure, the **market**
8579 **outlook for this STRUBIAS pathway is associated to a large degree of uncertainty** as the
8580 resulting pyrolysis material is the only output material that will be brought on the market. The
8581 **economic valuation of pyrolysis & gasification materials is at present, however, largely**
8582 **unknown**, as well as the degree of consumer confidence associated to the end-material.
8583 Expressed on a P-basis, the producers of pyrolysis & gasification materials claim a higher
8584 sales price for pyrolysis & gasification materials than for traditional P-fertilisers based on

8585 allegations of high agronomic efficiencies ($> 100\%$, expressed on a P-basis relative to mined
8586 rock phosphate and processed P-fertilisers) and additional benefits from increased soil
8587 fertility. Nonetheless, at present, scientific and experimental evidence is lacking that
8588 demonstrates the superiority of pyrolysis material from slaughter residues compared to
8589 traditional P-fertilisers in terms of fertiliser efficiency. Preliminary test results seem to point
8590 to a relative agronomic efficiency (RAE_{PUE}) that is, at a maximum, close to a value of 1 (thus
8591 equivalence to mined rock phosphate and processed P-fertilisers; see section 6.2.4).

8592

8593 **It is assumed that the market potential of animal bone-derived pyrolysis material in the**
8594 **conventional agricultural sector is indeterminate in the short-term, i.e. before the year**
8595 **2030.** Given the lack of availability of concentrated P-fertilisers for organic farming,
8596 pyrolysis & gasification materials could potentially make an entry into the organic farming
8597 sector. It is re-iterated that the use of mined and synthetic fertilisers is heavily restricted under
8598 the existing legislation (Council Regulation (EC) No 834/2007 on organic production and
8599 labelling of organic products). Synthetic resources and inputs may only be permissible if
8600 there are no suitable alternatives. Such products, which must be scrutinised by the
8601 Commission and EU countries before authorisation, are listed in the annexes to the
8602 implementing regulation (Commission Regulation (EC) No. 889/2008).

8603

8604 Animal bone biochar would be the most P-dense fertiliser having a P content similar to
8605 phosphate rock, but with an improved plant P-availability. Therefore, the higher price setting
8606 of animal bone biochar relative to mined rock phosphate and processed P-fertilisers could
8607 potentially be compensated by the higher sales prices of organically-grown food products.
8608 Here, animal-bone derived pyrolysis & gasification materials could potentially replace
8609 current organic P-inputs such as manure, compost, meat and bone meal and meat and bone
8610 meal ashes in the organic farming sector. **Given the limited availability of P-dense**
8611 **fertilisers that meet the principles and requirements for organic farming, it is believed**
8612 **that there might be a potential demand for animal bone-derived pyrolysis & gasification**
8613 **materials in the organic farming sector.** A market entry in this sector may also enable
8614 further long-term product testing under realistic circumstances.

8615

8616 7.3.6 STRUBIAS materials from municipal wastewaters

8617 7.3.6.1 *Introduction*

8618 Historically, the P present in materials resulting from municipal wastewater treatment plants
8619 was largely returned to the agricultural field as sludge. Due to the physical-chemical
8620 processes involved in the wastewater treatment, the sludge tends to concentrate heavy metals
8621 and poorly biodegradable trace organic compounds as well as potentially pathogenic
8622 organisms (viruses, bacteria, etc.) present in wastewaters. Sludge is, however, rich in
8623 nutrients such as N and P and contains valuable organic matter that may prove useful when
8624 soils are depleted or subject to erosion. Sludge is usually treated before disposal or recycling
8625 in order to reduce its water content, its fermentation propensity or the presence of pathogens.
8626 Several treatment processes exist, such as anaerobic digestion, thickening, dewatering,

8627 stabilisation and disinfection, and thermal drying. The sludge may undergo one or several
8628 treatments. Once treated, **sludge can be recycled or disposed of using three to four main**
8629 **routes: recycling to agriculture (landspreading), composting, incineration or landfilling.**

8630
8631 The direct or indirect return of sewage sludge to agricultural land through these routes might
8632 be associated to emissions of pollutants into the soil, and indirect emissions into air and
8633 water. Other emissions into the air include exhaust gases from transportation and application
8634 vehicles. Although the EU Sludge Directive 86/278/EEC enables the return of treated sludge,
8635 some **Member States have adopted national regulations with provisions that go beyond**
8636 **the requirements of the Directive 86/278/EEC** (see section 7.3.6.2). **Therefore, the**
8637 **fraction of sewage sludge that is disposed of by incineration is increasing in Europe.** The
8638 disposal of sludge is considered by most stakeholders to have the disadvantage of wasting the
8639 fertilising value of the sludge.

8640
8641 **STRUBIAS materials can be produced from nutrient-rich materials originating from**
8642 **wastewater treatment plants, and thus provide a possibility for the safe return of P**
8643 **present in sewage to agricultural land.** Specifically, municipal wastewaters and sewage
8644 sludges are listed as eligible input materials for precipitated phosphate salts & derivatives and
8645 thermal oxidation materials & derivatives.

8646

8647 *7.3.6.2 Policy and legal framework*

8648 *European legislation*

8649 The legal framework established by the European Commission and regulating the various
8650 sludge routes is mainly composed of Directives which have to be transposed into national
8651 legislation by Member States. The ones most relevant to sludge management are the
8652 following:

- 8653 • Council Directive of 21 May 1991 concerning urban wastewater treatment
8654 **(91/271/EEC), known as the Urban Waste Water Treatment Directive**, is aimed at
8655 protecting the environment from the adverse effects of wastewater discharges. This
8656 Directive sets minimum sewage treatment standards to be achieved in stages by the
8657 end of 2005, and provides for advanced wastewater treatment for the removal of
8658 nitrogen and phosphorus from sensitive areas. Sensitive areas are defined as: areas
8659 particularly susceptible to eutrophication, surface waters intended for the abstraction
8660 of drinking water with high nitrate levels, and other waters that require a higher
8661 standard of treatment to satisfy the requirements of other Directives. Directive
8662 91/271/EEC supports the use of sewage sludge in article 14: "sludge arising from
8663 waste water treatment shall be re-used whenever appropriate";
- 8664 • Council **Directive 86/278/EEC on the protection of the environment when sewage**
8665 **sludge is used in agriculture.** This Directive sets minimum quality standards for the
8666 soil and sludge used in agriculture, and defines monitoring requirements when sludge
8667 is spread on agricultural land. The limit values defined in this Directive concern heavy
8668 metals concentration for sewage sludge as well as for soil when sewage sludge is used

- 8669 on land and maximum annual heavy metals loads through the application of sewage
8670 sludge
- 8671 • Sludge applications in agriculture must also comply with limits set by other EU
8672 legislation on nutrients in the environment, such as the **Nitrates Directive**
8673 **(91/676/EEC)** that limits the amounts of nitrates in water;
 - 8674 • The **Waste Framework Directive (Directive 2008/98/EC)** confirms the waste
8675 management hierarchy; preference has to be given to waste prevention followed by
8676 waste reduction, re-use, (nutrient) recycling, and energy recovery. This Directive
8677 establishes principles for the use and disposal of waste, waste management plans,
8678 approval procedures and monitoring;
 - 8679 • The Directive on the **landfill of waste 1999/31/EC** restricts disposal of sludge to
8680 landfill, by gradually reducing the allowed quantities of biodegradable waste going to
8681 landfill and prohibiting the landfilling of both liquid and untreated wastes;
 - 8682 • **Directive 2010/75/EU on industrial emissions** sets limit values for emissions of
8683 pollutants to air from waste incineration.

8684

8685 Outlook for sewage sludge treatment and management options in Europe

8686 The current trend in sewage sludge treatment is to reduce the amount of sewage sludge that is
8687 landfilled due to the increasing costs and increasing legislative restrictions on the landfilling
8688 of biodegradable waste (Milieu Ltd - WRc - RPA, 2010a). **This leaves two mid to long-term**
8689 **options for the fate of sewage sludge: (1) landspreading – possibly after treatments such**
8690 **as anaerobic digestion and composting, and (2) incineration.**

8691

8692 The provisions of the Waste Framework Directive (Directive 2008/98/EC) oblige the
8693 Member States to expressly apply the **waste hierarchy** as a priority order in legislation and
8694 policy. In accordance with Article 4(2) of Directive 2008/98/EC, when applying the waste
8695 hierarchy, **Member States must take measures to encourage the options that deliver the**
8696 **best overall environmental outcome.**

8697

8698 There is scientific evidence that the **landspreading of sewage sludge to agriculture can**
8699 **provide agronomic benefits**, in particular the recycling of plant nutrients such as N and P.
8700 Indeed, one of the most commonly recognised environmental benefits is the recycling of P in
8701 the food chain. This contributes to the conservation of P reserves and also reduces external
8702 inputs of Cd originating from phosphate rock. Sludge also provides other plant
8703 macronutrients, such as K and S, and micronutrients such as Cu and Zn. The beneficial
8704 effects of sludge application on soil organic matter status, structural properties and soil
8705 moisture retention are also well documented. **The accumulation and recycling of**
8706 **contaminants present in the sewage sludge is, however, a major concern when**
8707 **determining environmental impacts**, especially in population-dense regions where limited
8708 land is available for the spreading of sewage sludge close to wastewater treatment plants.
8709 Environmental impacts of transport of the high-volume sludge should also be considered.
8710 **Benefits in terms of climate change and greenhouse gases emissions** from recycled
8711 sewage sludge to agriculture are claimed, in particular that a portion of the C in sludge used

8712 in agriculture will be sequestered in the soil. However, it remains unknown to what extent the
8713 long-term effect is **scientifically substantiated and, at present, national inventories of**
8714 **greenhouse gas emissions do not consider sequestered carbon from sludge used in**
8715 **agriculture (Milieu Ltd - WRc - RPA, 2010b).**
8716

8717 The environmental impacts associated to incineration are dependent on whether the sludge is
8718 combusted in mono- or co-incinerators. In simple terms, **co-incineration will score better on**
8719 **impacts related to global warming potential and energy recovery, whereas mono-**
8720 **incineration enables the potential recovery of P at the expense of a lower energy**
8721 **recovery potential.** The energy content of sludge is better used when it is co-fired at a coal-
8722 fired power plant compared to mono-incineration (de Ruijter et al., 2015). This is caused by a
8723 different design of the plants, where the advantage of a coal-fired plant comes from a larger
8724 scale and use of inputs with a lower corrosive effect. Ashes from a coal-fired plant, however,
8725 are not suitable for P recovery because of their low P content. Requirements for flue gas
8726 cleaning are stricter for mono-incinerators compared to coal-fired power plants. The oven of
8727 a mono-incinerator is designed for a specific type of input and including another type of input
8728 would require another oven. This means that current co-incinerated inputs cannot simply be
8729 diverted to existing mono-incinerators.

8730
8731 The fact that recycling of nutrients has a higher priority than energy recovery in the waste
8732 hierarchy suggests **that mono-incineration followed by P-recovery from the ashes may be**
8733 **the preferred incineration option.** This observation is even more important given that P is a
8734 finite element, and phosphate rock is itemised on the EU list of critical raw materials.
8735 Moreover, **benefits for environmental protection and human health safety are assured** as
8736 thermal oxidation materials & derivatives will have to comply with contaminant limits in the
8737 proposed revision of the Fertiliser Regulation that are more strict than the provisions of the
8738 sludge Directive 86/278/EEC. The complex technologies and operational costs required to
8739 extract and produce materials from sewage sludge make this route, however, **less cost**
8740 **efficient in comparison to landspreading.** The cost for landspreading of semi-solid or
8741 digested sludge is about 126-185 Euro per tonne sludge (dry matter basis), whereas the cost
8742 for the mono-incineration of sewage sludge is estimated at 411 Euro per tonne sludge (dry
8743 matter basis) (Milieu Ltd - WRc - RPA, 2010a). Mono-incineration of sewage sludge thus
8744 increases treatment costs with a factor 2.2 - 3.2. The supplementary cost is, however, only 3%
8745 of the total costs for wastewater treatment and disposal (Nattorp et al., 2017). Significant
8746 investments in mono-incinerators would be required in specific Member States. At present,
8747 only Austria, Belgium, Denmark, Germany, the Netherlands and the UK - all of them EU-13
8748 countries - have operational dedicated sewage sludge mono-incinerators (European
8749 Commission, 2017c). A total of 43 mono-incinerators are present in Europe, of which the
8750 overall share (23) is located in Germany (European Commission, 2017c). For cities and
8751 regions where infrastructure with mono-incinerators is available and P-rich ashes are already
8752 generated, **recovering P from ashes with best available ash-process techniques is**
8753 **associated to a relatively small cost (compared to ash disposal) if revenues from P-**
8754 **fertilisers sales are taken into consideration** (see section 8.10). This is exemplified by the
8755 agreement between EcoPhos and Dutch mono-incinerating facilities (60.000 tonne of sewage

8756 ashes per year), indicating the commercial viability to transform P-rich mono-incineration
8757 ashes into high-value P-sources such as pure DCP.

8758

8759 There is an ongoing debate on the best practices for the recycling of sewage sludge to the
8760 field, and **Member States continue to differ widely in the weighing of environmental,**
8761 **social and economic impacts associated to sewage sludge management** (Milieu Ltd - WRc
8762 - RPA, 2010b). The uncertainty related to future sewage sludge handling routes makes it
8763 highly challenging to provide an accurate estimate on the market for STRUBIAS materials
8764 derived from sewage sludge.

8765

8766 **Germany and Austria have already taken up a clear position** and are currently
8767 transposing the provisions of the Waste Framework Directive into national legislation that
8768 **makes the recovery of P from mono-incinerated sewage sludge ashes mandatory.**
8769 According to the final version of the Bundes-Abfallwirtschaftsplan (Federal Waste Plan) in
8770 **Austria**, two options for P-recovery have been brought forward, including (i) mono-
8771 incineration of the sewage sludge and P-recovery from the resulting ashes, or (ii) at least 45%
8772 P recovery of the P present in the incoming municipal waste water, if P is recovered from the
8773 digester supernatant and/or the sewage sludge. The draft Federal Waste Plan focusses on
8774 Wastewater Treatment Plants with capacities of over 20 000 to 50 000 people equivalents
8775 (depending on the results of a feasibility study), within a transition phase of 10 years. In
8776 **Germany**, the new sewage sludge ordinance will make phosphorus P recovery from sewage
8777 sludge obligatory for all German wastewater treatment plants with a capacity larger than
8778 50,000 person equivalents (p.e.). They will have to recover the P by 50% from the sludge, if
8779 the sludge contains more than 2% P of the sludge dry matter content, or to an end
8780 concentration of <2% P of the sludge dry matter content. Otherwise the sludge with a high P
8781 load can be mono-incinerated, with the obligation to recover 80% of the containing P in the
8782 ashes. Land application of sludge will only be allowed under strict conditions for wastewater
8783 treatments plants < 50,000 p.e. The ~500 plants that are projected as subject to the
8784 requirement of P-recovery represent roughly 66% of the total P removed from German
8785 wastewater and transferred into the sludge.

8786

8787 The **Swedish government** has recently announced the launch of an inquiry aimed at
8788 introducing new laws to ensure that P can be recycled from sewage sludge in order to
8789 accelerate the country's transition towards a circular economy. Sweden's environment
8790 ministry also said the same inquiry will look at a proposal to ban the spreading of sewage
8791 sludge on farmland.

8792

8793 The **Swiss Ordinance on the Avoidance and Disposal of Waste (VVEA)** came into force in
8794 2016. The recovery of P from phosphorus-rich waste, i.e. effluent sludge and animal and
8795 bone meal not recovered as feed has become legally binding at ordinance level, with a 10-
8796 year transitional period. Given a 10-year grace period, P-recovery will have to be
8797 implemented until 2026. Current studies are on-going to determine the on-the-ground
8798 implementation (e.g. minimal recovery rates).

8799

8800 The implementation of the **EU directive on waste water treatment and sludge handling** in
8801 the other Member States varies considerably. Certain Member States have implemented
8802 stricter provisions for the landspreading of sludge than those of Council Directive
8803 86/278/EEC, especially in terms of maximum allowed levels of heavy metals and organic
8804 compounds. **In particular, in countries such as Austria, Belgium, Denmark, Finland,**
8805 **France, Germany, Luxembourg, the Netherlands and Sweden, the limit values in**
8806 **national regulations are extremely stringent**, although use in agriculture at present still
8807 remains an important outlet for sludge in these countries. The landspreading of sewage sludge
8808 is already banned or highly restricted in the Netherlands and Belgium-Flanders, and – after a
8809 transition period – in Austria and Germany. The reasons for restricting landspreading relate to
8810 concerns on pollutants and the objective to reduce competition for the return of organic
8811 materials to the available land in the form of manure. **In the United Kingdom, Portugal,**
8812 **Spain, and the EU-13 countries, farmers’ associations and authorities support the**
8813 **agricultural use of sludge, both for economic and for agronomic reasons** (mainly in terms
8814 of providing an economically feasible option for the return of organic matter and P to the
8815 agricultural field). Spain, for instance, has issues related to soil erosion and desertification,
8816 and so the recycling of sewage sludge to agricultural land is the preferred option, as indicated
8817 in the National Sewage Sludge Plan of wastewater treatment plants 2001-2006: "As long as
8818 sewage sludge complies with legal requirements, including those which might be established
8819 in the future (...) it is considered that the most sustainable option is the recycling of nutrients
8820 and organic matter by agricultural land application" (art. 1.3.). Italy, Greece and Ireland have
8821 not taken up a strong position on sludge recycling in agriculture, as far as can be judged from
8822 the available information.

8823
8824 STRUBIAS materials could be recovered in the form of precipitated phosphate salts &
8825 derivatives and thermal oxidation materials & derivatives from municipal wastewaters and the
8826 resulting sludges. The 2030 outlook for the latter could be estimated as follows:

- 8827 • The total amounts of wastewaters that will be treated in the EU and sludges that will
8828 be generated are expected to increase in the future due to the increased
8829 implementation of the Urban Waste Water Treatment Directive (91/271/EEC). An
8830 annual increase of 13% in sewage sludge volumes has been estimated for the period
8831 2010-2020 within the EU-28 (Milieu Ltd - WRc - RPA, 2010b). If this growth rate is
8832 extrapolated to the **year 2030, the total incoming P in municipal waste water**
8833 **treatment plants would be estimated at 360 kt of P** (based on the sum of P in
8834 communal sewage sludge and urban waste water treatment effluent for the year 2005;
8835 van Dijk et al., 2016).
- 8836 • Milieu Ltd – WRc - RPA (2010b) indicated a decadal 18% increase in incinerated
8837 sludge for the period 2010-2020. When this growth rate is extrapolated to the year
8838 2030, **the share of sludge disposal through incineration would equal 37%**. This
8839 value corresponds reasonably to the sum of the sewage sludge amounts that are
8840 currently already incinerated (27.3%) and landfilled (9.2%) (based on available data
8841 from Eurostat averaged for the period 2010 - 2012; this period corresponds to the
8842 latest EU-28 representative reporting period). In line with the Waste Framework
8843 Directive provisions that prioritise nutrient recycling over energy recovery and the

8844 additional technical challenges to recover P from co-incinerated sludge, **it is assumed**
8845 **that mono-incineration is the single route for incineration.** Potentially, the high
8846 costs of investment and operation required for a mono-incinerator can be partly off-set
8847 by the increased revenues from the valorisation of mono-incinerated ashes and higher
8848 gate fees for sewage sludge ashes. The possible non-compliance with the highly
8849 ambitious 100% mono-incineration assumption is presumed to be counteracted by
8850 sludge shifts from landspreading towards the incineration routes. The reduced
8851 acceptance for landspreading and possible stricter (national or EU) legislation on
8852 contaminant levels in landspreaded sewage sludge, and the possible synergies of
8853 incineration with energy recovery could drive shifts in sewage sludge management.

8854

8855 7.3.6.3 *P-precipitation at municipal waste water treatment plants*

8856 The Urban Waste Water Treatment Directive (91/271/EEC) requires that more stringent
8857 treatment is required for discharges into sensitive areas (cf. Article 5 of the Directive).
8858 According to the latest summary report on urban wastewater treatment (European
8859 Commission, 2011), a total of 72.8% of EU-27 territory was identified as sensitive
8860 area/catchment of sensitive area and therefore requires more stringent treatment. The territory
8861 of sensitive areas in EU-28 increased by 4.8% compared to the last Implementation Summary
8862 of the year 2001 (i.e. 4.8% increase/decade). In 2011, tertiary treatment was in place for 89%
8863 of the load for EU-15 and for 27% of the generated load for EU-12 (European Commission,
8864 2011). As the infrastructure in place cannot always achieve quality standards in line with the
8865 Directive's requirements, 79% of the total generated load for EU-15 and 24% of the total
8866 generated load for EU-12 were reported to work adequately (European Commission, 2011).
8867 For the 2030 market estimate, it is assumed that the growth in sensitive areas will lead to an
8868 equivalent growth rate for wastewater treatments that rely on tertiary treatment (i.e. 4.8% per
8869 decade for the period 2010 – 2030). Therefore, **the total generated load for adequately**
8870 **operating wastewater treatment plants with more stringent treatment in the year 2030**
8871 **is estimated at 83% and 26% for EU-15 and EU-13, respectively.** Given that ~75% of the
8872 disposed sludge is generated in the EU-15 (Eurostat, 2017), **a weighted average for the EU-**
8873 **28 of the relative wastewater load connected to more stringent treatment is estimated at**
8874 **69%.**

8875

8876 The most popular P removal techniques to remove P from wastewaters treatment at waste
8877 water treatment plants that apply more stringent treatment are enhanced biological
8878 phosphorus removal (EBPR) and the more widely used chemical phosphorus removal
8879 (Chem-P) using iron or aluminium salts. The capacities of municipal wastewater purification
8880 in the EU have increased in the past years. Especially many new plants were constructed in
8881 medium-sized and small towns in Eastern Europe. **Already existing plants in large cities**
8882 **were equipped with biological wastewater treatment and additional treatment**
8883 **technology.** Most EU-15 member states have completed the development of their municipal
8884 wastewater treatment systems. Thus, maintenance and renewal investments dominate in
8885 countries such as Germany, the Netherlands as well as in Scandinavia. Although no exact
8886 data are available for the EU as a whole, Wilfert et al. indicated **that in Western Europe,**

8887 **exclusive use of Chem-P is the dominant configuration for P removal in wastewater**
8888 **treatment (around 60%;** expressed on sludge produced or people equivalents). The
8889 remaining 40% of the plants rely on EBPR or EBPR with Chem-P support, configurations
8890 that would enable the P-recovery as precipitated phosphate salts from the digested sludge or
8891 the sludge liquor (see section 15).

8892

8893 Given the substantial operational benefits of the implementation of phosphate salt
8894 precipitation units for EBPR waste water treatment plants, it is assumed that all EBPR plants
8895 will be equipped with such P-recovery units. **First generation phosphate salt precipitation**
8896 **units** show a typical recovery of about 10-20%, and mainly involve the installation of the
8897 reactor in existing configurations (e.g. after digester, or after decanter). **Second generation**
8898 **P-recovery units** that are integrated in the waste water treatment plant typically rely on
8899 additional treatment units in the sludge line prior to the anaerobic digester (e.g. WASSTRIP,
8900 thermal hydrolysis, etc). Such processes lead to high P-recovery efficiencies of up to 50%,
8901 and provide substantial economic benefits through the reduction of sludge volumes and
8902 sludge dewatering capabilities. Due to the higher investment costs of second generation P-
8903 recovery units, it is assumed that those would only be installed in waste water treatment
8904 plants of agglomerations that treat >150000 people equivalents.

8905

8906 Box 4: Precipitated phosphate salts & derivatives at EBPR wastewater treatment plants.

8907

8908 To derive the substitution potential of P-fertilisers containing STRUBIAS materials through
8909 this route, following assumptions and calculations were made:

8910

8911 1) For the year 2030, the total incoming P in municipal waste water treatment plants would be
8912 estimated at **360 kt of P**.

8913

8914 2) 69% of the EU-28 urban wastewaters will be processed with **more stringent treatment**.
8915 Struvites are produced at 100% of the wastewater treatment plants that apply more stringent
8916 treatment and rely on unique on EBPR, or on EBPR with Chem-P support. Such plants
8917 process 40% of the incoming P in municipal waste waters. For the year 2030, the current
8918 **share of the plants with tertiary treatment that partly rely on EBPR configurations is**
8919 **maintained**. At present, there is no clear techno-scientific or economic evidence that justifies
8920 a radical change in wastewater treatment plant configurations, for which reason only minor
8921 shifts can be expected in sludge that is treated in the year 2030.

8922

8923 3) Given 1) and 2), **EBPR wastewater treatment plants will treat about 99 kt P yr⁻¹**.

8924

8925 4) **First generation** with an assumed P-recovery rate is 15% is applied to 60% of the
8926 incoming municipal waste waters at EBPR plants (59.4 kt P yr⁻¹). **Second generation P-**
8927 **precipitation** is set in place for the remainder 40% of the incoming municipal waste waters at
8928 EBPR plants (i.e. 39.6 kt P yr⁻¹), with an assumed P-recovery potential of 50%. Total P
8929 recovery is thus equal to 28.8 kt P yr⁻¹.

8930

8931 5) The **relative agronomic efficiency** (RAE_{PUE}) of precipitated phosphate salts & derivatives
8932 relative to mined rock phosphate and processed P-fertilisers is assumed to be 1.05 (see
8933 section 6.2.2).

8934
8935 6) Considering 1) - 5), **the P-recovery in the form of precipitated phosphate salts** at EBPR
8936 wastewater treatment plants **is estimated at 30 kt of P**. It is estimated that these materials
8937 will be brought on the market directly as P-fertilisers or as part of a physical blend, and that
8938 their further processing in recovered phosphate salt derivatives (e.g. MAP, DAP, TSP,
8939 nitrophosphate, etc.) is unlikely.

8943 7.3.6.4 Sewage sludge mono-incineration

8944 Egle et al. (2016) indicated the techno-economic **viability of P recycling from mono-**
8945 **incinerated sewage sludge ashes**. The P-recovery from Chem-P wastewater treatment
8946 configurations is somewhat more challenging than from EBPR sludges. Nonetheless, specific
8947 chemical and thermochemical processes can handle both ashes produced at EBPR and
8948 ChemP waste water treatment plants (see section 15.2.2). **Processes of high TRL level such**
8949 **as the acidulation process, the Ecophos process and thermo-reductive RecoPhos process**
8950 **(ICL) all produce inorganic intermediates (H_3PO_4 , P_4) that can be used to produce**
8951 **conventional, mineral P-fertilisers (MAP, DAP, DCP, SSP, TSP, nitrophosphate, etc.).**
8952 Given that these end-materials are associated to a high degree of market and consumer
8953 readiness in the conventional sector, the manufacturing of such end-materials is a highly
8954 probable route. Other routes that produce P-fertilisers of a different chemical composition are
8955 associated to a higher production cost and lower market readiness (lack of comprehensive
8956 testing on agronomic value, P present in less concentrated form resulting in higher transport
8957 and application costs, etc.). Therefore, it is unlikely that such materials will conquer a
8958 significant share of the conventional agricultural market, but minor volumes of such slow P-
8959 release fertilisers could be possible traded in niche markets and/or organic farming sectors.

8960
8961 **The bottleneck that will limit the volumes of recovered P-fertilisers derived from sewage**
8962 **sludge is the relative share of sludge that will be subject to the (cost-intensive) mono-**
8963 **incineration.**

8964
8965 As indicated in section 7.3.6.2, **it is estimated that 37% of all generated sludge will be**
8966 **treated via mono-incineration followed by P-recovery in the year 2030**. It is assumed that
8967 downstream P-recovery from the ashes is performed on all incinerated ashes, regardless of
8968 any P already recovered in the form of precipitated salts at the waste water treatment plant.
8969 After all, specific P recovery processes can (e.g. EasyMining Ash2Phos) can recover sludge
8970 ashes with lower phosphorus from ashes with a lower P content than from mono-incineration.

8971
8972 **Box 5: Thermal oxidation materials & derivatives from mono-incinerated sewage sludge ashes**
8973

8974 To derive the substitution potential of P-fertilisers containing STRUBIAS materials through
8975 this route, following assumptions and calculations were made:

8976

8977 1) The calculations are based on the **implementation of the provisions of the Waste**
8978 **Framework Directive** (Directive 2008/98/EC) with P being effectively recovered from P-
8979 rich sewage sludge, either through landspreading of the sludge or through the return of
8980 STRUBIAS materials to the agricultural field.

8981

8982 2) The predicted P-content in sewage sludge corresponds to 95% of the P present in the
8983 incoming municipal waste water. It is assumed that 37% of all generated sludge will be
8984 incinerated in the year 2030. The P that was already recovered upstream through first
8985 generation P-precipitation in reactors integrated in waste water treatment plants (section
8986 7.3.6.3) is subtracted from this figure to avoid double-counting. Hence, the total P in the
8987 sewage sludges ashes corresponds to $(0.95 \times 360 \text{ kt P yr}^{-1}) \times 0.37 - 29 \text{ kt P yr}^{-1} = 98 \text{ kt P yr}^{-1}$.

8988

8989 4) The recovered P will be used to produce water-soluble mineral P-fertilisers that have, per
8990 definition, a **100% relative agronomic efficiency relative** to their mined counterparts.

8991

8992 5) Given 1) to 5), a **P-substitution potential of 98 kt of P yr⁻¹ through this route is**
8993 **estimated with thermal oxidation material derivatives (e.g. TSP, DAP, etc.) as end-**
8994 **material of the production process.**

8995

8996

8997

8998

8999 7.3.7 STRUBIAS materials derived from food processing industry wastewaters

9000 According to the assessment of van Dijk et al. (2016), the P-losses from this sector were
9001 estimated at a moderate 44 kt P for the year 2005, of which about 8 kt P occurs as wastewater
9002 effluents.

9003

9004 **Wastewaters from certain food processing industries are rich in P, either because of the**
9005 **properties of the source material (e.g. dairy industry, sugar beet industry, meat**
9006 **processing, fish and seafood processing) or due to the P-rich additives applied to the**
9007 **production processes (e.g. potato industry).** At present, STRUBIAS materials are
9008 recovered as P-fertilisers from the potato industry and dairy industry as struvite, included in
9009 the STRUBIAS category "precipitated phosphate salts & derivatives". To the best of the
9010 authors' knowledge, these are currently the only TRL 7-9 processes that manufacture P-
9011 fertilisers meeting the conditions as outlined for PFC 1. Nutrient recovery processes from
9012 other residual waste water streams from food processing industries have not been
9013 documented. The underlying reasons for this observation remain unknown, but may be
9014 associated to the **spatial scattering of the food processing facilities** (i.e. lack of central
9015 collection possibilities of the wastewaters and sludges), **the chemical composition of the**
9016 **waste water** (a phosphate content $< 50 \text{ mg P L}^{-1}$ making them unsuitable for precipitation as

9017 Ca- or Mg-phosphates), **the transfer to urban waste water treatment plants, or the direct**
9018 **return to agricultural land of the uncontaminated sludges and waste waters.** With the
9019 exceptions indicated for specific food industries, waste waters from other food processing
9020 industries are mostly characterised by rather low phosphate contents, for which reason they
9021 are unsuitable for P-recovery in the form of precipitated phosphate salts & derivatives.
9022 **Therefore, production processes from food processing industries, other than those from**
9023 **the dairy and potato industry, are not considered in this 2030 market assessment.**

9024

9025 The P-losses from the dairy industry are more difficult to estimate. The phosphate contents in
9026 the wastewaters vary largely between facilities, but most plants rely on the use of Fe
9027 coagulants in order to meet effluent quality requirements in line with the Water Framework
9028 Directive (Crittenden et al., 2008). **The suitability of the wastewater for P-recovery in a**
9029 **more plant-available form (e.g. struvites) relative to ChemP sludges will vary with**
9030 **wastewater characteristics across dairy plants.**

9031

9032

9033 **Box 6: Precipitated phosphate salts & derivatives from the food processing industry**

9034

9035 To derive the substitution potential of P-fertilisers containing STRUBIAS materials through
9036 this route, following assumptions and calculations were made:

9037

9038 For the year 2030, there is a potential for P-recovery in the form of precipitated phosphate
9039 salts & derivatives from **wastewaters from the potato industry and the dairy industry.** P-
9040 precipitation from other food processing industries is not considered due to a lack of current
9041 TRL 7-9 processes. Other STRUBIAS pathways are not considered as the thermochemical
9042 conversion of wastewaters from the food processing industry will not produce sludges that
9043 can be converted to P-fertilisers via incineration or pyrolysis.

9044

9045 A. Potato industry

9046

9047 At present, more than 8.3 million tonnes of potatoes are processed in Belgium and the
9048 Netherlands. In theory, 1 tonne of recovered phosphate salt can be precipitated as struvite
9049 from 500 tonnes of potatoes (Schoorjans Stekhoven, 2015), resulting **in a total maximal**
9049 **recovery potential of about 16.6 kt of struvite per year (~ 2 kt P yr⁻¹).**

9050

9051 B. Dairy industry

9052

9053 About 2-3% of the incoming milk is lost during cleaning operations, via washing steps and
9054 through occasional milk spills (Hach company, 2017). Typically, milk contains 1 kg of P per
9055 tonne. In 2015, about 150 million tonnes of milk was collected by dairies in Europe (Eurostat,
9056 2017). By multiplying these numbers, the total P recovery potential from the dairy sector
9057 would equal 3 - 4.5 kt of P. Under the assumption that the precipitation of recovered
9058 phosphate takes place with a recovery efficiency of 75%, **the maximal potential P-recovery**
9058 **from the dairy industry is about 2-3 kt of P.**

9059

9060 The increased monetary valorisation of precipitated phosphate salts & derivates will provide
9061 a competitive advantage over chemical P-removal, at least for the largest facilities that
9062 process large amounts of waste waters of high P-content. Assuming that 25-75% of all
9063 wastewater treatment plants from the potato and dairy industry would rely on Ca and/or Mg
9064 salts for precipitation, **results in a total P-recovery potential of 1-3 kt of P yr⁻¹, with a best
9065 estimate of 2 kt of P yr⁻¹**. Note that, at present, about one third (640 t P yr⁻¹) of this value is
9066 realised.

9068 7.3.8 Conclusion

9069 7.3.8.1 Market estimate for TRL 7-9 processes under the anticipatable 2030 legislative 9070 framework

9071 **The estimates given in sections 7.3.4 - 7.3.7 are subject to many uncertainties and as a
9072 result should only be interpreted with the necessary precaution.** This is due to
9073 uncertainties regarding existing data sources, the future development in technology, the
9074 legislation in place for the year 2030, consumer confidence in STRUBIAS materials, the
9075 development of alternatives for dealing with eligible input materials, and the preliminary cost
9076 assessments. The results are based on the information gathered, including the responses from
9077 consultations, **and therefore represent the best estimate currently possible with the
9078 information available.** For selected STRUBIAS production processes, the JRC will evaluate
9079 costs and impacts on the environment and human health. These techno-economic analyses
9080 may serve as a basis to validate the information provided, and make the necessary corrections
9081 on market potential, where relevant.

9082
9083 Summing up the best estimates for the production of STRUBIAS materials from manure,
9084 municipal waste waters, slaughter residues, the food processing industry, **a total of 213 kt of
9085 plant-available P could be recovered as precipitated phosphate salts & derivates and
9086 thermal oxidation materials & derivates** (Table 10). Although there could be a market for
9087 **pyrolysis & gasification materials**, the 2030 market potential **remains indeterminate**,
9088 mainly due to the lack of comprehensive test results on agronomic efficiency for this
9089 STRUBIAS group. Therefore, it remains unclear if farmers are willing to pay for a material
9090 that is traded at prices that exceed those of mineral P-fertilisers, expressed on a monetary
9091 basis per unit of P present in the material. The estimates of production pathways for which
9092 the market potential remains indeterminate (pyrolysis & gasification materials; thermal
9093 oxidation materials & derivates from slaughter residues) have not included in the total market
9094 potential for STRUBIAS materials.

9095
9096 STRUBIAS materials expected to be on the market in 2030 are **almost exclusively derived
9097 from municipal waste waters (60%) and manure (39%)** (Table 10). Although significant
9098 progress has been made, the current handling of P in the sewage sludge and manure is not
9099 fully in line with the principles of sustainable use and recycling, because large P amounts
9100 from these sources are accumulating in soils, landfilled or removed from the biogeochemical
9101 P cycle in the form of construction materials (Schoumans et al., 2015). The applicable

9102 legislative framework and policy impacting upon water and soil quality are therefore heavily
9103 determining the STRUBIAS market and trade potential.

9104

9105 It is estimated that **thermal oxidation materials & derivates will be the dominant**
9106 **STRUBIAS output material group with a total estimated production volume of 133 kt P**
9107 **yr⁻¹** or 62% of all STRUBIAS materials (Table 11). It is estimated that a major share of
9108 thermal oxidation materials & derivates will be brought on the market in a **chemical form**
9109 **that is already available on the market** (DAP, MAP, SSP, TSP, nitrophosphate). Such
9110 materials may have a competitive advantage because of the high consumer confidence
9111 associated to these products in the conventional agricultural market. It is estimated that also
9112 the market for **precipitated phosphate salts & derivates (80 kt P yr⁻¹; 38% of the total**
9113 **plant-available P recovered as STRUBIAS)** will grow exponentially in the coming years
9114 (Table 11), mainly due to **process benefits at wastewater treatment plants that rely on**
9115 **enhanced biological P-removal techniques and synergies between P-recovery and**
9116 **renewable energy production in anaerobic digesters.**

9117

9118 **For specific fertiliser materials, and especially those derived through pyrolysis**
9119 **processes, the organic farming sector is a potential trade market.** The use of high-quality
9120 struvite and calcinated ashes for the organic farming sector has already been positively been
9121 evaluated by the sector, and possibly more STRUBIAS materials can be authorised under the
9122 existing legislation on organic farming in the EU (Council Regulation (EC) No 834/2007 on
9123 organic production and labelling of organic products). In this market, materials are often
9124 traded at a higher price and few P-dense fertiliser alternatives are authorised in this sector. At
9125 present, about 6% of the utilisable agronomic area is destined for organic farming in the EU.
9126 A market entry into the organic farming could enable comprehensive testing of the material
9127 quality, especially for agronomic efficiency. These results could potentially open an avenue
9128 towards expansion within the conventional agricultural sector, where STRUBIAS materials
9129 could replace and complement other P-sources of organic nature. Additionally, smaller
9130 volumes of STRUBIAS materials could also be valorised in specific niche sectors, other than
9131 organic farming, such as for example the horticulture market and actors that highly value the
9132 circular economy framework.

9133

9134 **Most P-recovery in the form of STRUBIAS materials will take place in Western**
9135 **Europe.** The regional distribution of STRUBIAS production pathways is mainly a result of
9136 issues related to renewable energy production through digestates, high livestock densities that
9137 lead to P-excess in soils and possible issues related to water eutrophication, and reduced
9138 acceptance for the landspreading of sewage sludge (Table 10). With thermal oxidation
9139 materials & derivates as the dominant STRUBIAS pathways, EU Member States that have
9140 mono-incineration facilities also have a competitive advantage for STRUBIAS production
9141 (reduced infrastructure investments). Nonetheless, it should be noted that incineration ashes
9142 will also be shipped to facilities in other European regions (e.g. EcoPhos manufacturing site
9143 in Bulgaria).

9144
9145
9146
9147

Table 10: Market estimate for TRL 7-9 processes under the anticipatable 2030 legislative framework, the importance of the different processes across EU regions, and the major market drivers that will positively stimulate the market (values given are best possible estimates based on the information available and are subject to a high degree of uncertainty and as a result should only be interpreted as a rough approximation of the total estimates).

process pathway	section	recovered STRUBIAS material	recovered total P (kt P yr ⁻¹)	relative agronomic efficiency (%)	recovered bio-available P (kt P yr ⁻¹)	share of total bio-available P recovered (%)	regional distribution in Europe	major market drivers that will stimulate the market
P-precipitation after anaerobic digestion, dominantly from manure	7.3.4.3.	precipitated phosphate salts & derivates	45	105	48	23	livestock dense regions having soils showing P-excess and water bodies subject to P-eutrophication	reducing externalities due to manure excess (water quality), renewable energy targets.
thermal oxidation of solid manure fractions	7.3.4.4.	thermal oxidation materials	39	90	35	16	livestock dense regions having soils showing P-excess and water bodies subject to P-eutrophication	reducing externalities due to manure excess (water quality), renewable energy targets.
P-precipitation at municipal wastewater treatment plants	7.3.6.4.	precipitated phosphate salts & derivates	29	105	30	14	regions and cities that apply more stringent treatment at water treatment plants	increased share of biological waste water treatment plants.
thermal oxidation of sewage sludge	7.3.6.5.	thermal oxidation material derivates (e.g. DAP, MAP))	98	100	98	46	regions with low acceptance for sewage sludge landspreading and mono-incineration capacity	focus on increased soil protection from metal accumulation and nutrient excess, ban on landfilling of biodegradable waste.
P-precipitation from the food processing industry	7.3.7	precipitated phosphate salts & derivates	2	105	2	1	regions with dairy and potato processing industries	focus on externalities and costs associated to industry waste water discharges.
thermal oxidation of slaughter residues	7.3.5	thermal oxidation material derivates (e.g. DAP, MAP))	indeterminate	indeterminate	indeterminate	indeterminate	livestock dense regions	synergies with energy recovery from animal by-products
pyrolysis materials of solid manure fractions	7.3.4.4.	pyrolysis & gasification materials	indeterminate	indeterminate	indeterminate	indeterminate	livestock dense regions having soils showing P-excess and water bodies subject to P-eutrophication	reducing externalities due to manure excess (water quality), soil quality improvement, increased consumer and market acceptance.
pyrolysis of slaughter by-products	7.3.5.3.	pyrolysis & gasification materials	indeterminate	indeterminate	indeterminate	indeterminate	potentially somewhat more important in livestock dense regions	increased consumer and market acceptance.
OVERALL TOTAL			213		213	100		

9148



9149 **Table 11: Market estimate for TRL 7-9 processes under the anticipatable 2030 legislative framework as aggregated per STRUBIAS material group**
 9150 **and per input material (values given are best possible estimates based on the information available and are subject to a high degree of uncertainty**
 9151 **and as a result should only be interpreted as a rough approximation of the total estimates).**

	P content (kt P yr-1)	relative contribution (% of total)
<i>Aggregated per STRUBIAS material group</i>		
precipitated phosphate salts & derivates	80	38
thermal oxidation materials & derivates	133	62
Pyrolysis & gasification materials	indeterminate	not considered
<i>Aggregated per input material</i>		
manure	78	39
municipal wastewater	128	60
food processing industry	7	1

9152

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9153 7.3.8.2 *Further market stimulations*

9154 The inclusion of STRUBIAS CMCs in a revised EU Fertiliser Regulation could significantly
9155 contribute to increasing the sustainability in the EU agricultural sector and reducing negative
9156 externalities of production and consumption patterns. These topics are high on the political
9157 EU agenda that includes ambitious targets for waste recycling, water quality improvements,
9158 and reducing human exposure to contaminants. Although highly challenging to quantify, it is
9159 believed that shifting policy agenda targets towards 2030 plus further developments of
9160 specific TRL 6 processes could further stimulate the potential 2030 market for P-fertilisers
9161 derived from STRUBIAS materials. **Positive feedback loops induced by legislation could**
9162 **possibly further increase the production volumes of STRUBIAS materials, especially in**
9163 **case of acceptable implementation costs.**

9164
9165 There is a continued political and public focus on externalities caused by the agricultural
9166 sector as well as on concerns on newly emerging pollutants (e.g. personal care products and
9167 pharmaceuticals). The recycling of P from manure and sewage sludge in the form of high-
9168 quality STRUBIAS materials can contribute to reducing nutrient leaching to water bodies and
9169 decreasing the accumulation of contaminants in soils **compared to reference scenarios of**
9170 **landspreading**. Especially in regions of nutrient excess, the **nutrient use efficiency** of
9171 STRUBIAS materials can be greater than for these organic sources because the nutrient
9172 release can be better synchronized with plant needs, thus reducing the scope for its loss to
9173 deeper soil layers and surrounding water bodies (see section 8.9.2). Moreover, benefits are
9174 associated to the improved logistics for P-material storage, transport and handling,
9175 **improving the efficient return of nutrients to P-depleted soils and regions**. Finally,
9176 STRUBIAS production pathways for precipitated phosphate salts & derivatives and thermal
9177 oxidation materials & derivatives could effectively reduce organic and inorganic contaminants
9178 from the input materials, and thus **reduce the abundance of contaminants in the**
9179 **environment** relative to some of the currently applied business-as-usual scenarios (e.g. land
9180 spreading).

9181
9182 The below-mentioned scenarios include examples of such further progress on legislative and
9183 policy measures that could stimulate the production volumes of STRUBIAS materials. Note
9184 that the second scenario is based on the breakthrough of promising technological
9185 developments for manure fractions; this assumption is reasonable as there are various TRL 6
9186 processes that show a significant 2030 market potential.

9187
9188 1. As part of an ex-ante impact assessment, the European Commission has already
9189 investigated the impact of restricting the application of sewage sludge on soil (Milieu Ltd -
9190 WRc - RPA, 2010c). Any changes in Council Directive 86/278/EEC of 12 June 1986 on the
9191 protection of the environment, and in particular of the soil, when sewage sludge is used in
9192 agriculture will largely impact the STRUBIAS market potential. An option that has been
9193 investigated is to introduce, for instance, **more stringent standards on heavy metals in**
9194 **landspreaded sewage sludge** (option 3 – stricter limits on heavy metals as described in
9195 Milieu Ltd - WRc - RPA, 2010a). Under such possible new provisions, 53% of all sewage

9196 sludge would have to be incinerated. Under such a scenario the total P recovered from
9197 municipal waste waters would increase from 98 kt P yr⁻¹ to 156 kt P yr⁻¹ (+ **58 kt P yr⁻¹**).
9198

9199 2. As indicated in section 7.3.4, EU Member States should tackle the sources of pollution by
9200 fully implementing the Water Framework Directive measures and water-related legislation,
9201 especially the Nitrates Directive, Industrial Emissions Directive and Urban Waste Water
9202 Treatment Directive. In the present assessment, a total amount of 83 kt of recovered P is
9203 recovered from the agricultural sector, a number that is in line with the P that is lost to
9204 surrounding water bodies (81 kt of P yr⁻¹; van Dijk et al., 2016). However, also about 924 kt
9205 P yr⁻¹ of P accumulates yearly in European soils (van Dijk et al., 2016), indicating the
9206 significant potential for P-recovery from this fraction. **An interesting TRL 6 STRUBIAS is**
9207 **to apply a pre-treatment to manure (e.g. moderate acidification, thermal hydrolysis**
9208 **technology, and others) to increase the phosphate content of the liquid digestate from**
9209 **which the recovered phosphate salt will be precipitated.** At present, such technologies are
9210 already applied on manure in Europe, although the extent of occurrence in the year 2010 was
9211 still limited (Foget et al., 2011). In 2010, only 1377 t manure-P was acidified, whereas 665 t
9212 manure-P was subjected to thermal hydrolysis (Foget et al., 2011) but the combination of
9213 these techniques with P-precipitation has not yet been demonstrated in an operation
9214 environment.

9215 Acids can be added prior to the digestion process to decrease the pH and shift the
9216 phosphate/total phosphorus equilibrium, and thus the P-recovery potential (up to 80% of the
9217 total P present). The thermal hydrolysis process is a high-pressure, high-temperature steam
9218 pre-treatment application for anaerobic digestion feedstocks. The feedstock is heated and
9219 pressurised by steam within a reaction tank before being rapidly depressurised (flushed). This
9220 results in the breakdown of cell structure within the biomass. As the organic matter is
9221 presented to the digester in a broken-down condition, the digestion process is more effective,
9222 resulting in increased gas production and improved digestate quality (Pell Frischmann
9223 Consultants Ltd, 2012). As such, the P-recovery efficiency could be increased from 13% to
9224 50%, simultaneously optimising the N/P ratio of the solid digestate fraction. In case the pre-
9225 treatment process could be applied on manures that will be further processed by anaerobic
9226 digestion, an increase in P-recovery efficiency of 13% to 50% would result in an additional
9227 recovery of **131 kt P yr⁻¹** (from 48 kt P yr⁻¹ to 179 kt P yr⁻¹).
9228

9229 Another option to improve P recycling from manure is the use of manure incineration ashes
9230 as replacement for phosphate rock by the mineral fertiliser industry. The solid digestate
9231 fraction is combusted in order to achieve destruction of organic matter. If the moisture
9232 content within the digestate is sufficiently low and the incinerator efficiency is high, the
9233 process can become autothermal (the process generates sufficient heat to allow combustion to
9234 continue without the need for an external heat source or additional fuel) and energy recovery
9235 can be achieved (Pell Frischmann Consultants Ltd, 2012). Alternatively, the solid digestate
9236 fraction can be thermochemically treated in a rotary kiln by reaction addition (e.g. Si and/or
9237 Na₂SO₄; AshDec process) or pyrolysed. The char produced by the process can be used as a
9238 soil improver or as a partial replacement for peat in growing media production.
9239

9240 3. **Fish residues** in Europe and Norway are still a largely unexplored P-source. As outlined in
9241 section 14.4.2, the P content of fish residues from catches and aquaculture for the EU-28
9242 could amount of up to 27 kt P yr⁻¹. Moreover, the fish catches and aquaculture production in
9243 Norway equal about 45% of the total fish residues in Europe. Fish excreta and non-digested
9244 feed from land-based aquaculture also form a P-source that can potentially be recovered as
9245 STRUBIAS materials. The STRUBIAS sub-group indicated that these residues are already
9246 used for the production of P-fertilisers in Norway. Giving that the characteristics of the
9247 protein fraction of fish residues are similar to those of terrestrial animal by-products, it is
9248 believed that fish residues could further increase the P-recovery potential in an indeterminate
9249 manner (up to 40 kt P yr⁻¹).

9250

9251 7.3.8.3 *Substitution effect*

9252 Results from the previous section will be used to estimate **the substitution effect of mined**
9253 **and synthetic fertilisers by fertilising products containing precipitated phosphate salts**
9254 **& derivatives, pyrolysis & gasification materials and thermal oxidation materials &**
9255 **derivates for the year 2030**. This is based on the opening of the EU market, taking into
9256 account existing feedstock, the expected recovery rate and the equivalence of the fertilising
9257 features of recovered nutrients compared to those of mined and synthetic inorganic fertilisers.

9258

9259 By summing the values given in section 7.3.8.1, it is estimated that **a total of 213 kt bio-**
9260 **available P yr⁻¹ could be recovered**. In case the further **market stimulations for sewage**
9261 **sludge and manure as outlined in section 7.3.8.2 would materialise, an additional 189 kt**
9262 **P yr⁻¹ could be recovered in the EU-28 as P-fertilisers**.

9263

9264 The 2030 apparent consumption of mined rock phosphate and processed P-fertilisers is
9265 estimated at 1220 kt P yr⁻¹ (see section 7.2.3.2). To avoid double-counting during the
9266 calculation of the substitution effect, it is required to check the alternative fate and treatment
9267 scenario of the STRUBIAS input materials (manure, sewage sludge, wastes from food
9268 processing). Any bio-available P derived from organic sources that currently contributes to
9269 plant P uptake, but is projected to be used as an input material for STRUBIAS production
9270 processes, should thus be corrected for. It should be added to the estimated 1220 kt bio-
9271 available P yr⁻¹ that is applied as P-fertilisers on land. The following assessment is made for
9272 each of the pathways:

9273 i. *Manure slurries to be used as an input material to produce K-struvite (section*
9274 *7.3.4.3).*

9275 These manure fractions are typically characterised by a low nutrient density and an
9276 N:P ratio that often imbalanced relative to plant demands. Therefore, these materials
9277 are (i) subject to nutrient removal (e.g. aeration to remove N, P-removal using salts;
9278 cfr. Process *Stichting Mestverwerking Gelderland - SMG*), or applied on land in
9279 regions characterised by nutrient excess and thus leading to a large accumulation of P
9280 in agricultural soils, especially in livestock dense regions (van Dijk et al., 2016).
9281 Under such conditions, the mineral P substitution efficiency of these manure
9282 fractions is below the relative share of P that is recovered from the manure as

9283 precipitated phosphate salts (see section 8.6.2). Hence, the fraction recovered is only
9284 the P that is supplied in excess relative to plant P demands. Therefore, the added
9285 value of these manures as a P fertiliser and their contribution to plant P nutrition is at
9286 this moment negligible, and **the newly produced STRUBIAS material will thus**
9287 **not replace present-day plant nutrients.**

9288 ii. *Poultry litter combusted to poultry litter ashes (section 7.3.4.4).*

9289 At present, most of the excess poultry litter is subject to hygienisation and drying in
9290 order to enable transported over relatively large distances and their application as a P-
9291 fertiliser in agricultural areas characterised by soils that are poorer in P. Therefore, a
9292 correction should be made to avoid double-counting. Assuming that poultry litter has
9293 a relative agronomic efficiency of 0.85 relative to mined rock phosphate and
9294 processed P-fertilisers (Eghball et al., 2002; see section 9), **total fertiliser P-demand**
9295 **for the year 2030 is estimated to increase with 33 kt P yr⁻¹ (39 kt P yr⁻¹ x 0.85).**

9296 iii. *Effluents and sludges from municipal waste water treatment plants as input materials*
9297 *for P-precipitation and thermal oxidation processes (section 7.3.7).*

9298 As outlined in section 7.3.8.1, these processes will mostly take place in countries of
9299 Western Europe (Netherlands, Belgium, Germany, Austria, etc.) where the land
9300 application of sewage sludge is, anyhow, largely restricted (see section 14.5).
9301 Moreover, the budgeted sludge fraction that is considered in the thermal oxidation
9302 pathway (39%) corresponds reasonably to the sum of the sewage sludge amounts that
9303 are currently already incinerated (27.3%) and landfilled (9.2%). Therefore, no
9304 correction for double-counting is required for the processes listed in Table 10.
9305 However, in case further market stimulations would materialise resulting in an
9306 increased amount of sewage sludge that is incinerated (see section 7.3.8.2), the
9307 supplementary P-recovery would effectively take place on sewage sludge that is
9308 currently spread on land, possibly after anaerobic digestion or composting. Therefore,
9309 a correction should be made to avoid double-counting. The agronomic efficiency of
9310 the P in sewage sludge relative to mined rock phosphate and processed P-fertilisers is
9311 estimated at 0.46 (Oenema et al., 2012). **Therefore, total fertiliser P-demand for**
9312 **the year 2030 under this scenario of further market stimulations is estimated to**
9313 **increase with 27 kt P yr⁻¹ (58 kt P yr⁻¹ x 0.46).**

9314 iv. *Waste waters and wastes from the food processing industry to be used as an input*
9315 *material for precipitated phosphate salts (section 7.3.7)*

9316 These input materials consist of waste water from the potato industry and dairy
9317 industry. At present, these materials are not returned to agricultural land, but rather
9318 subject to chemical precipitation processes and removal of the flocculant-rich sludges
9319 from the biogeochemical P cycle. Therefore, no correction for double-counting is
9320 required for this process pathway.

9321
9322 Taken into consideration the points i) to iv), it is estimated that the total demand for P-
9323 fertilisers in the year 2030 will be 1253 kt P yr⁻¹ when considering the processes listed in
9324 Table 10. If the further STRUBIAS market stimulations outlined in section 7.3.8.2 would
9325 materialise, the total demand will increase to 1280 P yr⁻¹.

9326

9327 **In summary, as a best estimate, the opening of the P-fertiliser market to STRUBIAS**
9328 **materials will result in a substitution effect of mined and synthetic fertilisers by**
9329 **fertilising products containing precipitated phosphate salts & derivates and thermal**
9330 **oxidation materials & derivates of 17-31%.** Moreover, it should be noted that pyrolysis &
9331 gasification materials have not been included in this assessment because an initial entry is
9332 considered more likely into the organic farming sector. The on-the-ground use of pyrolysis &
9333 gasification materials might enable the detailed testing of the agronomic efficiency of
9334 pyrolysis & gasification materials, possibly leading to more refined and precise estimates
9335 given in section 6.2.4. In case these results lead to increased market and consumer confidence
9336 for the use of these materials in conventional agriculture, the substitution potential will
9337 further increase. It is noted that these estimates are associated to a large degree of uncertainty
9338 as many STRUBIAS materials are mostly a co-product of a process that has a different
9339 primary aim (e.g. waste management and control, biogas production, manure hygienisation,
9340 etc.). STRUBIAS materials mostly fit in transformation cascades of biogenic materials. In
9341 many occasions, STRUBIAS materials are only a co-product of these processes, and it will be
9342 the main driver for the process that determines the extent of placing on the market of
9343 STRUBIAS materials.
9344

9345 **7.4 Market outlook for non-fertiliser PFCs derived from STRUBIAS materials for the** 9346 **year 2030**

9347 STRUBIAS materials – and more specifically thermal oxidation materials & derivates and
9348 pyrolysis & gasification materials - can also be used in PFCs other than PFC 1 – fertilisers.
9349 STRUBIAS materials could be applied as liming materials, soil improvers, plant
9350 biostimulants, or as part of a fertiliser blend. Three main types of such STRUBIAS materials
9351 were indicated by the STRUBIAS sub-group: pulp biomass ashes, slags from the iron and
9352 steel industry, and C-rich char-like materials. Nonetheless, possibly more materials could be
9353 produced as the proposed STRUBIAS recovery rules enable the use of a broad range of input
9354 materials and production process conditions. Estimating a 2030 market for such fertilising
9355 materials is extremely challenging and associated with large uncertainties. Biomass ashes and
9356 slags from the iron and steel industry are by-products from production processes focusing of
9357 a different primary product (energy, paper and cardboard, and iron and steel, respectively).
9358 Therefore, the market for these materials will be determined by and the economical aspects
9359 and policy decisions to be taken in the coming years.
9360

9361 **Bark, wood and pulp residues** from wood handling can be combusted for energy recovery.
9362 The ashes contain nutrients and have a neutralising value and can thus be suitable as a (forest)
9363 fertiliser or liming material as long as the wood originated metals meet harmonised
9364 requirements for fertilisers. Wood and pulp biomass is used for energy production in many
9365 EU Member States, especially in northern Europe. Wood and biomass combustion in
9366 Denmark, Finland and Sweden generate >290 kt of biomass ashes, whereas the combined
9367 wood ashes of Austria, Germany, Ireland, Italy and the Netherlands add another 300 kt of
9368 wood ashes (van Eijk et al., 2012). The market outlook for the near future for these materials

9369 remains uncertain, amongst others due to the decisions to be taken in the framework of
9370 renewable energy.

9371

9372 Slags are produced as by-products from the metallurgical industry through a variety of
9373 techniques (see section 14.8). Due to their high Ca and sometimes relatively high P contents,
9374 slags from the iron and steel industry are currently applied on land as liming materials or
9375 fertilisers. The ratios of slag to steel output indicate that large volumes of slags are produced.
9376 Manufacturing a tonne of pig iron produces, for instance, 0.25–0.30 tonnes of blast furnace
9377 slag that can be further processed to granulated blast furnace slag (Jewell and Kimball, 2014).
9378 The output mass of basic oxygen furnace slag per tonne of crude steel is 0.10–0.15 tonnes
9379 (Jewell and Kimball, 2014). Altogether, slags from the steel industry are produced in Europe
9380 in an amount of approximately **25 - 40 million tonnes** (Branca et al., 2014; European
9381 Commission, 2016b).

9382 Iron slag and steel slag are used primarily as aggregates in concrete, asphaltic paving, fill, and
9383 road bases. Slags can also be used as a feed for cement kilns. About 2-3 percent of the slags,
9384 representing > 800 000 tonnes, are used as for the production of **fertilising products**
9385 (European Commission, 2016b). In Germany, slag use as fertilisers and liming materials has
9386 a long tradition; about half a million tonnes of steel industry lime are used in agriculture.
9387 Blast furnace slag, basic oxygen furnace slag and secondary metallurgic ladle slag from the
9388 production of low alloyed steel are used as fertilising materials. **Based on preliminary**
9389 **evaluations and confidential data submitted by the STRUBIAS sub-group, the overall**
9390 **share of the blast furnace slag and secondary metallurgic slag have rather low metals**
9391 **levels and would be able to meet the proposed criteria at CMC for thermal oxidation**
9392 **materials & derivates.** Slag can be used as a liming material or P-fertiliser production and
9393 micro-nutrients supply. The marketing of these products is today a reality in Germany,
9394 Austria, Finland, Sweden, France and probably other Member States. Basic slags are an
9395 effective liming material, having a high content of Ca (25 – 30%) and some Mg. Due to their
9396 low P contents (~ 0.01% - 2%; European Commission, 2017d), steel industry slags make
9397 today a low to moderate contribution to the European agriculture. The steel industry is,
9398 however, currently testing processes that aim to increase the quality and the P-content of the
9399 output materials to enable their use as an added value quality fertilising material (e.g.
9400 FEhS/Salzgitter process; see section 15.2.2).

9401

9402 **C-rich char-like materials as produced through a wet or dry pyrolysis process from**
9403 **biomass (e.g. plant materials, food processing residues, biowaste)** show a relatively high
9404 production cost that might limit the open-field applications at large application rates.
9405 Nonetheless, the STRUBIAS sub-group indicated their potential to be used as part of soilless
9406 plant growing media in horticulture, where it could possibly replace or complement other
9407 substrates like peat and lignite (Gruda, 2012). The growing media industry in the EU has a
9408 1.3 billion Euro turnover for peat based substrates. It is particularly important in Germany,
9409 Italy, the Netherlands, France and the UK. A smaller market segment is represented by the
9410 lignite, which is largely produced in Germany and Poland, and consumed for fertilizer
9411 production, or directly as growing media in horticulture. It has been estimated that, among
9412 the 22 Mm³ of soil conditioning product consumed for professional horticulture, 86% is peat.

9413 Also for gardening 15 Mm³ of soil improvers and growing media are consumed every year of
9414 which 69% of which is peat. The global lignite consumption in EU is around 450 Mt per
9415 year, of which 7% is used in agriculture. Most of the lignite addressed to agriculture sector is
9416 used to produce synthetic fertilizer (anhydrous ammonia & ammonium sulfate), but more
9417 than 200 kt per year are directly used as soil improver or growing media (EUBIA, 2015). The
9418 reasons for using pure peat or as a main component of growing media are to be found in its
9419 availability in Northern Europe, relatively low cost and its good chemical, biological and
9420 physical properties (Barrett et al., 2016). Increasing concern over the environmental impacts
9421 of some commonly used materials, has led researchers to identify and assess more
9422 environmentally sound alternatives. There has been an understandable focus on pyrolysis &
9423 gasification materials that have shown promise at an experimental level, but at present few
9424 have been taken up on a significant scale (Barrett et al., 2016). Further market uptake will
9425 depend on the interaction between economic and environmental concerns for the sector and
9426 the performance of pyrolysis & gasification materials relative to the current materials used,
9427 including not only peat but also to other alternatives such as compost, coir, soft-wood bark,
9428 wood fibre and wool.

9429

9430 **7.5 Conclusions on market potential for STRUBIAS materials**

9431 Based on the preliminary market assessment, market demand and trade is expected for all
9432 three STRUBIAS material groups in different segments of the EU agricultural sector. The
9433 most important share of the STRUBIAS materials will be used as fertiliser that can be used to
9434 provide nutrient, mostly phosphorus, inputs to European agriculture. Some STRUBIAS could
9435 also serve other fertilising functions and includes uses as liming material, soil improver or
9436 growing medium.

9437

9438 **8 Life cycle analyses - environmental and human health impacts, and production cost**

9439 **The protection of human health and the environment through the production and use**
9440 **phase of STRUBIAS materials is enforced through** (1) the implementation of **the**
9441 **technical requirements for STRUBIAS materials and CE marked fertilising products**
9442 that contain such materials, and (2) any **other relevant EU and national legislation that**
9443 **applies to these materials**, such as for instance, the Industrial Emissions Directive
9444 2010/75/EC, the Water Framework Directive 2000/60/EC or the Nitrates Directive
9445 91/676/EEC (see section 5). This section will assess the impacts associated to the production
9446 and use phase of STRUBIAS materials, as well the production cost of these materials in order
9447 to evaluate the impacts on the environment (e.g. eutrophication, global warming, etc.), the
9448 human health (e.g. carcinogenic and other toxic effects), and the cost of production.

9449
9450 For this assessment, **the focus is on the plant available P as a product to be used by**
9451 **farmers**. The life cycle assessment encompasses the whole life cycle of the final P-product,
9452 from transport, to processing, to final use on land. This also includes the effects associated
9453 with eventual co-services and co-products generated alongside throughout the manufacturing
9454 chain. By incorporating information on the capital and operation costs for the different life
9455 cycle stages, an assessment of the production and opportunity cost for STRUBIAS materials
9456 will be brought forward.

9457
9458 Here we evaluate an extensive set of feedstock-process technology combinations collected
9459 from frontrunner operating P-recovery facilities using a standardised and comprehensive life
9460 cycle methodology. The results brought forward in this section should be interpreted as
9461 **preliminary estimates for a P-recovery industry that is still in the initial stages of**
9462 **development**. It is noted that the results are highly dependent on the technological design and
9463 development scale for specific STRUBIAS production pathways and counterfactual handling
9464 scenarios for their input materials. Moreover, uncertainties exist due to variations in costs for
9465 chemicals. Hence, the results can by no means be interpreted as final conclusions; it is a
9466 preliminary and momentary evaluation for an emerging and continuously developing
9467 industrial sector of the circular economy.

9468 **8.1 Objective of the life cycle assessment**

9470 Phosphorus is essential for life and irreplaceable. It is a key element in our DNA and all
9471 living organisms require P intake to produce energy. A reduced dependence on the finite
9472 phosphate rock is a huge benefit for the society. Whereas other non-renewable natural
9473 resources can be replaced by other primary materials when they deplete, phosphate rock has
9474 no substitute from primary sources. Achieving long-term food security means we must
9475 change the way we source P in global food production. A core aim of STRUBIAS
9476 technologies that repackage dissipated P into concentrated P-fertilisers is to decouple end P
9477 users from source risk. **In view of improving food security in the long-term, this objective**
9478 **gives good reason for the development of STRUBIAS technologies that redirect**
9479 **otherwise dissipated P into value-added concentrated P-fertilisers.**

9480

9481 The occurrence of meaningful shifts in P-fertilisers manufacturing processes thanks to the
9482 opening of the fertiliser market to STRUBIAS materials might considerably alter the
9483 environmental and human health impacts, both “upstream” and “downstream” for a P-
9484 fertiliser manufacturer or supplier. Conceptual frameworks often refer to possible
9485 environmental and monetary co-benefits of the circular economy model, including avoided
9486 energy- and cost-intensive transport of manure, mitigated eutrophication, economic savings
9487 due to energy recovery, and reduced waste management costs (Elser and Bennett, 2011;
9488 Mehta et al., 2015; Macdonald et al., 2016; Mayer et al., 2016). Nonetheless, case studies
9489 assessing advanced P-recovery through STRUBIAS processes from municipal wastewaters
9490 (Bradford-Hartke et al., 2015; Amann et al., 2018) and food waste (Styles et al., 2018) in
9491 Europe identified **trade-offs between environmental impacts and suggested that any**
9492 **environmental and human health savings or burdens are largely dependent on the**
9493 **technology applied and the resulting fertilising material properties.** Economic analyses
9494 indicate supplementary costs for most, but not all, P-recovery pathways from municipal waste
9495 waters (Egle et al., 2016; Nattorp et al., 2017).

9496

9497 Therefore, **the objective of this section is to identify development opportunities, sector**
9498 **challenges and mechanisms that maximise the socio-environmental benefits of emerging**
9499 **P-recovery pathways.** This information may help to guide nascent manufacturers in the
9500 optimisation of innovative and sustainable production processes adapted to local settings and
9501 regional priorities, and aid policy makers to assess the sustainability of particular routes to
9502 reduce dependence on phosphate rock, in order to make informed decisions. Rather than
9503 focusing on the numerical results of each of the individual STRUBIAS pathways, this section
9504 aims to (i) provide insight in the way impacts and costs for STRUBIAS production pathways
9505 are properly envisaged and conceptualised, and (ii) focus on the main drivers of the impacts
9506 and costs for STRUBIAS processes.

9507

9508 **8.2 Standardised methodology for STRUBIAS materials**

9509 In order to make a sound judgement on the technical, economic, market, environmental and
9510 human health aspects related to the production and use of STRUBIAS materials, **a**
9511 **standardised and uniform scientific analysis needs to be performed across all**
9512 **STRUBIAS material categories.** Whereas STRUBIAS materials may already have been the
9513 subject of individual studies encountered in the scientific literature (Jossa and Remy, 2015;
9514 Egle et al., 2016; De Graaff et al., 2017; Nattorp et al., 2017; Styles et al., 2018) these studies
9515 (i) feature their own goals, scope, system boundaries, and datasets, and (ii) only make an
9516 assessment for specific input material – STRUBIAS process pathway combinations. The
9517 result is a **fragmented information landscape**, which currently complicates a comparison of
9518 STRUBIAS materials. Therefore, the JRC has decided to perform an independent assessment
9519 that relies on a standardised methodological approach (environmental assessment based on
9520 the ISO 14040:2006 standard) and state-of-the-art methodology (for monetary evaluation).

9521

9522 8.3 Conceptualisation of life cycle systems

9523 For a good understanding of the reader on this section of the report, it is fundamental to
9524 outline some basic aspects and principles of the life cycle methodology applied to assess
9525 human and environmental impacts and costs for STRUBIAS materials. Fertilising products
9526 can be manufactured from either primary or secondary raw materials, with both types of
9527 processes resulting in products with a similar or equal function that will be placed on the
9528 market. From a conceptual point of view for life cycle analyses, both types of processes are,
9529 however, fundamentally different.

9530
9531 The starting point for phosphate rock derived P-fertilisers is constituted by the extraction of a
9532 primary raw material. **In case phosphate rock is not extracted from nature, it will remain**
9533 **stored in natural bedrock layers**; it is assumed to be an inert material and adequately
9534 protected from exposure to assume that the environmental impact from the natural weathering
9535 of the phosphate rock is negligible. The situation is different for P-fertilisers derived from
9536 secondary raw materials as the latter materials are already part of the biogeochemical
9537 processes occurring on earth, and further processing and/or handling for these biogenic
9538 materials is anyhow required. Biogenic secondary raw materials cannot be withdrawn from
9539 the biogeochemical cycles, unless they are further processed into materials that can be
9540 deposited in the long-run; in reasonable present-day conditions and under existing and future
9541 EU policies and legislations, biogenic materials cannot simply be landfilled. **A direct**
9542 **consequence of the handling of the feedstock material through a STRUBIAS production**
9543 **pathway is that an alternative handling scenario of the (biogenic) feedstock material**
9544 **will be avoided.** This observation indicates that a proper analysis will have to consider the
9545 impacts of the *counterfactual lifecycle of the secondary raw materials*, as well as the costs
9546 that are associated to the handling of the secondary raw material in a counterfactual scenario.
9547 It is thus essential that a relevant counterfactual scenario is included in the assessments as any
9548 handling scenario of the secondary raw material is associated to an environmental impact and
9549 a cost, and those impacts and costs are replaced by others when that secondary raw material
9550 enters into the transformation cycle that ends up with a STRUBIAS material. Relevant
9551 examples of counterfactual life stages of secondary raw materials are, for instance, the co-
9552 incineration of sewage sludge followed by transport to a landfill, or the processing (e.g.
9553 anaerobic digestion), storage (e.g. in storage tanks at the farm), and transport (over variable
9554 distances, depending on the regional situation) of pig manure. This implies, for example, that
9555 the production cost for SSP manufactured from sewage sludge should be reduced by the cost
9556 of the pertinent alternative treatment (e.g. the co-incineration of sewage sludge), and that the
9557 environmental impacts of producing struvite from manure should be decreased by the impact
9558 of handling manure under the counterfactual handling scenario (e.g. energy recovery in
9559 anaerobic digestion, emissions from transport, and possible eutrophication resulting from the
9560 use on land of digested manure). **This observation points towards (1) the importance of**
9561 **selecting relevant counterfactual scenarios in the life cycle analyses, and (2) the fact that**
9562 **impacts and "production costs" for STRUBIAS fertilisers are dependent on the**
9563 **situation-specific context** (e.g. direct land application of manure on the farm may take place

9564 in Croatia, but the same manure should be transported over long distances to enable land
9565 application in line with the legislative framework in the Netherlands).

9566

9567 **Secondary raw materials of biogenic origin typically include a manifold of valuable**
9568 **substances (e.g. carbon, nitrogen, energy, etc.) and contaminants (e.g. metals).** Nutrient
9569 recovery may even be part of a production process that has a different aim (e.g. biogas
9570 production, processed manure with a balanced nutrient supply for specific agricultural lands,
9571 etc.). In the circular economy, in the bio-economy and in many STRUBIAS P-fertiliser
9572 production processes, different co-products are generated that can also be placed on the
9573 market as added-value materials, and thus replace other products. These **co-products have to**
9574 **be taken into consideration for both the STRUBIAS scenarios as well as for the**
9575 **counterfactual scenarios for the handling of secondary raw materials.** This is exemplified
9576 by a STRUBIAS scenario where poultry litter ash is produced from poultry manure, and a
9577 counterfactual scenario where the manure is directly applied on land. In such a case, (i) the
9578 sales price of the energy recovered from the incineration of poultry manure will be subtracted
9579 from the gross production cost of the STRUBIAS material, and (ii) the STRUBIAS material
9580 production cost should be increased because plant available nitrogen is returned to land in the
9581 counterfactual scenario and thus the cost of purchasing mineral N is avoided; N is, however,
9582 lost during the thermal oxidation process. Similarly, the environmental footprint of
9583 STRUBIAS materials derived from manure can be decreased when in the counterfactual
9584 scenario manure might be associated to N-leaching towards water bodies, but be increased
9585 when disproportionate transport of the manure to the STRUBIAS production facility is
9586 required relative to a counterfactual scenario of on-farm manure landspreading. Also here the
9587 situation is thus different for STRUBIAS than for mined phosphate rock and processed P-
9588 fertilisers where the manufacturing aims at manufacturing a single product, being the P-
9589 fertiliser.

9590

9591 All these observations already indicate that reporting on the absolute environmental and
9592 human health impact from the production and use of STRUBIAS materials provides little
9593 added value. The environmental and human health impacts originate from different life cycle
9594 stages for STRUBIAS production and use on land, including the avoided emissions from the
9595 alternative use of the input material, the manufacturing stage, and the use on land phase.
9596 Therefore, the present STRUBIAS report will **rely on scenario modelling for the**
9597 **assessment of environmental and human health impacts and estimates for production**
9598 **costs of STRUBIAS pathways.**

9599

9600 It is indicated that a consequential life cycle approach is the most suitable conceptual
9601 approach in line with the ISO standard (14040:2006) because the **handling of the feedstock**
9602 **material and the system co-products are expected to change as a direct consequence of**
9603 **the manufacturing of STRUBIAS fertilisers.** In view of maintaining the basic principle of
9604 mass and energy conservation and economic accounting in the life cycle system, the life
9605 cycle approach therefore requires expanding the life cycle system to include the impacts and
9606 costs related to the handling of feedstock and system co-products.

9607

9608 **8.4 Scenario modelling**

9609 **Scenario modelling** will be applied to assess ten different **production options** (P1-P10) for
9610 P-fertilisers. The selected production options for STRUBIAS materials include 9 different
9611 relevant P-fertilisers of high TRL outlined in section 7.3, which rely on manure, sewage
9612 sludge and rendered animal by-products as input materials. Additionally, the option to
9613 produce **mined rock phosphate and processed P-fertiliser** was investigated (P10,
9614 production of single super phosphate).

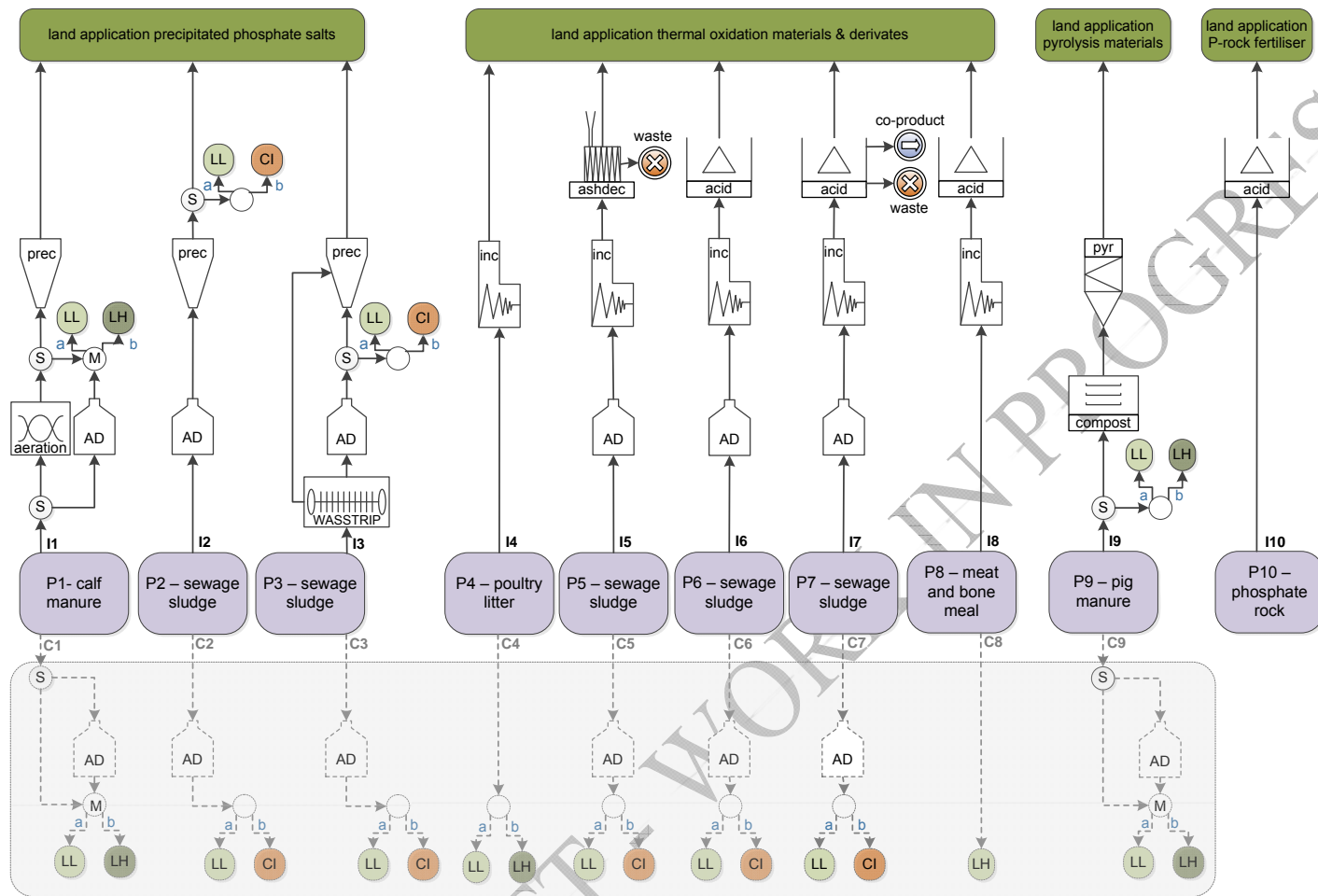
9615
9616 The different input materials for each of the **production options P1-P9** can be processed
9617 through a STRUBIAS production pathway ("**induced scenarios**", I1-I9) or through a
9618 different route under business-as-usual practices in Europe ("**counterfactual scenario**", C1-
9619 C9). The impacts and cost for each of the production shifts is then the difference between the
9620 induced scenario and the counterfactual scenario (see section 8.5.1 for details). Additionally,
9621 the production of a **mined rock phosphate and processed P-fertiliser** was investigated (I10,
9622 production of single super phosphate). As this pathway involves the use of a primary raw
9623 material phosphate rock, no counterfactual scenario is applied (or alternatively, the impacts of
9624 the counterfactual scenario are zero; thus C10 = 0).

9625
9626 **Nine STRUBIAS processes** were investigated covering precipitated phosphate salts (3
9627 pathways, I1 – I3, starting from veal calf manure and thickened sewage sludge as input
9628 materials), thermal oxidation materials & derivatives (5 pathways, I4 – I8, starting from poultry
9629 litter, sewage sludge and meat and bone meal as input materials), and pyrolysis materials (I9,
9630 starting from pig manure as input material) (scenarios I1-I10; Figure 21). I1 involves the
9631 removal of nutrients from manure slurries through aeration (N) and K-struvite precipitation,
9632 and is performed by Stichting Mestverwerking Gelderland in the Netherlands. I2 and I3
9633 involve the precipitation of struvites from sewage sludge prior to anaerobic digestion (I2,
9634 Airprex) and bypassing partly the anaerobic digester (I3, WASSTRIP plus Ostara – Pearl
9635 precipitation) at predominantly biological waste water treatment plants. I4 (BMC Moerdijk)
9636 is the thermal oxidation of poultry litter and the direct application of the poultry litter ashes
9637 on the field. I5 (AshDec) involves the treatment of sewage sludge mono-incineration ashes
9638 with a sodium sulphate to partially remove heavy metals and to increase the plant availability
9639 of P contained in the sewage sludge (RAE of ~90%, see section 6.2.3). I6 is the process
9640 envisaged by the mineral fertiliser industry for the production of SSP from sewage sludge
9641 ashes; it involves the acidulation of sewage sludge mono-incineration ashes with sulphuric
9642 ashes to produce SSP without significant metal/metalloid removal from the ashes. I7 is the
9643 Ecophos process in which sewage sludge mono-incineration ashes are acidulated with HCl,
9644 after which the metals/metalloids are separated from the P (H₃PO₄) and co-products (CaCl₂,
9645 FeCl₃). I8 is equal to I6 (mono-incineration plus acidulation using H₂SO₄), but uses meat-
9646 and-bone meal as input material. I9 involves the composting of the solid pig manure fraction
9647 as obtained after solid-liquid separation, followed by the slow pyrolysis of the compost. I10 is
9648 the production from SSP through the acidulation of phosphate rock with sulphuric acid. **Total**
9649 **P-recovery** is low to medium for pathways that recover P as precipitated phosphate salts (I1:
9650 13%, I2: 15%, I3: 46%) and pyrolysis materials (I9: 58%), but almost complete for the other

9651 pathways (I4-I8 and I10: >95%). The different induced scenarios are schematically outlined
9652 in **Figure 21** and described in detail in section 15.

9653

9654 **Counterfactual scenarios will be applied in function of the input material applied, and**
9655 **dependent on the regional situation** (scenarios C1-C9; Figure 21). In order to account for
9656 regional variations in Europe for the counterfactual handling of the input materials "*nutrient*
9657 *deficient areas (NDA)*" and "*nutrient surplus areas (NSA)*" were envisaged. The
9658 counterfactual handling of **manure** (C1, C4, C9) in NDA includes land application, possibly
9659 after anaerobic digestion, at low application rates that takes full advantage of all
9660 macronutrients present in the manure. It is assumed that sufficient land is available to spread
9661 the manure in NDA. In NSA, manure is applied at an application rate in line with the
9662 maximum for manure nitrogen application of 170 kg N ha⁻¹ yr⁻¹, as determined by Council
9663 Directive 91/676/EEC concerning the protection of waters against pollution caused by
9664 nitrates from agricultural sources. As a result of such application, P and K might be applied at
9665 rates that exceed crop requirement, and thus not contribute to plant nutrition but only to
9666 possible adverse effects (e.g. nutrient leaching and run-off to surrounding waters). As
9667 indicated by van Dijk et al. (2016), this situation is especially prevalent for P in various
9668 livestock dense regions in Europe and is one of the major reasons resulting in excessive P-
9669 accretion in European soils. It is also referred to section 8.6.2 for the principles governing the
9670 calculation of the nutrient fate. The fates of manure in NDA and NSA thus represent common
9671 scenarios for the handling of manure in Europe (see section 14.3). The counterfactual
9672 handling for **sewage sludge** (C2-C3, C5-C7) in NDA includes anaerobic digestion at the
9673 waste water treatment plant followed by land application at low application rates that takes
9674 full advantage of all macronutrients present in the sewage sludge. For NSA, co-incineration
9675 together with mixed municipal waste at a co-incineration plant, followed by further use of the
9676 ashes as road base material was assumed. For P-recovery scenarios that only recover a share
9677 of the P present in the sewage sludge as precipitated phosphate salts, the fraction not
9678 recovered as a STRUBIAS material was assumed to have the same fate as the sewage sludge
9679 in the counterfactual scenario (i.e. land application and co-incineration in NDA and NSA,
9680 respectively). The fates of sewage sludge in NDA and NSA include the most common routes
9681 for the return of sewage sludge in Europe (see section 14.5). The counterfactual handling
9682 scenario for **animal by-products other than manure** (C8 – meat and bone meal) includes
9683 their transport and direct application on land as an (organic) fertiliser. This situation is
9684 envisaged for both NDA as for NSA. At present, about 20% of the category 2 and 3 by-
9685 product material is applied as fertiliser on land, with the remaining 80% fraction not being
9686 used as fertiliser material (mainly used as pet food or feed, see section 14.4.4).



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Figure 21: Schematic representation of the 10 production options for P-fertilisers through STRUBIAS production routes (P1-P9) and through the acidulation of phosphate rock (P10). The results for each pathway P1-P9 are obtained from the difference between the induced use (I1-I9; upper half) and the counterfactual use (C1-C9; low half, in grey box/dashed lines) (S: solid-liquid separation, M: multiple inputs, AD: anaerobic digestion, prec: precipitation of phosphate salts, inc: mono-incineration, pyr: slow pyrolysis, acid: acidulation process; the lowercase blue letters indicate the use routes for biogenic materials within nutrient deficient areas (NDA, a) and nutrient surplus areas (NSA, b) as follows - LL: land application of co-products at low application rates; LH: land application of co-products at high application rates; CI: co-incineration of co-products).

9695 **8.5 Study boundaries**

9696 8.5.1 Life cycle stages

9697 The **boundaries of the life cycle system start at the extraction or inflow of the primary or**
9698 **secondary raw material to the P-fertiliser production plant and end with the use on land**
9699 **phase of the manufactured P-fertiliser.** The impacts of supplying such feedstock to
9700 STRUBIAS production processes are accounted for by applying the same input material both
9701 for the induced as for the counterfactual scenario. The life cycle stages included in the impact
9702 and cost assessment include **transport** from the production site of the input material to the
9703 processing plant, **material transformation and manufacturing stages** as depicted in Figure
9704 21, **granulation, transport** to use on land, **storage** at the farm, **land application**, and **use on**
9705 **land.** The cost assessment does not include externalities (e.g. additional cost for drinking
9706 water production from surface waters) due to the uncertainty associated to their monetary
9707 values; these will only be presented as separate environmental impacts. The approach to
9708 calculate the STRUBIAS production cost is also known as life cycle costing and aims to
9709 assess the conventional budget costs, without monetising environmental impacts (e.g.
9710 Martinez-Sanchez et al., 2015).

9711
9712 Under the default scenario modelling approach, a **standard transport distance of 25 km**
9713 was assumed for all transport stages (e.g. from site of collection to processing plant, from
9714 waste water treatment plant to incineration facility, from P-fertiliser manufacturing site to use
9715 on land). The only exception was the transport from the place of phosphate rock extraction to
9716 the manufacturing site. As part of the **uncertainty analyses**, transport distances for manure
9717 were varied to simulate a scenario where the manure is exported from one EU member state to
9718 another, with an assumed transport distance of 500 km. **Storage** was assumed for all
9719 materials that will be applied on agricultural land in the induced and counterfactual scenarios,
9720 and was material specific (e.g. liquid manure in covered lagoon, solid manure in a (covered)
9721 field heap with an impermeable concrete floor, P-fertilisers in an indoor silo). Nutrient losses
9722 during storage were considered (e.g. ammonia volatilisation, methane and nitrous oxide
9723 emissions, etc.). It was assumed that storage only occurred after the material transformation
9724 cycle, and thus prior to use on land by the farmer. The assessment includes the
9725 **granulation/pelletising** of slurries or powders formed within a manufacturing process for all
9726 P-fertilisers. Granulation is not included for manures and processed manures that are applied
9727 on land.

9728
9729 The cost assessment includes **capital costs** with an investment amortisation time of 20 years,
9730 and a net interest rate of 5%. **Operational costs** include costs of intermediates (e.g. sulphuric
9731 acid, hydrochloric acid, lime; purchased as primary raw materials on the market) and labour.
9732 Revenues from co-products (e.g. energy, bio-available nutrients present in processed manure
9733 fractions, $\text{CaCl}_2/\text{FeCl}_3$ in I7) were included. For P-recovery as precipitated phosphate salts at
9734 biological waste water treatment plants, the benefits of reduced polymer needs and sludge
9735 volumes for dewatering were taken into consideration as well as the reduced energy needs for
9736 the plant (e.g. due to the precipitation of N in struvites) and chemical coagulant needs relative
9737 a default biological waste water treatment plant. Operational benefits due to reduced plant

9738 maintenance needs and avoided tube clogging were, however, not considered due to the lack
9739 of available data. In all scenarios, it was assumed that heat was not recovered as a marketable
9740 product.

9741

9742 8.5.2 Energy and mass balances

9743 The impacts associated to following elements was assessed: **carbon**, the **macronutrients N,**
9744 **P, and K**, and the **metals and metalloids** Arsenic (As), Cadmium (Cd), Chromium (Cr),
9745 Copper (Cu), Mercury (Hg), Nickel (Ni), Lead (Pb), and Zinc (Zn). The impact of other
9746 micronutrients and/or possible contaminants was disregarded in this assessment because of
9747 their limited impact on the overall results when compliant with the STRUBIAS recovery
9748 rules. Energy and mass were traced throughout the system by fully closing the mass and
9749 energy system balances. The output material of the system was in agreement with the product
9750 quality (nutrient content, metal/metalloid content) for the P-fertilisers.

9751

9752 8.6 Calculations

9753 8.6.1 Functional unit and basic calculation approach

9754 The **functional unit** of the assessment is **1 kg of bio-available P recovered in the P-**
9755 **fertiliser material**, either being a STRUBIAS material (P1-P9) or SSP as a selected mined
9756 phosphate rock and processed P-fertiliser (P10).

9757

9758 **Co-products and co-services other than bio-available P in the P-fertiliser (e.g. energy,**
9759 **bioavailable N and P in manure) were diverted and credited**, both from an impact
9760 perspective (e.g. possible N leaching from manure fractions) as from a monetary point of
9761 view (e.g. avoided cost for farmer to purchase mineral N fertiliser; see also section 8.6.3) (see
9762 Figure 22).

9763

9764 The choice of this functional unit implies that, for each individual scenario Px, different
9765 quantities of input materials are processed, depending on the P content of the input material,
9766 the P-recovery efficiency and the agronomic efficiency of STRUBIAS material resulting
9767 from pathway Ix relative to mined and synthetic P-fertilisers (Table 12). Based on these data,
9768 the amount of input material that is applied to obtain 1 kg of bio-available P recovered in the
9769 P-fertiliser material in the induced pathways (I1-I10) can be calculated. **The results for the**
9770 **counterfactual pathways are then obtained by processing the same amount of the input**
9771 **material through pathways C1-C9.**

9772

9773 **Table 12: Conversion factor between functional unit for the life cycle assessment, and input and**
 9774 **output materials applied for the different production option for P-fertilisers as outlined in**
 9775 **Figure 21 (SSP: single superphosphate; TSP: single superphosphate).**

pathway	Functional unit	Total P in STRUBIAS material (kg)	Total weight of STRUBIAS material (kg)	composition STRUBIAS material	Total weight of input material applied (kg)	Type of input material applied
P1		1.00	16.7	K-struvite	12410	raw calf manure (slurry, 4% DM)
P2		1.00	11.0	struvite	5731	undigested sewage sludge (5% DM)
P3		1.00	7.9	struvite	1772	undigested sewage sludge (5% DM)
P4	1 kg bio-available	1.08	17.6	poultry litter ash	139	raw poultry litter (48% DM)
P5	P in STRUBIAS	1.11	15.0	AshDec fertiliser	925	undigested sewage sludge (5% DM)
P6	material	1.00	18.0	SSP-like material	817	undigested sewage sludge (5% DM)
P7		1.00	5.0	TSP	824	undigested sewage sludge (5% DM)
P8		1.00	11.5	SSP-like material	31	meat-and-bone meal (97% DM)
P9		1.18	28.3	pyrolysis material	3565	raw pig manure (slurry, 5% DM)
P10	1 kg bio-available P in SSP	1.00	12.7	SSP	7.5	phosphate rock (100% DM)

9776
 9777
 9778 The environmental and human health impacts for fertilising products containing precipitated
 9779 phosphate salts & derivates, thermal oxidation materials & derivates, and pyrolysis &
 9780 gasification materials are thus calculated by attributing the impacts and costs of the material
 9781 transformation process to the P-fertiliser based on the calculated impacts/costs and the bio-
 9782 available P recovery efficiency for each pathway, as follows:

$$9784 \quad IM(Ix/Cx) = \sum_{m=1, Ix/Cx}^{M, Ix/Cx} IM_{man} + \sum_{t=1, Ix/Cx}^{T, Ix/Cx} IM_{TS} + \sum_{k=1, Ix/Cx}^{K, Ix/Cx} AIM_{co} + \sum_{o=1, Ix/Cx}^{O, Ix/Cx} IM_{UOL-OFM} + IM_{UOL-PF, Ix}$$

9785
 9786 With $IM(Ix/Cx)$: results for a specific impact category for pathways Ix or Cx,
 9787 $\sum_{m=1, Ix/Cx}^{M, Ix/Cx} IM_{man}$: the sum of the impacts resulting from manufacturing operations for the
 9788 different life cycle stages in the manufacturing chain (1→M) of scenarios Ix or Cx;
 9789 $\sum_{t=1, Ix/Cx}^{T, Ix/Cx} IM_{TS}$: the sum of the impact resulting from the different transport and storage life
 9790 cycle stages (1→T); $\sum_{k=1, Ix/Cx}^{K, Ix/Cx} AIM_{co}$: the sum of avoided impacts resulting from the
 9791 different co-products and co-services (1→K) generated for scenarios Ix or Cx (e.g. avoided
 9792 energy production, avoided fertiliser production); $\sum_{o=1, Ix/Cx}^{O, Ix/Cx} IM_{UOL-OFM}$: the sum of the
 9793 impacts resulting from the use on land (1→O) from fertilising materials, other than the P-
 9794 fertiliser (e.g. processed manure); $IM_{UOL-PF, Ix}$: the impact resulting from the use on land of
 9795 the P-fertiliser, thus the STRUBIAS material for I1-I9 or SSP for I10.

$$9797 \quad COST(Ix/Cx) = \sum_{l=1, Ix/Cx}^{L, Ix/Cx} CAPEX_{man} + \sum_{l=1, Ix/Cx}^{L, Ix/Cx} OPEX_{man} + \sum_{t=1, Ix/Cx}^{T, Ix/Cx} COST_{TS} + \sum_{c=1, Ix/Cx}^{C, Ix/Cx} savings_{co}$$

9798

9799 With $COST(Ix/Cx)$: production cost for pathways Ix or Cx, $\sum_{l=1, Ix}^{L, Ix/Cx} CAPEX_{man}$:
9800 the sum of the capital cost of the equipment for the different life cycle stages (1→L) of the
9801 manufacturing chain; $\sum_{l=1, Ix}^{L, Ix/Cx} OPEX_{man}$: the sum of the operational cost for the different life
9802 cycle stages (1→L) in the manufacturing chain; $\sum_{t=1, Ix/Cx}^{T, Ix/Cx} COST_{TS}$: capital and operational
9803 costs associated to transport and storage; and $\sum_{c=1, Ix}^{C, Ix/Cx} savings_{co}$: monetary savings due to
9804 the avoided production of conventional market products due to co-products and co-services
9805 (1→C) (e.g. avoided energy production, avoided mineral N fertiliser production).

9806

9807 Based on these results, the impacts and costs can then be calculated for each entire production
9808 option as follows:

9809

$$9810 \quad IM(Px) = IM(Ix) - IM(Cx)$$

9811

9812 With $IM(Px)$: results for a specific impact category for STRUBIAS production
9813 option Px, $IM(Ix)$: results for the specific impact category for pathway Ix, and $IM(Cx)$:
9814 results for the specific impact category for pathway Cx.

9815

$$9816 \quad COST(Px) = COST(Ix) - COST(Cx)$$

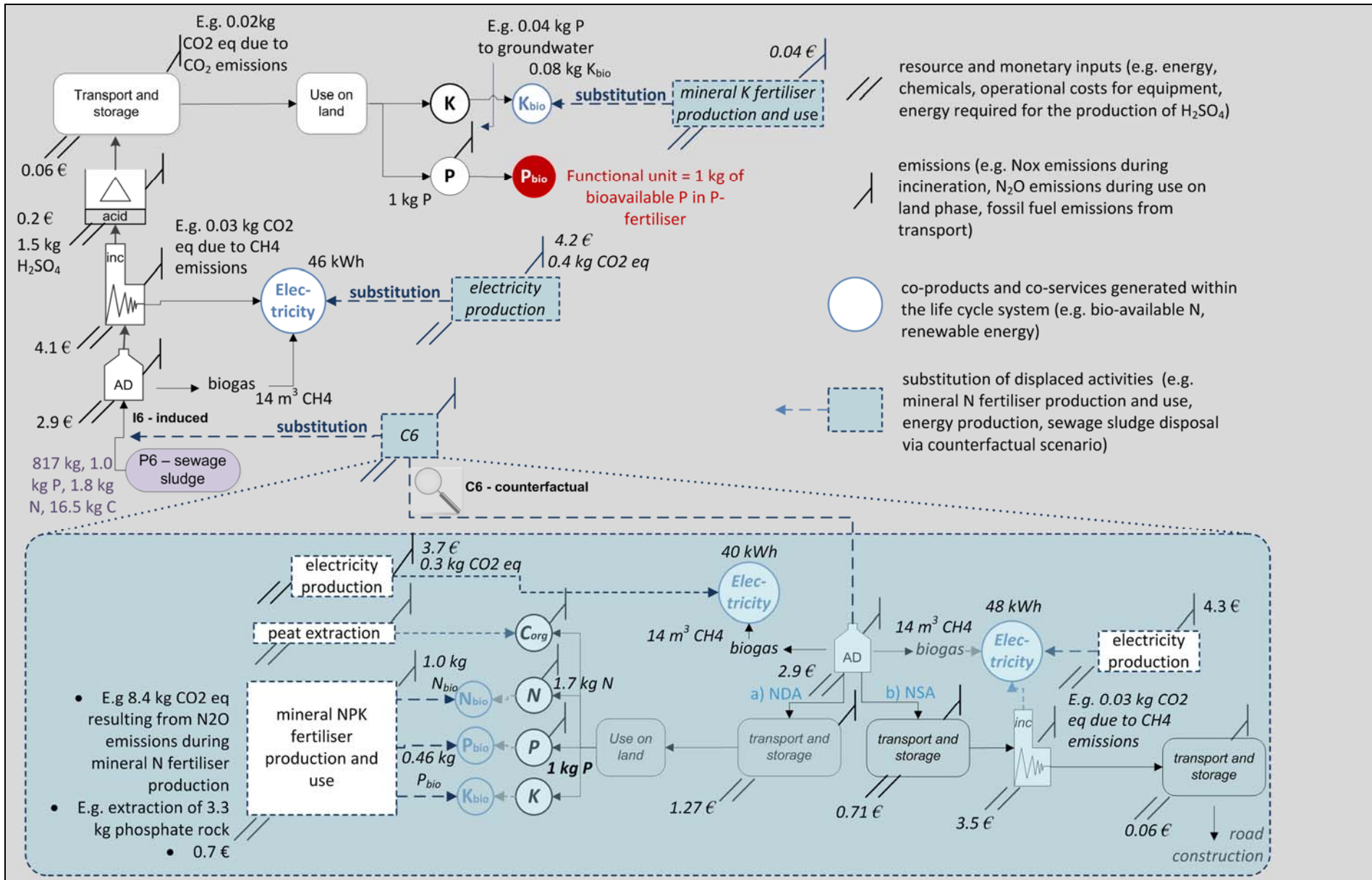
9817

9818 With $COST(Px)$: estimated production cost for STRUBIAS production option Px,
9819 $COST(Ix)$: production cost for pathway Ix, and $COST(Cx)$: production cost for pathway Cx.

9820

9821 The conceptualisation of the life cycle system applied as well as the calculation principles are
9822 outlined schematically in Figure 22.

9823



9825 A consequential product system has been used to answer the research question: “What are the impacts related to the full share of those activities that are expected to change
9826 when shifting the source material for the production and consumption producing of a P-fertiliser?” Therefore, the life cycle system is approached from a product perspective
9827 and *1 kg of bio-available P in the P-fertiliser* is used as functional unit for this life cycle assessment (red box P_{bio}; note that the quantity of the input material applied has been
9828 back-calculated in order to end up with the functional unit at the end of the production and use chain). Impacts can then be compared for all production options (P1-P10),
9829 regardless of source material used.

9830 Consequential models reflect physical and monetary causalities, and the consequences associated to the substitution of displaced activities are considered. This includes,
9831 amongst others, the avoided handling and use of the biogenic material that is used as feedstock to produce STRUBIAS materials. The impacts associated to the alternative
9832 feedstock handling are the net result of sum of different processes (possibly also involving processing, transport and use on land as possible life cycle stages), and may
9833 ultimately determine the overall system result. In order to better understand the impacts from the avoided counterfactual feedstock handling (C), these results are presented in
9834 a disaggregated manner in addition to the gross impacts from the induced pathway (I). The net results for the pathways P1-P9 are then calculated as $P_{1-9} = I_{1-9} - C_{1-9}$. The
9835 source material for mined rock phosphate and processed P-fertilisers starts is obtained through the extraction of a primary raw material. In case phosphate rock is not
9836 extracted, it will remain stored in natural bedrock layers adequately protected from exposure so that environmental impact due natural weathering can be ignored. Therefore,
9837 the impacts of the counterfactual feedstock handling scenario for P10 are considered zero and $P_{10} = I_{10}$.

9838 Now, the impacts and costs of the induced (I6) and counterfactual (C6) scenario are calculated individually. This implies that we have to take into consideration all impacts,
9839 costs and possible savings from the scenario. For instance, if the STRUBIAS manufacturing process involves the mono-incineration of the sewage sludge then this process is
9840 associated to a cost (e.g. costs of building and operating the incinerator plants), an environmental impact from input (e.g. mono-incineration requires limestone; the impacts of
9841 extracting the limestone from nature are taken into consideration) and output materials (e.g. NO_x emissions to air leaving the incinerator), and a saving (some energy can be
9842 recovered from the sewage sludge; as this energy is not part of the functional unit applied, it is assumed that the energy is diverted and credited both from an impact
9843 perspective as from a monetary point of view; the placing on the market of the renewable energy implies e.g. that fossil fuel emissions to air from coal combustion are
9844 avoided, and that the STRUBIAS manufacturer will receive a monetary compensation for the avoided energy production he substitutes on the market).

9845 By opting for the STRUBIAS pathway instead of the counterfactual scenario, all impacts and costs that come along with the counterfactual scenario have to be deducted,
9846 whether they are positive or negative. For instance, the bio-available nutrients (N_{bio}, P_{bio}, K_{bio}) present in the digested sludge in the counterfactual scenario (NDA) are not part
9847 of our functional unit and thus assumed to be a co-product or co-service in the C scenario. This implies that the bio-available nutrients are diverted and credited in the C
9848 scenario; the placing on the market of the bio-available nutrients in the NDA counterfactual scenario implies that the environmental and cost impacts from the production and
9849 use of mineral N, P, and K fertilisers are displaced or avoided. Note that for the overall production option results, the substitution of displaced activities in the counterfactual
9850 scenario are ultimately system burdens ($P = I - C = I - (\text{impacts}_{\text{counterfactual}} - \text{savings}_{\text{counterfactual}}) = I - \text{impacts}_{\text{counterfactual}} + \text{savings}_{\text{counterfactual}}$; represented by boxes that again lose
9851 their blue colour and italic text in the counterfactual scenario).

9852 The possible diverting and crediting of bio-available P derived from biogenic feedstocks in the counterfactual scenario may result in an altered demand for phosphate rock.
9853 This is exemplified by comparing NDA to NSA. In the counterfactual scenario C for NDA, where P is brought back to agricultural land, the crediting will result in the
9854 substitution by phosphate rock, but not in the counterfactual scenario for NSA, where P is lost in road construction materials. In the counterfactual scenario for NSA, the
9855 biogenic material is fully removed from the biogeochemical cycle, and any P-recovery from the dissipated P will effectively contribute to a reduced phosphate rock
9856 dependence relative to the production and use of mined rock phosphate fertilisers. In NDA, the biogenic material is already a plant available P-source in the counterfactual
9857 scenario; turning it into a STRUBIAS material will therefore only reduce the depletion of phosphate rock in case the effective plant P uptake from the biogenic material is
9858 increased during the STRUBIAS manufacturing process.

9859

9860 These conceptual and calculation approaches are exemplified as follows for fictitious monetary costs, but the same principles apply to the environmental impacts.

9861 The cost of producing 1 kg of bio-available P through the induced pathway is:

9862
$$COST(I6) = 2.9 \text{ € (anaerobic digestion)} + 4.1 \text{ € (mono-incineration)} + 0.2 \text{ € (acidulation unit)} + 0.06 \text{ € (transport and storage of SSP-like material)} - 4.2 \text{ €}$$

9863
$$\text{(avoided energy production through substitution)} - 0.04 \text{ € (avoided K-fertiliser production through substitution)} = 3.0 \text{ €}$$

9864 The cost of processing the same amount of input material through the counterfactual pathway in NDA is:

9865
$$COST (C6 \text{ for NDA}) = 2.9 \text{ € (anaerobic digestion)} + 1.3 \text{ € (transport and storage)} - 3.7 \text{ € (avoided energy production through substitution)} - 0.7 \text{ € (avoided NPK}$$

9866
$$\text{fertiliser production through substitution)} = - 0.2 \text{ €}$$

9867 The cost of processing the same amount of input material through the counterfactual pathway in NSA is:

9868
$$COST (C6 \text{ for NSA}) = 2.9 \text{ € (anaerobic digestion)} + 0.7 \text{ € (transport and storage)} + 3.5 \text{ € (co-incineration)} + 0.06 \text{ € (transport and storage)} - 4.3 \text{ € (avoided}$$

9869
$$\text{energy production through substitution)} = 2.9 \text{ €}$$

9870

9871 Hence, the net cost for P6 is (COST(P6) = COST (I6) – COST (C6)):

9872
$$COST (P6 \text{ for NDA}) = 3.0 \text{ € (COST I6)} - (-0.2 \text{ € (COST C6 for NDA)}) = 3.2 \text{ €}$$

9873
$$COST (P6 \text{ for NSA}) = 3.0 \text{ € (COST I6)} - 2.9 \text{ € (COST C6 for NSA)} = 0.1 \text{ €}$$

9874 The cost relative to pathway 10 (SSP from mined rock phosphate) can be calculated by comparing COST(P6) to COST(P10).

9875 **Figure 22: Conceptualisation of the life cycle system applied in this study as exemplified by pathway P6, with landspreading ((a) on the lower left**
9876 **hand side), and co-incineration ((b) on the lower right hand side) as selected counterfactual scenarios for nutrient deficient areas (NDA) and nutrient**
9877 **surplus areas (NSA), respectively. Note that the processes and numbers given below are fictitious and incomplete, therefore the results do not**
9878 **correspond to the actual result of this pathway P6.**

9879

9880

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9881 8.6.2 Fate and credits for fertilising materials other than STRUBIAS

9882 It was assumed that farmers require plant available NPK and use organic C as part of good
9883 farming practices. When plant-available nutrients and organic C were returned to land in the
9884 scenarios, the **avoided cost for the purchase of mineral NPK fertilisers and peat as a**
9885 **substitute for the organic C was thus taken into consideration** as outlined above.

9886 In case fertilising substances were brought back to land, the fate of the included nutrients was
9887 modelled as follows for N, P, K, and organic C in **nutrient deficient areas (NDA)**:

9888 • For **inorganic N fractions**, the nitrogen use efficiency was assumed to be 80%, the mean
9889 value of the targeted ranges for good management practices as outlined by Brentup and
9890 Palliere (2010). It is thus assumed that plants take up 80% of the inorganic N supplied
9891 under good management practices. It is acknowledged that wide variation in N budgets
9892 across Europe take place, amongst others depending on agricultural intensity, soil types,
9893 and farm management practices (de Vries et al., 2011). For the loss of N by emission of
9894 N₂O via denitrification, we used the Intergovernmental Panel on Climate Change linear
9895 Tier 1 N₂O default emission factor of a 1% loss of applied N as N₂O-N (Good and Beatty,
9896 2011). Minimal default losses of 1% were also assumed for NH₃ emissions under good
9897 management and storage practices. The remainder 18% was then assumed to be equally
9898 distributed between denitrification (9%) and N leaching losses to groundwater (9%).
9899 For the **organic N fractions (manure, sewage sludge)**, it was assumed that the stable
9900 organic N fraction was not available to the crops in the long-term. The latter fraction was
9901 assumed to be 11% of the total organic N, in line with Bruun et al (2006). Hence, it was
9902 assumed that 89% of the organic fraction was available in the long-term to plants.
9903 Because of the long-term N release from the organic fraction, the nitrogen use efficiency
9904 of the plant-available organic N fraction was assumed 60% in line with the average values
9905 given for conditions that involve a risk for (over-winter) N leaching losses (Brentup and
9906 Pallière, 2010). The supplementary N losses relative to inorganic N fractions were fully
9907 attributed to N leaching losses, resulting in a value of 29% for leaching losses from
9908 organic manure N sources. Other losses and emissions from the plant-available N fraction
9909 were assumed to be equal to mineral N fertiliser: NH₃ losses (1%), N₂O losses (1%), N₂
9910 losses (8%), and N surface run-off (1%). Plant N uptake was then calculated as the sum of
9911 the inorganic N plus the plant-available organic N being taken up, as follows: $((N_{\text{inorganic}} \times$
9912 $0.8) + (N_{\text{organic}} \times 0.89 \times 0.6)) / (N_{\text{inorganic}} + N_{\text{organic}})$.

9913 **The nitrogen agronomic efficiency of STRUBIAS material resulting from pathways**
9914 **relative to synthetic mineral N-fertilisers** were assumed to be 100% for struvites, and
9915 10% for the pyrolysis derived from pig manure. Thermal oxidation materials & derivatives
9916 do not contain nitrogen as the N is lost during the manufacturing process.

9917 • For **mineral P fractions**, it was considered that crops take up 90% of the applied P (Syers
9918 et al., 2008). P losses to water were estimated at 8% of the P applied, equally distributed
9919 over losses to surface waters through run-off (4%) and groundwater through leaching
9920 (4%) (van Dijk et al., 2016). The remainder 2% was estimated to be stored in the soil. The
9921 mineral P fertiliser substitution efficiency of **manure and processed manure P fractions**
9922 was assumed to be the average for P-deficient (70%) and areas with adequate P-

9923 background soil concentrations for plant growth (100%), based on Eghball et al. (2002).
9924 Hence, plant P uptake from organic P fractions was estimated at 76.5% (0.85 x 90%).
9925 Losses to surface (4%) and ground (4%) water for organic P fractions are assumed similar
9926 for mineral P-fertilisers, and the fraction of P stored in soils was slightly increased
9927 relative to mineral P fertilisers (15.5%). The mineral P fertiliser substitution efficiency of
9928 anaerobically digested sewage sludge and meat and bone meal was assumed to be 46%
9929 and 40%, respectively (Oenema et al., 2012). The agronomic efficiency of STRUBIAS
9930 materials resulting from pathways relative to mined and synthetic P-fertilisers was
9931 assumed to be 100% for all pathways, with the exception of poultry litter ashes, AshDec
9932 fertiliser and pig manure biochar for which relative agronomic efficiencies of 93%, 90%
9933 and 85% were assumed, respectively (see section 6).

9934 • The mineral K fertiliser substitution efficiency of **organic K fractions** was assumed to be
9935 73%, based on Eghball et al. (2002). Potassium losses from the soil ecosystem were not
9936 further analysed as K has no influence on any of the considered impact categories.

9937
9938 It was assumed that the fate of the applied nutrients could not only be constrained by the
9939 intrinsic properties of the fertilising material, but also by inappropriate fertilising
9940 management practices that lead to the supply of nutrients in excess to plant demand. Manure
9941 and organic fertilising materials are sometimes characterised by imbalanced stoichiometric
9942 ratios, especially N/P ratios. As a result, the application of high amounts of manure or
9943 processed manure can result in the inefficient uptake of certain nutrients that are applied in
9944 excess to plant needs. With N often being the limiting element for plants, the application of
9945 manure and processed manure at the maximal application rates of 170 kg ha⁻¹ yr⁻¹ as laid
9946 down in the EU Nitrates Directive, can lead to a P and K surplus in the soils that are then
9947 stored in the soil matrix or leach towards ground waters. This situation is not uncommon as
9948 39% of all P entering the EU as P-fertilisers and animal feed is accumulated in agricultural
9949 soils as a result of ineffective nutrient management practices (van Dijk et al., 2016).

9950 For NSA, it was assumed that manure is applied at an application rate in line with the
9951 maximum for manure nitrogen application of 170 kg N ha⁻¹ yr⁻¹ from the Nitrates Directive.
9952 The recommended P and K application rates for productive cropland ecosystems were
9953 estimated at 17.5 kg P ha⁻¹ yr⁻¹ and 76.8 kg K ha⁻¹ yr⁻¹, respectively, based on typical
9954 application rates and FAO fertiliser guidelines for major crops (Johnston and Steen, 1999;
9955 Roy et al., 2006). The recommended P application rates are at the higher end of the
9956 recommended P application rate for most EU Member States (0 - 22 kg P ha⁻¹ yr⁻¹ for most
9957 countries in West and North Europe; Tóth et al., 2014). **Any bioavailable P applied in
9958 excess of the recommended application rates was considered not to contribute to plant
9959 nutrition.**

9960
9961 Across all pathways, it was assumed that **STRUBIAS fertilisers and mineral fertilisers
9962 were applied according to best management practices**. This implies that no constraints
9963 apply for plant nutrient uptake due to possible fertiliser applications in excess of plant
9964 nutrient demands.

9965

9966 8.6.3 Other assumptions

9967 With respect to electricity production, the **standard electricity mix for the Netherlands**, as
9968 a representative country for P-recovery processes was used in the assessment. With respect to
9969 conventional nitrogen fertiliser, the average EU mix was assumed (27% AN, 33.3% CAN,
9970 15.3% urea-AN and 24.3% urea).

9971 In line with the IPCC guidelines, **zero carbon emissions from biogenic wastes** with a short
9972 turnover time were assumed. It was, however, assumed that the **stable C fraction of**
9973 **processed manures and pyrolysis materials contributes to the mitigation of greenhouse**
9974 **gas emissions**. Therefore, the fraction of C remaining in the soil after the applied life cycle
9975 time period of 100 years was accounted for as sequestered carbon for the impact category
9976 "global warming potential, GWP". This fraction was assumed to be 11% and 90% of the
9977 organic C applied, for processed manure (Bruun et al., 2012) and pyrolysis materials
9978 (Lehmann and Joseph, 2015), respectively.

9979

9980 **8.7 Data sources for life cycle inventories**

9981 A part of the primary data of the life cycle inventories for the different induced and
9982 counterfactual data were collected by a third party (RDC Environnement) on behalf of the
9983 JRC from STRUBIAS material producers and literature information (Wiechmann et al.,
9984 2013b; Janik et al., 2015a; Jossa and Remy, 2015; Egle et al., 2016; Eurostat, 2016; STOWA,
9985 2016a; Centre, 2017; De Graaff et al., 2017; ECN, 2017; Nattorp et al., 2017).

9986

9987 **Primary data from life cycle inventories as provided by the manufacturers was, in some**
9988 **cases, modified by JRC for standardisation purposes** (e.g. transport distances, liquid-solid
9989 separation efficiencies; energy and biomass recovery efficiency, etc.). Therefore, **the**
9990 **presented results can by no means be generalised and a significant modification for the**
9991 **results can be expected in case the actual implementation differs from the assumptions**
9992 **applied in this study**. The results presented here are thus not fully representative for specific
9993 recovery pathway or operators, and actual results may be dissimilar. It is important to recall
9994 that this section of the report relies on the use of hypothetical scenario modelling. As a matter
9995 of fact, it may be most informative to focus on the results provided for the different life cycle
9996 stages in the Tables as these results enable a better visualisation of the driving mechanisms of
9997 the net results for the different environmental impact categories and production costs.

9998

9999 **8.8 Phosphate rock depletion**

10000 STRUBIAS P-fertilisers are not derived from phosphate rock, but from secondary raw
10001 materials. Nonetheless, the counterfactual handling scenario of the input materials applied for
10002 STRUBIAS manufacturing scenarios may involve land application (e.g. manure, sewage
10003 sludge in NDA), and may thus serve as a P-source for a farmer. Therefore, the net effect on
10004 phosphate rock depletion is dependent on the efficacy of the P-return in the counterfactual
10005 scenario; the more efficient the P return in the counterfactual scenario, the less interesting the
10006 STRUBIAS pathway becomes to address source risks.

10007

10008 The **net impact on phosphate rock depletion is highest for pathway P10** (Figure 23). For
10009 every kg of bio-available P produced, 7.2 kg of phosphate rock is extracted. The production
10010 of 1 kg of bio-available P in the STRUBIAS scenario results in net phosphate rock extraction
10011 values that range from 0 to 6.5 kg of phosphate rock (Figure 23).

10012 The phosphate rock depletion values are typically **higher in NDA** because the counterfactual
10013 use of the biogenic materials involves landspreading; in case the counterfactual scenario is
10014 avoided, the bio-available P contained in the biogenic material is assumed to be replaced by
10015 mined rock phosphate P-fertilisers. Because the plant P bio-availability is lower for sewage
10016 sludge and meat and bone meal than for manure, the greater savings can be obtained for the
10017 former than for the latter. In **NSA**, the landspreading of manure at high application rates
10018 results in the accumulation of P in the soil; the P applied exceeds the plant P demand. Co-
10019 incineration was assumed as fate of the sewage sludge and no bio-available P is thus applied
10020 on land in the counterfactual scenario. Hence, the production of 1 kg of bio-available P
10021 exclusively occurs from dissipated P sources and the net result is a zero phosphate rock
10022 extraction rate (Figure 23).

10023 Note that the **overall potential of the different STRUBIAS pathways to address source**
10024 **risks** is not only dependent on the net phosphate rock depletion per kg of bio-available P
10025 produced, but also the total amount of bio-available P that can produced from the available
10026 feedstock through each pathway (thus dependent on feedstock availability and P-recovery
10027 efficiency with the latter typically being higher for thermal oxidation materials & derivates
10028 and pyrolysis & gasification materials than for precipitated phosphate salts & derivates.)

10029

10030 **8.9 Environmental and human health impacts**

10031 The results for the induced and counterfactual scenarios for the different production options
10032 P1-P10 are presented in a disaggregated manner in Table 13 and Table 14 for nutrient
10033 deficient areas (NDA) and for nutrient surplus areas (NSA). The aggregated net results ($P = I$
10034 $- C$) are presented in Figure 23. Specific impact categories have been presented, but results
10035 and trends for other impact categories are in line with the presented results as follows: (i)
10036 global warming potential ~ photochemical ozone formation, particulate matter, fossil
10037 resource depletion; (ii) marine eutrophication – N ~ terrestrial acidification, freshwater
10038 eutrophication; and (iii) human toxicity - cancer ~ human toxicity – non-cancer, ecotoxicity.

10039 **Positive values indicate a burden** to the environment, while **negative values indicate a**
10040 **saving**. The sum of burdens and savings provide the overall net contribution; please notice
10041 that this sum may also be negative. This may be a result of credits from co-products.

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10044

Table 13: Results of the life cycle analyses presented in disaggregated form for the different life cycle stages for the impact categories global warming potential, marine eutrophication – nitrogen, and human toxicity - cancer for the pathways Ix and Cx in nutrient deficient areas (NDAs) as graphically presented in Figure 21 (see section 8.6.1 for explanations on the abbreviations).

category	stage	P1		P2		P3		P4		P5		P6		P7		P8		P9		P10
		I1	C1	I2	C2	I3	C3	I4	C4	I5	C5	I6	C6	I7	C7	I8	C8	I9	C9	I10
global warming potential (kg CO ₂ -eq kg ⁻¹ P bioavailable)	IM _{man}	37.1	51.6	104.7	97.8	24.7	30.3	1.5	0.0	17.6	15.8	15.9	13.9	20.8	14.1	2.2	0.0	17.6	16.7	3.5
	IM _{TS}	72.4	75.9	8.0	8.4	1.2	2.6	0.8	16.4	0.5	1.4	0.4	1.2	0.4	1.2	0.3	0.4	26.4	26.1	0.0
	AIM _{CO}	-195	-523	-134	-135	-41.3	-41.7	-7.8	-35.4	-3.7	-21.8	-3.3	-19.2	-4.1	-19.4	-1.6	-25.3	-79.5	-114.6	0.0
	IM _{UOL-OFM}	46.8	163.0	49.0	50.8	13.9	15.7	0.0	-0.4	0.0	8.2	0.0	7.2	0.0	7.3	0.0	7.4	25.4	34.9	0.0
	IM _{UOL-PF}	0.0	0.0	1.4	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-30.2	0.0	0.0
	Total		-38.3	-232	29.1	22.2	-0.4	6.9	-5.6	-19.3	14.3	3.6	13.0	3.2	17.2	3.2	0.9	-17.5	-40.3	-36.8
marine eutrophication - nitrogen (kg N-eq kg ⁻¹ P bioavailable)	IM _{man}	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	IM _{TS}	0.01	0.04	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
	AIM _{CO}	-1.73	-4.84	-1.29	-1.29	-0.40	-0.40	0.00	-0.32	0.00	-0.21	0.00	-0.18	0.00	-0.19	0.00	-0.28	-0.73	-0.92	0.00
	IM _{UOL-OFM}	4.32	12.22	3.26	3.38	1.01	1.05	0.00	0.63	0.00	0.55	0.00	0.48	0.00	0.49	0.00	0.74	0.68	1.02	0.00
	IM _{UOL-PF}	0.00	0.00	0.05	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total		2.61	7.42	2.03	2.10	0.65	0.65	0.00	0.33	0.00	0.34	0.00	0.30	0.00	0.30	0.00	0.46	-0.04	0.12
human toxicity - cancer (kg CTUh kg ⁻¹ P bioavailable x 1E-07)	IM _{man}	1.21	1.59	8.29	8.12	1.67	2.51	1.03	0.00	2.04	1.31	1.89	1.16	1.90	1.17	0.49	0.00	1.86	0.38	0.36
	IM _{TS}	2.18	2.17	0.08	0.08	0.02	0.02	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.75	0.74	0.00
	AIM _{CO}	-12.69	-19.43	-8.26	-9.08	-2.00	-2.81	-0.95	-2.17	-0.43	-1.47	-0.38	-1.29	0.00	-1.31	-0.23	-1.08	-2.60	-5.13	0.00
	IM _{UOL-OFM}	5.33	5.35	50.77	51.08	15.79	15.80	0.00	4.08	0.00	8.25	0.00	7.28	0.00	7.35	0.00	0.24	1.62	1.96	0.00
	IM _{UOL-PF}	0.02	0.00	0.31	0.00	0.00	0.00	4.08	0.00	3.73	0.00	3.66	0.00	0.13	0.00	0.21	0.00	0.35	0.00	1.28
	Total		-3.95	-10.31	51.19	50.20	15.49	15.52	4.18	1.93	5.36	8.10	5.19	7.16	2.39	7.22	0.48	-0.83	1.97	-2.04

10045



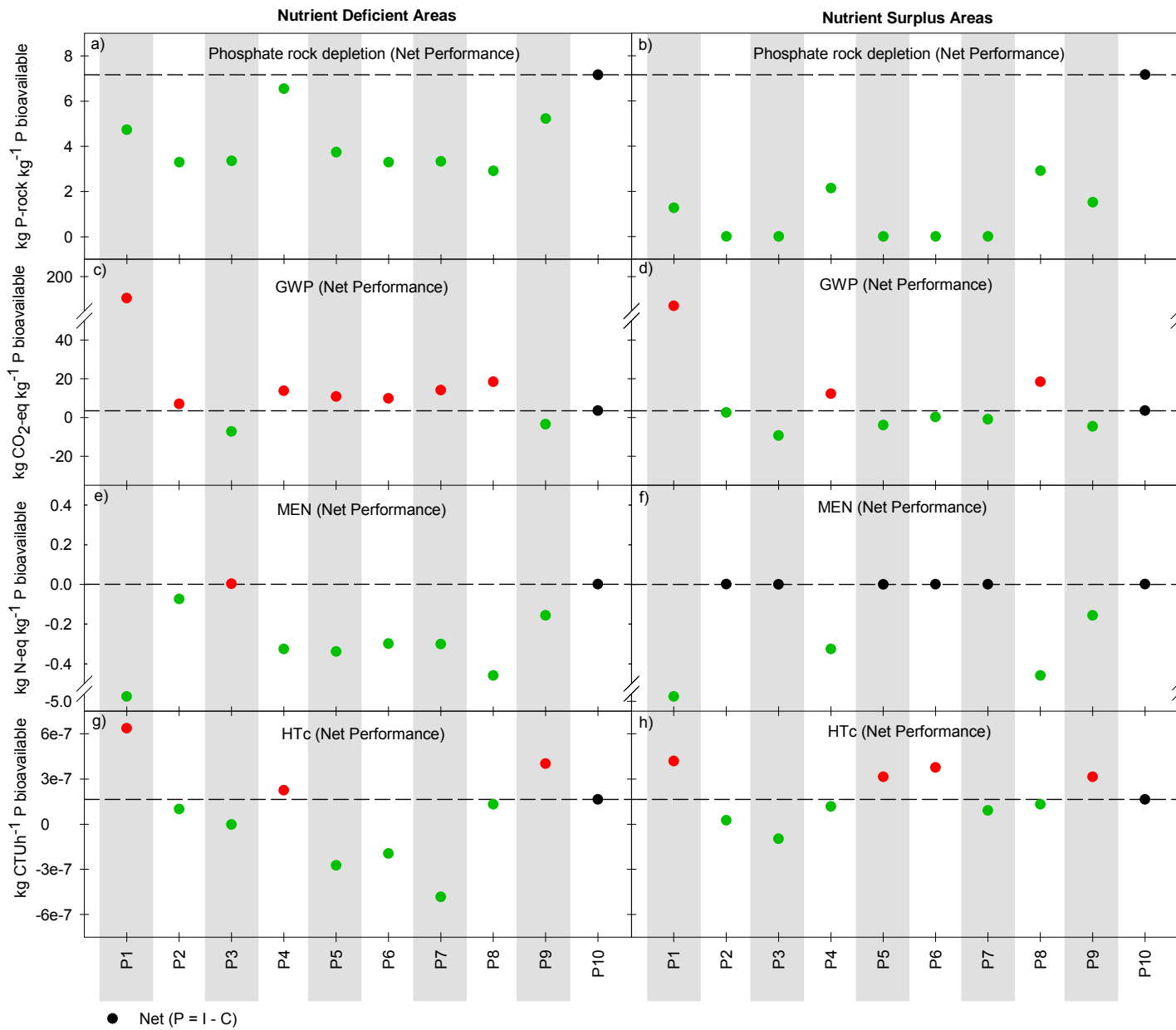


Figure 23: Aggregated net results for the impact categories phosphate rock depletion, global warming potential (GWP), marine eutrophication – nitrogen (MEN), and human toxicity cancer (HTc) for the production options Px in nutrient deficient areas (graphics on the left) and nutrient surplus areas (graphics on the right) as graphically presented in Figure 21.

Green dots indicate benefits from the STRUBIAS production option compared to the production of the mined rock phosphate and processed P-fertiliser SSP (P10).

Red dots indicate burdens from the STRUBIAS production option compared to the production of the mined rock phosphate and processed P-fertiliser SSP (P10).

Black dots indicate no net effects from the STRUBIAS production option compared to the production of the mined rock phosphate and processed P-fertiliser SSP (P10).

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Table 14: Results of the life cycle analyses presented in disaggregated form for the different life cycle stages for the impact categories global warming potential, marine eutrophication – nitrogen, and human toxicity - cancer for the pathways Ix and Cx in nutrient surplus areas (NSAs) as graphically presented in Figure 21 (see section 8.6.1 for explanations on the abbreviations).

category	stage	P1		P2		P3		P4		P5		P6		P7		P8		P9		P10
		I1	C1	I2	C2	I3	C3	I4	C4	I5	C5	I6	C6	I7	C7	I8	C8	I9	C9	I10
global warming potential (kg CO ₂ -eq kg ⁻¹ P bioavailable)	IM _{man}	37.1	51.6	119.4	113.0	29.1	34.9	1.5	0.0	17.6	18.2	15.9	16.1	16.0	16.3	2.2	0.0	17.6	16.7	3.5
	IM _{Ts}	72.4	75.9	2.7	2.7	0.8	0.8	0.8	16.4	0.5	0.4	0.4	0.4	0.4	0.4	0.3	0.4	26.4	26.1	0.0
	AIM _{co}	-187.6	-513.3	-27.9	-22.7	-11.6	-7.0	-7.8	-33.8	-7.1	-3.7	-2.9	-3.2	-4.1	-3.3	-1.6	-25.3	-79.5	-113.4	0.0
	IM _{UOL-OFM}	46.8	163.0	0.0	0.0	0.0	0.0	0.0	-0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.4	25.4	34.9	0.0
	IM _{UOL-PF}	0.0	0.0	1.4	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-30.2	0.0	0.0
	Total	-31.3	-222.8	95.6	93.0	19.4	28.8	-5.6	-17.8	11.0	15.0	13.4	13.3	12.4	13.4	0.9	-17.5	-40.3	-35.7	3.5
marine eutrophication - nitrogen (kg N-eq kg ⁻¹ P bioavailable)	IM _{man}	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	IM _{Ts}	0.01	0.04	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
	AIM _{co}	-1.72	-4.84	-0.05	-0.01	-0.04	0.00	0.00	-0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.28	-0.73	-0.92	0.00
	IM _{UOL-OFM}	4.32	12.22	0.00	0.00	0.00	0.00	0.00	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.74	0.68	1.02	0.00
	IM _{UOL-PF}	0.00	0.00	0.05	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	2.61	7.42	0.01	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.46	-0.04	0.12	0.00	
human toxicity - cancer (kg CTUh kg ⁻¹ P bioavailable x 1E-07)	IM _{man}	1.21	1.59	12.87	12.86	3.04	3.98	1.03	0.00	2.04	2.08	1.89	1.83	1.92	1.85	0.49	0.00	1.86	0.38	0.36
	IM _{Ts}	2.18	2.17	0.09	0.09	0.03	0.03	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.75	0.74	0.00
	AIM _{co}	-8.30	-12.86	-2.65	-2.58	-0.85	-0.80	-0.95	-1.09	-0.97	-0.42	-0.33	-0.37	0.00	-0.37	-0.23	-1.08	-2.60	-4.26	0.00
	IM _{UOL-OFM}	5.33	5.35	0.00	0.00	0.00	0.00	0.00	4.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24	1.62	1.96	0.00
	IM _{UOL-PF}	0.02	0.00	0.31	0.00	0.00	0.00	4.08	0.00	3.73	0.00	3.66	0.00	0.13	0.00	0.21	0.00	0.35	0.00	1.28
	Total	0.45	-3.74	10.62	10.36	2.22	3.20	4.18	3.01	4.82	1.67	5.24	1.48	2.40	1.49	0.48	-0.83	1.97	-1.17	1.64

10084



10085 8.9.1 Global warming potential

10086 The impact on the global warming potential is largely **dependent on the regional situation**
10087 **where the P-recovery and nutrient return to agricultural land takes place.** For *NDA*,
10088 producing and using STRUBIAS materials is generally associated to a net positive
10089 contribution to the global warming potential, except for P3 (WASstrip followed by struvite
10090 precipitation) and P9 (pyrolysis of pig manure). The contribution to the global warming
10091 potential is often larger than for mined phosphate rock and processed P fertilisers. The major
10092 reason for this observation is that STRUBIAS production processes, with the exception of
10093 struvite precipitation at biological waste water treatment plants, involve a reduction or
10094 removal of the bio-available nitrogen (and to a lesser extent organic C) that is returned to
10095 agricultural land. This is not the case in the counterfactual scenarios. Therefore, the **avoided**
10096 **mineral fertiliser production (through the Haber-Bosch process) and peat extraction**
10097 **(necessary to account for C losses)** is generally much higher (i.e. incurring relatively more
10098 savings on global warming potential) in the counterfactual scenarios. These observations
10099 indicate that reducing and removing bio-available N from the input materials that are returned
10100 to land in the STRUBIAS production scenarios has a significant impact on the global
10101 warming potential. With the exception of P3, STRUBIAS manufacturing processes in *NDA*
10102 also generally contribute to increasing the global warming potential, often due to energy
10103 requirements for the additional operations at the manufacturing site (e.g. incineration). For
10104 *NSA*, the counterfactual scenarios for the different input materials involve the co-incineration
10105 of sewage sludges. For this regional situation, nitrogen and organic C are thus not returned to
10106 land in either the induced or the counterfactual scenarios for thermal oxidation materials &
10107 derivatives. Minor amounts of nitrogen are even returned to agricultural land in the induced
10108 scenario for precipitated phosphate salts & derivatives, but not in the counterfactual scenario of
10109 incineration. Hence, **benefits from N** returned to field are overall small in induced and
10110 counterfactual scenarios for *NSA*, and do not influence the net results for the production
10111 options. For this reason, the net impact on the global warming potential is generally lower
10112 compared to *NDA*; many scenarios show an overall impact close to zero. At some occasions,
10113 a lower contribution to global warming relative to mined phosphate rock and processed P
10114 fertilisers was observed. This shows the crucial importance of considering local context and
10115 nutrient management to capture the environmental consequences associated with these
10116 technological pathways.

10117 For most options, **the use on land phase of the STRUBIAS material does not largely**
10118 **affect the overall impacts for global warming due to their low N content, and thus N₂O**
10119 **emissions.** In case the feedstock is not thermally processed in full, **the use on land of the**
10120 **rest fraction** (e.g. rest sludge after struvite separation), however, contributes significantly to
10121 the global warming potential, mostly due to **N₂O emissions.** For P9, the **pyrolysis of pig**
10122 **manure**, the return of the STRUBIAS material to land is associated to a negative
10123 contribution for global warming due to the assumed stability of the C contained in the
10124 material incurring long-term C sequestration. According to the scenario modelling applied
10125 here, this effect is, however, partly neutralised because of avoided energy and nitrogen
10126 fertiliser production in the counterfactual scenario. Nonetheless, under the assumption that

10127 90% of the C contained in the pyrolysis material remains in the soil after 100 years, still a net
10128 saving is observed for global warming potential for P9.

10129 Relative to the **counterfactual scenarios of the direct landspreading of unprocessed and**
10130 **digested biogenic materials, STRUBIAS production option provide generally a net**
10131 **contribution** to global warming, expect for the Wasstrip option (due to some avoided
10132 nitrogen fertiliser production) and the pig manure pyrolysis option (due to the increased
10133 stability of the C contained in the material after soil application). This is indicated by the
10134 negative net values for pathways where (co-)incineration is not applied in the counterfactual
10135 scenario.

10136

10137 8.9.2 Nitrogen eutrophication

10138 In general lines, **STRUBIAS production pathways show a lower impact on nitrogen**
10139 **eutrophication than SSP, the mined phosphate rock and processed P fertiliser assessed**
10140 **in this study**. Whereas nitrogen does not play any role in the production or use of SSP and
10141 therefore does not contribute to N eutrophication either, the better performance of
10142 STRUBIAS materials is attributed to partially avoiding the N eutrophication from the
10143 counterfactual scenarios. **Reduced N leaching** from the use on land phase of the STRUBIAS
10144 materials and other fertilising materials relative the counterfactual scenario was thus the main
10145 reason for the reduced eutrophication footprint of the STRUBIAS options. This mechanism
10146 was most expressed for option P1, where significant eutrophication benefits were obtained
10147 due to reduced N leaching from the processed manures in the induced scenario (low in N
10148 thanks to the aerobic treatment) relative to the counterfactual scenario (high in N; no aerobic
10149 treatment). **The impacts are dependent on the regional situation for sewage sludge, but**
10150 **not when manure and meat-and-bone meal were used as feedstock**. For manure and meat-
10151 and-bone meal, land application is assumed in the counterfactual scenarios for both NDA and
10152 NSA. Therefore, the achieved benefits for eutrophication remain equal for STRUBIAS
10153 production options that rely on the use of these input materials in NDA and NSA. In the
10154 counterfactual scenarios for the management of sewage sludge, however, eutrophication
10155 occurs when the sewage sludge is directly applied on land in NDA, but not in NSA where co-
10156 incineration is assumed as the counterfactual scenario. Therefore, no net effects were
10157 observed for N eutrophication. **The relative contributions of the manufacturing process**
10158 **and the transport and storage to the overall impacts for N eutrophication were minor**.

10159 Relative to the **counterfactual scenarios of the direct landspreading of unprocessed and**
10160 **digested biogenic materials, STRUBIAS production options provide generally net**
10161 **savings** for eutrophication in almost all cases (indicated by the negative net values for
10162 pathways where (co-)incineration is not applied in the counterfactual scenario).

10163

10164 8.9.3 Human health

10165 The impact on human health is largely **dependent on the STRUBIAS production option**
10166 **applied and the regional situation where the P-recovery and nutrient return to**
10167 **agricultural land takes place**. Relative to the production and use of mined phosphate rock

10168 and processed P fertiliser, the impacts of STRUBIAS materials is scattered, with better
10169 human health impacts for some options and worse human health impacts for others. Even, the
10170 comparative safety assessment relative to mined phosphate rock and processed P fertilisers is
10171 dependent on the regional situation; for P6, for instance, improvements for human health are
10172 observed in NDA, but mined phosphate rock and processed P fertilisers perform better for
10173 human health protection in NSA.

10174 For **precipitated phosphate salts**, no net impacts were observed for the use on land phase
10175 under NDA and for the salts derived from manure (P1) in NSA. This implies that for these
10176 scenarios the bio-available P that is used on land has a significantly lower impact than mined
10177 phosphate rock and processed P fertilisers. Yet, one should bear in mind that the precipitation
10178 process is a separation process that produces a P-fertiliser low in contaminants, but that the
10179 contaminants end up in the rest fraction. When the rest fraction is incinerated (i.e. NSA with
10180 sewage sludge as input material), a negligible impact from use on land phase for the options
10181 P2 and P3 is observed, with an overall lower net contribution than for P10 (SSP production
10182 and use on land) due to the decreased metal (especially Cd) concentrations in the struvites.
10183 This leaves the avoided fertiliser production as the most contributing life cycle stage is for
10184 precipitated phosphate salts. The substitution effect of NK fertilisers is typically higher in the
10185 counterfactual scenario where landspreading of other fertilising materials generates more
10186 savings in this respect. However, the net difference I-C is always smaller than the total
10187 human health impact of SSP in production option 10. For P1, the impact on human health is
10188 higher for the induced than for the counterfactual scenario, resulting in a high positive
10189 contribution of the option to human health impacts. The main reason is related to the avoided
10190 emissions from mineral N fertiliser application in the counterfactual N scenario.

10191 For thermochemical conversion processes resulting in the formation of **thermal oxidation**
10192 **materials & derivates and pyrolysis & gasification materials** (P4 – P9), the results are
10193 dependent on the levels of contaminants in the STRUBIAS materials. Some impacts are also
10194 associated to the manufacturing stage, with effects being more expressed for the production
10195 options when no thermochemical conversion takes place in the counterfactual scenario.
10196 Specific production options that involve a partial (P5) or almost complete (P7) removal of the
10197 metals present in the input material, followed by their disposal in landfills (i.e. final sink)
10198 expectedly perform better than others (P4, P6, P8, and P9). For sewage sludges as input
10199 materials, the best environmental benefits are achieved for NDA as the ratio of metals to bio-
10200 available P is always lower in the induced than in the counterfactual scenario. For NSA, the
10201 human health performance depends even more on the metal content in the STRUBIAS
10202 materials. In general, the relative concentrations of metals in the STRUBIAS materials and
10203 the mined phosphate rock and processed P fertilisers are mirrored in the overall impacts for
10204 human health. Production options that involve a removal of the metals present in the input
10205 material to levels below the metal contents in mined phosphate rock and processed P
10206 fertilisers perform better for human health, and vice versa. Benefits for human health are at
10207 all times achieved when the STRUBIAS manufacturing production option involves a metal
10208 removal (P5 and especially P7), whereas impacts for STRUBIAS materials that rely on the
10209 mixing of sewage sludges ashes with acids to improve their P-bio-availability (P6) are
10210 situation-specific, i.e. dependent on the counterfactual treatment.

10211
10212 Relative to the counterfactual scenarios of **the direct landspreading of unprocessed and**
10213 **digested biogenic materials**, STRUBIAS production options can also increase **the**
10214 **protection of human health by effectively removing biological pathogens,**
10215 **pharmaceutical and personal care products, and other persistent and emerging organic**
10216 **pollutants.**

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10217 **8.10 Production cost**

10218 The production costs for the induced and counterfactual pathways are presented in disaggregated form in Table 15 and Table 16 for nutrient
 10219 deficient areas and nutrient surplus areas, respectively.

10220 **Table 15: Results of the life cycle cost analyses presented in disaggregated form for the different life cycle stages for the pathways Ix and Cx in**
 10221 **nutrient deficient areas (NDAs) as graphically presented in Figure 21 (see section 8.6.1 for explanations on the abbreviations).**

category	stage	P1		P2		P3		P4		P5		P6		P7		P8		P9		P10
		I1	C1	I2	C2	I3	C3	I4	C4	I5	C5	I6	C6	I7	C7	I8	C8	I9	C9	I10
production cost (EURO kg ⁻¹ P bioavailable)	CAPEX _{man}	179.7	6.6	24.0	20.5	5.2	6.3	5.5	0.0	8.8	3.3	7.2	2.9	7.2	2.9	3.7	0.0	25.4	4.6	0.1
	OPEX _{man}	39.5	42.9	14.1	10.7	6.4	3.3	2.4	0.0	4.1	1.7	3.3	1.5	4.4	1.5	2.5	0.0	28.4	10.4	1.0
	COST _{TS}	152.3	165.8	6.9	7.0	2.2	2.2	2.0	1.8	1.1	1.1	1.0	1.0	1.0	1.0	0.6	0.9	60.1	59.8	0.1
	savings _{co}	-13.4	-45.9	-28.7	-29.3	-8.0	-9.1	-7.9	-3.3	-4.0	-4.7	-3.5	-4.2	-3.8	-4.2	-1.4	-1.8	-5.4	-16.1	0.0
Total		358.0	169.4	16.2	8.9	5.7	2.8	2.0	-1.5	10.0	1.4	7.9	1.3	8.9	1.3	5.5	-0.9	108.5	58.6	1.2

10222

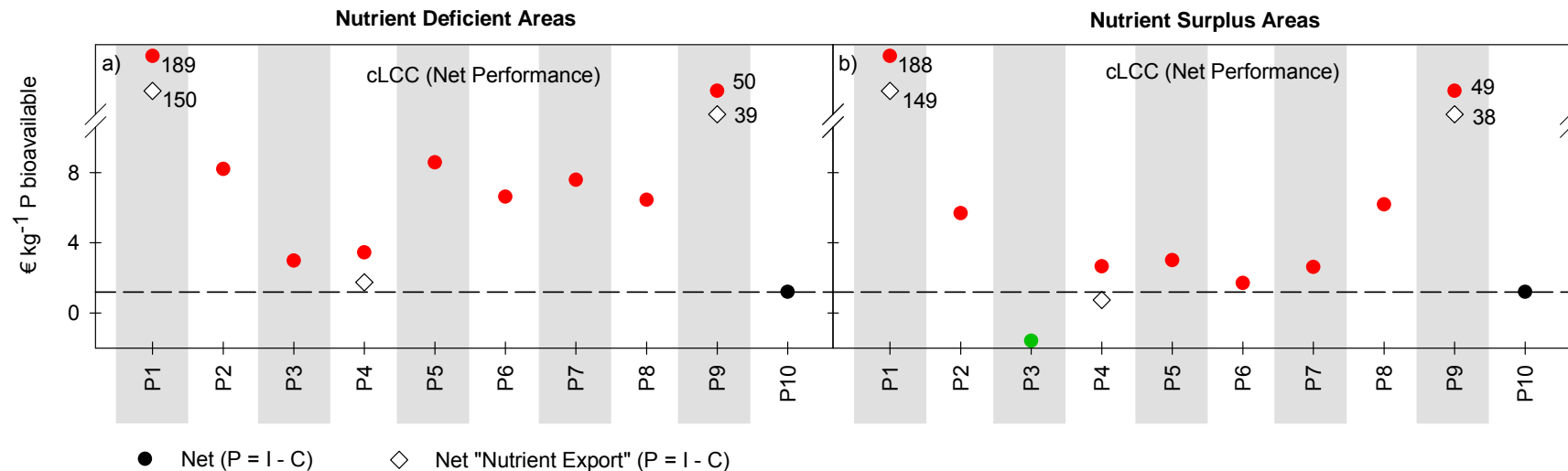
10223 **Table 16: Results of the life cycle cost analyses presented in disaggregated form for the different life cycle stages for the pathways Ix and Cx in**
 10224 **nutrient surplus areas (NSAs) as graphically presented in Figure 21 (see section 8.6.1 for explanations on the abbreviations).**

category	stage	P1		P2		P3		P4		P5		P6		P7		P8		P9		P10
		I1	C1	I2	C2	I3	C3	I4	C4	I5	C5	I6	C6	I7	C7	I8	C8	I9	C9	I10
production cost (EURO kg ⁻¹ P bioavailable)	CAPEX _{man}	179.7	6.6	48.0	45.3	9.4	14.0	5.5	0.0	8.8	7.3	7.2	6.5	7.2	6.5	3.7	0.0	25.4	4.6	0.1
	OPEX _{man}	41.6	44.6	19.7	16.5	8.0	5.1	2.5	0.0	4.1	2.7	3.3	2.4	4.4	2.4	2.3	0.0	28.4	10.4	1.0
	COST _{TS}	152.3	165.8	6.2	6.4	2.0	2.0	2.0	2.2	1.1	1.0	1.0	0.9	1.0	0.9	0.6	1.0	60.1	59.8	0.1
	savings _{co}	-12.5	-41.2	-24.8	-24.6	-7.6	-7.6	-7.9	-2.7	-4.0	-4.0	-3.5	-3.5	-3.8	-3.5	-1.4	-1.8	-5.4	-15.4	0.0
Total		361.0	175.7	49.2	43.5	11.9	13.5	2.2	-0.5	10.0	7.0	7.9	6.2	8.9	6.3	5.3	-0.8	108.5	59.3	1.2

10225

10226 The aggregated net results (I-C) for production options P1-P10 are presented in Figure 24.

10227



10228

10229 **Figure 24: Aggregated net results for the production cost in nutrient deficient areas** (graphics on the left) and **nutrient surplus areas** (graphics on the right) as graphically presented in Figure 21 (default scenarios with low transport distances of 25 km, purple dots). The open diamonds represent case scenarios where manure is exported from the country of production. Here, transport distances of 500 km are assumed between the site of production of the raw input materials and the sites where the processed materials (including both STRUBIAS materials and other fertilising materials) are applied on land.

10230 **Green dots** indicate savings from the STRUBIAS production option compared to the production of the mined rock phosphate and processed P-fertiliser SSP (P10).

10231 **Red dots** indicate additional costs from the STRUBIAS production option compared to the production of the mined rock phosphate and processed P-fertiliser SSP (P10).

10237

10238 Overall, the results indicate that **the production of STRUBIAS materials through one of**
10239 **the production options is more costly than the production of SSP derived from mined**
10240 **phosphate rock**, except for P3 in NSA.

10241 For precipitated phosphate salts, **the P3 result in net cost savings in NSA, even if the**
10242 **return of bio-available P to land is not considered** (net results < 0). This is because
10243 reduced sludge volumes will have to be co-incinerated. The net effect on CAPEX is in favor
10244 of the induced scenario because the increase in capital costs due to the installation of
10245 additional units (e.g. struvite reactor, WASstrip unit) are lower than the savings gained in
10246 reduced capital investments for other units (incineration, anaerobic digestion, dewatering).
10247 The OPEX is, however, somewhat increased for the waste water treatment operators due to
10248 the additional labour required to operate the supplementary units. For scenario P2, the
10249 increased investment and operational costs are, however, not offset as the impact on sludge
10250 volumes and polymer needs is relatively small based on our data. For NDA, the production
10251 cost for these options P2 and P3 is higher because the additional investment and operational
10252 cost required in the induced scenario is not compensated by any economic returns from the
10253 low-cost material handling in the counterfactual scenario (i.e. landspreading of digested
10254 sludge). Note, however, that in P2 and P3, the cost savings due to reduced maintenance (e.g.
10255 pipe clogging) at the waste water treatment plant have not been taken into consideration in
10256 this assessment. For P1, the high production cost is mostly caused by the high capital cost of
10257 the aerobic reactor and struvite precipitation costs that are very high relative to the volumes
10258 of materials that are currently being processed.

10259 For **thermal oxidation materials & derivatives**, the driving mechanism for the product costs
10260 is the implementation of additional processing steps (incineration, acidulation). For P4,
10261 CAPEX and OPEX from the incineration process mainly determine the cost of the production
10262 option as these manufacturing stages are not set in place in the counterfactual scenario of
10263 landspreading of the dried poultry litter. The supplementary costs are partly off-set by the
10264 increased savings from the energy recovery in this process, but still the production cost for P4
10265 is higher than for mined phosphate rock and processed P fertilisers. The supplementary
10266 incineration plus acidulation steps in the induced scenarios relative to the counterfactual
10267 scenarios (landspreading of digested sludge) also imply significant additional costs for
10268 options P5, P6 and P7 in NDAs. The production cost for options P5, P6 and P7 are reduced in
10269 NSA as here the counterfactual scenarios involve co-incineration; supplementary costs are
10270 due to shift from co-incineration to mono-incineration and the supplementary re-burning (P5)
10271 and acidulation process (P6, P7) for the induced scenario compared to the counterfactual
10272 scenario. In any case, these supplementary costs are higher than the production cost for P10
10273 (SSP; 1.2 EURO kg⁻¹ bio-available P; mostly originating from OPEX including the source
10274 materials). The differences between options P5, P6 and P7 are mainly due to the price of
10275 chemicals used in the market (e.g. sodium sulphate, lime, sulphuric acid, hydrochloric acid).
10276 Note that for this assessment we have assumed the use of primary raw materials, whereas the
10277 use of industrial by-products instead of 'primary' chemicals is a common practice in the
10278 fertilising sector. For P8 (meat and bone meal mono-incineration, followed by acidulation),
10279 significant CAPEX and OPEX are implied. Moreover, savings from the co-products (avoided

10280 energy and fertiliser production) for the induced scenario relative to the counterfactual
10281 scenario are small. The cost of producing N-fertilisers that are avoided in the counterfactual
10282 scenario is only slightly lower than any revenues obtained from the energy recovery potential
10283 from the meat-and-bone meal.

10284
10285 The production cost for option P9 - the production of **pyrolysis materials** from pig manure –
10286 are high. The main reason is the supplementary investment to build and operate the pyrolysis
10287 facility. In the recently developing sector, the CAPEX and OPEX are very high relative to the
10288 amount of material processed. It remains unknown to what extent these costs can be reduced
10289 when the market develops, and potentially the unit cost declines as production volume
10290 increases (scale effects). Also the loss of bioavailable N from the manure and the absence of
10291 energy recovery as a marketable product during the pyrolysis process sets this option at the
10292 disadvantage compared to the counterfactual scenario of anaerobic digestion.

10293
10294 In some cases, **manure** cannot be applied on land close to the site of production, and needs to
10295 be transported over longer distances and **exported**. This is a situation that is, for instance,
10296 illustrative in the Netherlands due to P-application quota for farmers. In this case, transport
10297 distances increase. For the scenario modelling, it was assumed that all solid fractions that will
10298 be used on land will be exported, but that the liquid manure fraction is applied locally. The
10299 greatest total reduction in mass for export is obtained for scenario P4 as all of the manure is
10300 transferred into ashes, containing only a minor amount of the weight of the poultry litter. As a
10301 result, the total production cost of the option P4 is significantly reduced because the transport
10302 costs increase in the counterfactual scenario, but only negligible increases in transport costs
10303 were observed for the induced scenario. The proportional costs reductions were much smaller
10304 for P1 and P9 as (i) the total cost of these production options was much higher, and (ii) the
10305 exported masses in the counterfactual scenarios are only a minor share of the total material
10306 that is transported (i.e. only solid fraction; liquid fraction applied locally). Therefore, the
10307 benefits obtained for these scenarios have only a minor impact on the total cost (P1 and
10308 P9).

10309

10310 **8.11 Life cycle and life cycle cost conclusions**

10311 The analysis confirms that the development of STRUBIAS production pathways reduces the
10312 dependence on the finite primary raw materials, but that the net impacts are highly dependent
10313 on the current counterfactual use of the biogenic input material applied. Given that biogenic
10314 materials already contribute to a variable extent to the return of bio-available P in NDA, these
10315 regions provide the lowest opportunities to mitigate risks associated to phosphate rock
10316 depletion through STRUBIAS pathways. **Nutrient surplus areas (NSA) provide greater
10317 opportunities for the development of STRUBIAS pathways due to the increased savings
10318 on phosphate rock depletion.**

10319

10320 Phosphorus nutrient recovery is often claimed to provide co-benefits for the environment and
10321 human health, but insightful and all-encompassing studies that assess these effects are still
10322 limited. This analysis indicates that the potential of STRUBIAS materials to contribute to

10323 these co-benefits relative to mined phosphate rock and processed P-fertilisers is dependent on
10324 the production option applied and the regional situation. The main mechanisms that
10325 **contribute positively** to the environmental and human health impacts relate to increasing the
10326 bio-availability of the nutrients contained in the biogenic input materials and reducing the
10327 metal therein contained. There are also **risks of adverse and unintended negative effects**,
10328 however, in processes involving the removal of other valuable materials in the biogenic input
10329 materials (e.g. nitrogen, organic C), the lack of removal of contaminants, and related to
10330 additional manufacturing steps that are associated to high chemical or energetic demands.
10331 This indicates that recovery processes in a circular economy should aim at maintaining the
10332 highest value of materials and products by isolating the target materials for recovery from the
10333 other valuable substances and contaminants during the manufacturing process, if possible.

10334
10335 A review of the P-recovery initiatives in the European Region indicates that most of the
10336 countries identified as leading in this field are EU Member States, particularly those in
10337 western and northern Europe (see section 15 and 7.1). From an economic perspective, this
10338 makes sense as **the supplementary cost of P-recycling is lowest in regions characterised**
10339 **by nutrient surpluses**. Based on the momentary evaluation, STRUBIAS production costs are
10340 for most options more expensive compared to mined phosphate rock and processed P-
10341 fertilisers. Nonetheless, options for a transition towards more circular economy approaches
10342 may include a mix of complementary instruments and approaches, including regulatory
10343 measures, economic incentives, education and awareness raising, and targeted funding for
10344 innovation and research (WHO, 2018). Hence, the materialisation of STRUBIAS production
10345 options is not only cost-dependent, but also subject to other decisions that impact on the need
10346 to process eligible input materials for STRUBIAS materials in a different manner relative to
10347 the current business-as-usual requirements, and further market stimulations. For example,
10348 stricter targets on water quality that restrict inputs of unprocessed manure in some vulnerable
10349 areas, stricter legislation on metal contents in sludges to be used as fertilising materials,
10350 stricter requirements to hygienise manure prior to landspreading, etc. Economic incentives to
10351 stimulate, for instance, the compliance with green energy targets or to disincentive the
10352 inefficient use of biological materials (e.g. landfilling) may further stimulate the
10353 materialisation of STRUBIAS pathways. Finally, nutrient recovery through STRUBIAS
10354 production processes is recently emerging in Europe and it is likely that scale effects will
10355 further reduce production costs once the industry further develops.

10356
10357 From a STRUBIAS **input material perspective**, **sewage sludge** is a likely candidate to be
10358 used as an input material due the lower production costs. Several production options have
10359 been developed that could provide combined improvements for the mitigation of global
10360 warming and eutrophication, and human health protection (e.g. P2, P3, P7). For **manure** as
10361 an input material for STRUBIAS production processes, the issue is that the raw feedstocks
10362 and their digestates are already a good fertiliser, with N and P being to a large extent bio-
10363 available and contributing to plant nutrition as long as the material is applied in a sustainable
10364 manner. The processing into STRUBIAS materials does not necessarily increase the bio-
10365 availability of the nutrients contained in the material, and might even result in losses of bio-
10366 available N from the material. As a result, the environmental costs for manure processing into

10367 STRUBIAS materials relative to the counterfactual management pathways are high in
10368 nutrient deficient regions where manure can best be applied directly on land, if possible; it is
10369 the most direct return of nutrients and organic matter with best impacts on the global
10370 warming and human health impacts. Therefore, the markets for STRUBIAS materials that
10371 apply manure as a feedstock are most likely to develop in regions characterised by a highly
10372 dense livestock and/or regions where manure exports are binding in legislation (e.g. the
10373 Netherlands). Nonetheless, also the removal of specific contaminants in manure (e.g.
10374 biological pathogens, veterinary antibiotics) and/or the production of other primary products
10375 (e.g. renewable energy) through STRUBIAS production processes could be a driver for the
10376 market growth of STRUBIAS derived from manure. As a matter of fact, it is believed that
10377 this mechanism will be the dominant driver for STRUBIAS production options from manure
10378 (see section 7.3.4). Hence, **especially for manure, it is believed that STRUBIAS**
10379 **production pathways could form part of material cascades in a developing bio-economy**
10380 **sector in the EU.**

10381
10382 Overall, this analysis indicates that **the implementation of STRUBIAS pathways to**
10383 **transform biogenic materials into concentrated P-fertilisers can provide opportunities**
10384 **to maximise benefits on food security, food safety and environmental protection.** The
10385 extent of the impacts is, however, dependent on the regional situation and the STRUBIAS
10386 production pathway applied. The development of some pathways (P2, P3 and P7 in nutrient
10387 surplus areas) will simultaneously result in reducing the dependence on phosphate rock,
10388 reduced impacts on global warming, and increased environmental protection relative to the
10389 production and use of mined rock phosphate and processed P-fertilisers. The development of
10390 STRUBIAS pathways in nutrient deficient areas and the realisation of specific pathways (P1,
10391 P4, P5, P6, P8 and P9) in nutrient surplus areas is associated to **trade-offs**, with potential
10392 benefits occurring at the expense of burdens for global warming potential or human health.
10393 This implies that the implementation of STRUBIAS pathways is dependent on the needs and
10394 priorities of local stakeholders, and thus the nexus of costs and impacts upon human health,
10395 agronomic yields, water quality, energy balances, resource depletion, climate regulation and
10396 long-term food security. The valorisation and prioritisation of the corresponding services by
10397 stakeholders are largely context-specific, but STRUBIAS production processes can also here
10398 provide opportunities for addressing critical issues related to phosphate rock depletion, global
10399 warming, eutrophication, and potentially human health, or a combination of those.

10400

10401 **9 Economic aspects**

10402 **9.1 Sales prices of P-fertilisers**

10403 9.1.1 DAP Free-on-Board as a benchmark for P–fertiliser prices

10404 Fertilisers, in the simplest of terms, have a very specific purpose: increasing crop yields per
10405 hectare. They achieve this purpose by compensating for any nutrient deficiencies in the soil,
10406 which could be due to a variety of reasons, from the geological nature of specific cropland
10407 areas, to weather events that remove topsoil nutrients, or again by bumper harvests that result
10408 in significant uptake of nutrients by plants themselves.

10409
10410 **This simplified reasoning suggests that, in an ideal market with perfect information, the**
10411 **expenditure of the farmer on fertiliser application will be equal to the marginal yield**
10412 **gain expressed in monetary terms:**

10413
10414
$$Expenditure_{fert\ application}^i = Price_{crop}^i * Area_{crop}^i * (Yield_{fert,crop}^i - Yield_{nofert,crop}^i)$$

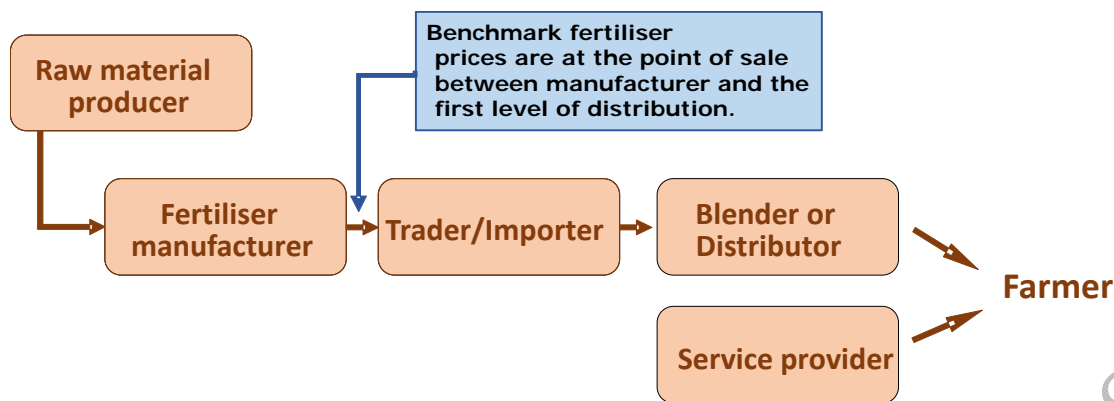
10415

10416 With $Expenditure_{fert\ application}$: the expenditure of the farmer on fertiliser application, as
10417 determined by the cost of fertiliser purchase, fuel, time and machinery, the $Price_{crop}$: the sales
10418 price for the crop as received by the farmer (Euro per tonne yield), $Area_{crop}$: the area of the
10419 cultivated crop (ha); $Yield_{fert,crop}$: the crop yield on fertilised areas (tonne yield per ha) and
10420 $Yield_{nofert,crop}$: the crop yield on unfertilised areas (tonne yield per ha).

10421 This formula is very simple in its structure; however it already suggests a significant
10422 complication, which is that the true value of fertilisers is specific to individual patches of
10423 land, their specific nutrient balances, the crops planted, and their reactivity to fertiliser
10424 application. Also, as fertilisers consist of various nutrients (primary nutrients being nitrogen
10425 (N), P and potassium (K)), the yield gain for each individual fertiliser will depend on the
10426 nutrient content of the actual fertiliser mix applied, and again the actual yield gain will
10427 depend not only on the nutrient considered, but on the balance for other nutrients and the
10428 form in which each is applied. Such a pricing model, albeit undoubtedly interesting, is far
10429 from the scope of this study and can only be replicated on a very site-specific scale with in-
10430 depth agronomic analysis.

10431 A more meaningful and robust approach looks a few steps back in the **value chain**, as
10432 described in Figure 25. It is important to notice that all the agents involved are sometimes the
10433 same company, for example the Norwegian company Yara would act as a raw material
10434 supplier to its own manufacturing sites, and would sell its own products via its own
10435 distribution system, including providing services to farmers like soil sampling, agronomic
10436 analysis, and in some cases even direct application to the field. Individual companies will
10437 have various degrees of integration along the value chain.

10438



10439

10440 **Figure 25: Schematic overview of fertiliser value chain**

10441

10442 When looking at the European market specifically, the most common structure sees a
 10443 separation between fertiliser manufacturers and traders/importers, which in turn are in many
 10444 cases distribution companies or blenders themselves. **For this reason, this work uses trade-**
 10445 **based prices:** this allows identifying prices more accurately, as these are observed at a
 10446 consistent point. Moreover, focussing on trade values allows for the identification of product-
 10447 specific prices: farmers would receive tailored formulations often bundled with various
 10448 additives (e.g. micronutrients) and services, which makes farm-gate prices less transparent. In
 10449 contrast to farmers, traders and importers tend to focus on more “commoditised” varieties,
 10450 such as diammonium phosphate (DAP), which is a sufficiently standardised product globally.
 10451 Prices are given for **Free on Board (FOB) agreements**. This implies that the seller is
 10452 obligated to deliver the goods to a destination for transfer to a carrier designated by the buyer.
 10453 The location designation in the FOB trade agreement is the point at which ownership is
 10454 transferred from the seller to the buyer; it is most often the port located in the country of
 10455 phosphate rock extraction.

10456

10457 Generally speaking, traded materials at this benchmark **would then be considered as a raw**
 10458 **material for further processing**, for example in the form of bulk blends (for blenders) or
 10459 physical NPK compounds (for fertiliser manufacturers). Straight application of commoditised
 10460 products is also practiced, but blends and compounds account for the majority of actual
 10461 application to the soil.

10462

10463 For the price setting of P-fertilisers, it is important to determine which product acts as a
 10464 “P₂O₅ benchmark” against which other products are priced. **On a global basis, DAP is**
 10465 **usually acknowledged as the main price-setting product, due to its larger traded**
 10466 **volumes, which makes prices relatively more transparent.** Also, DAP ranks amongst the
 10467 fertilisers with the highest values of “total nutrient content” (N+P₂O₅+K₂O) across
 10468 commoditised products, meaning that it minimises freight costs per tonne nutrient compared
 10469 to most alternatives. Generally speaking, markets in Western Europe tend to feature DAP as
 10470 the main price-setting product, while Eastern Europe tends to show a preference for MAP
 10471 instead. Fertecon's market assessment for different EU Member States (France, Germany,
 10472 Italy, Poland and Romania) indicated that expressed on a P-basis, **trade-based price**
 10473 **differences between DAP and TSP are relatively minor (~ <10%), whereas the sales**

10474 **price for SSP is slightly higher** (~ +20%). This difference can be explained by the increased
10475 logistic cost associated to the transport of SSP (low P-content; 16-22% P₂O₅ versus 46% P₂O₅
10476 in TSP/DAP). Trade volumes for SSP are relatively low due to the inefficient transport
10477 logistics; therefore, local producers face less competition, and therefore can push prices to the
10478 upper end of any reasonable range.

10479

10480 9.1.2 Historical and forecast overview on P-fertiliser prices

10481 **All prices are given for the conventional farming sector in the EU-28.** P-fertilisers sold to
10482 specific niche sectors (e.g. fertiliser use in horticultural application, home gardening and
10483 growing media) might be associated to higher sales prices, but such price settings are not
10484 covered in this document.

10485

10486 Through the **1990s and in to the early 2000s prices** for P-fertilisers, using DAP as a proxy,
10487 could be categorised as being low. Margins in the industry were generally poor – in most
10488 years in the range of 5-10% would be typical. This enabled producers to trade **moderately**
10489 **profitably**, but critically there was very **little incentive for existing producers to invest in**
10490 **new capacity**, and no incentive at all for new producers to enter the market. As a
10491 consequence, there was only limited investment in P-fertiliser capacity, mostly by state-
10492 owned enterprises, and closures in other parts of the world ensured that there was no major
10493 increase in overall productive capacity.

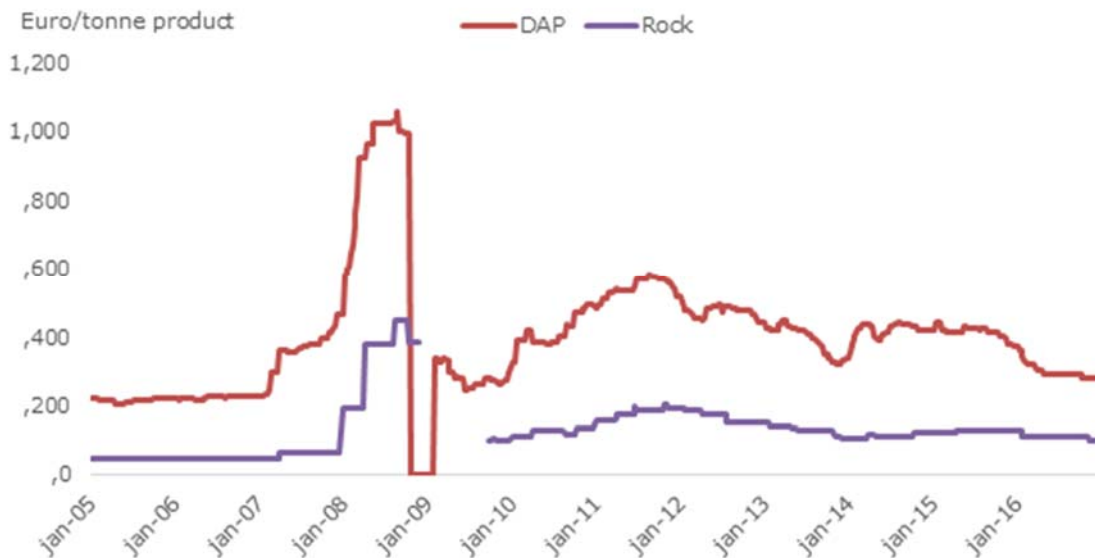
10494

10495 Following the Asian economic crash in 1997, economic growth around the world was strong
10496 over the 1997-2007 time period. Improving standards of living means that people generally
10497 consume more food (especially in developing nations) and can also afford more high-quality
10498 food especially proteins such as meat. Demand for cereals and other staple crops increases,
10499 both as food for humans and for animals which are then consumed by humans. **Increased**
10500 **demand for crops increased the use of fertiliser, which meant that fertiliser and P-**
10501 **fertiliser utilisation rates increased, and prices increased.**

10502

10503 The increase in margins during the period 2002 to 2007 began to encourage producers to
10504 consider projects and commence the building of P-fertiliser manufacturing construction sites.
10505 To build new phosphate fertiliser capacity will generally take between 36 and 48 months
10506 once construction begins, and clearly there will normally be a few years of planning required
10507 in advance, especially if it is for a greenfield development (as opposed to expanding an
10508 existing site). Therefore, **during the super-heating of the global economy in 2007 and**
10509 **2008, demand exceeded the industry's ability to supply, and consequently prices**
10510 **increased significantly.** In 2004 the average price of DAP on the basis of FOB Morocco was
10511 \$235/t (189 Euro/tonne), in 2007 it was \$425/t (310 Euro/tonne) and in 2009 it was \$1090/t
10512 (782 Euro/tonne). With the economic crash in late 2008 reality re-asserted itself, and in 2009
10513 price levels declined. Producers tried to hold on to gains for a period, but over 2009 and 2010
10514 it was very clear that if they were to do so it would be at the expense of production volumes.
10515 From 2011 onward there have also been the commissioning of projects which were planned
10516 in the mid-years (and later) of the 2000s. The other key (and related) structural change in the

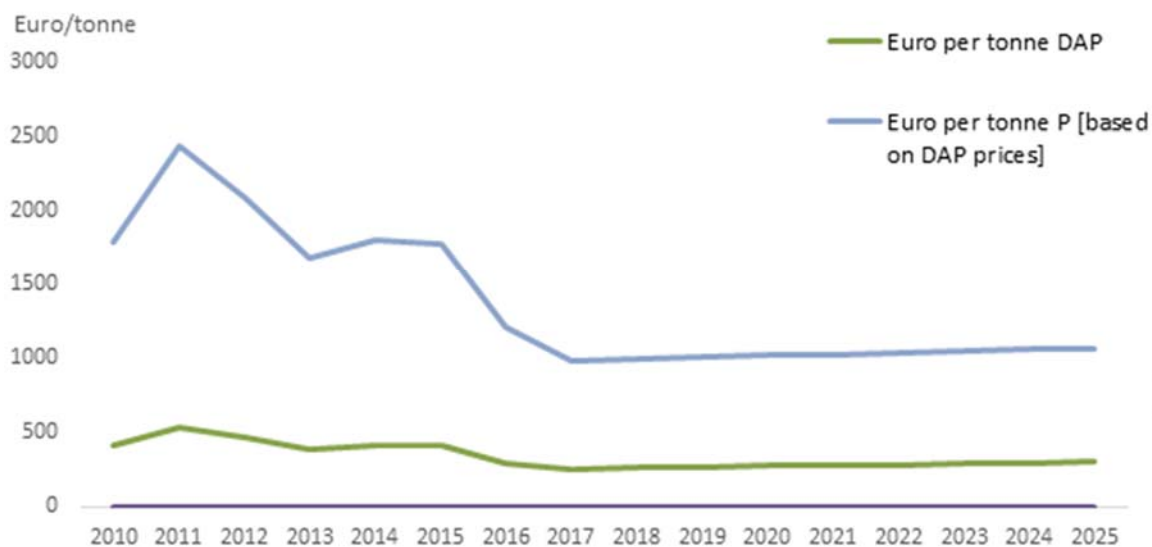
10517 market has been the build-up of production capability in China, which has meant that China
 10518 has gone from a net P-importer in the late 1990s to being a significant P-fertiliser exporter.
 10519 Although capacity has been decommissioned in less cost-efficient locations, P-fertiliser
 10520 production has returned to a position of net surplus, with a corresponding reduction in prices.
 10521 Figure 26 shows the price evolution for DAP and rock on the basis of FOB Morocco / North
 10522 Africa. The breaks in the prices were effectively when there was no market; producers
 10523 wanted prices buyers were unprepared to pay.
 10524



10525
 10526 **Figure 26: Price evolution for diammonium phosphate (DAP) and phosphate Rock (Euro/tonne**
 10527 **product; assuming an average exchange rate of 1.2 Euro/US dollar; prices given for Free on**
 10528 **Board agreements) (Source: Fertecon)**
 10529

10530 Looking forward, Fertecon is expecting the market to maintain the current (2017) level of
 10531 balance through to 2025, i.e. that growth in demand will be off-set by increased capacity to
 10532 supply, and therefore there will not be any significant improvement on utilisation rates in the
 10533 industry. This means that price levels will be maintained at levels which provide a margin for
 10534 the major producers, but will also progressively eliminate some of the marginal capacity.
 10535 Therefore, DAP prices are estimated to increase moderately from 2017 onwards with an
 10536 average price increase of 1-2% per year (green line, Figure 27).
 10537

10538 The price per tonne P in mined rock phosphate and processed P-fertilisers is evaluated based
 10539 on the DAP prices. For the calculations, the value of N present in DAP is subtracted from the
 10540 DAP price, after which the N-devaluated DAP is expressed on a P-basis. The N in DAP is
 10541 evaluated based on the ammonia price (381 US dollars per tonne ammonia-N, or 69 US
 10542 dollars for the 18% N in DAP). Also, a constant 1.2 Euro/US dollar exchange rate is used in
 10543 these calculations. **A price of 988 Euro per tonne P FOB is indicated for the year 2017.**



10544

10545 **Figure 27: Fertecon DAP Price Forecast to 2025 expressed per tonne of DAP and per tonne P**
 10546 **(FOB Morocco; exchange rate of 1.2 Euro/US dollar applied by JRC)**
 10547

10548 The 2025 FOB forecast is also within the range of prices experienced prior to the 2007-2009
 10549 super-cycle, when adjusted for inflation. This is a relevant comment: there are many bodies
 10550 that describe current price levels as low. This is factually accurate in comparison to recent
 10551 years, but not in the historical context. In comparison to the period 1990 to 2005, **the current**
 10552 **price level might be better described as ‘normal’.**

10553

10554 9.1.3 Price setting for STRUBIAS materials on the market

10555 Given the lack of legal outlets for many STRUBIAS materials in many EU Member States,
 10556 **these materials are at present not valorised within a stable reference framework.** At
 10557 present, the volumes of STRUBIAS materials on the internal fertiliser market are very low,
 10558 and mostly delivered to specific niches of the internal agricultural market. Depending on the
 10559 legal framework, market access is only granted to specific STRUBIAS materials, mostly
 10560 under national legislation. Therefore, it is impossible to provide a meaningful evolution of the
 10561 sales prices for a given fertilising product containing recovered materials in the EU observed
 10562 in order to determine the main factors affecting prices of STRUBIAS materials and their
 10563 relative importance. Moreover, the answers received in response to the JRC questionnaire
 10564 indicated that **in view of confidentiality, it is not appropriate to communicate sales prices**
 10565 **in publically available reports and do not provide added value to this report.**

10566

10567 Rather than giving an overview of the expected sales prices, this section provides a **general**
 10568 **benchmark** for the economic valuation of STRUBIAS materials and incineration ashes that
 10569 can be used as raw materials by the fertiliser industry. Sales prices generally vary broadly
 10570 across the different market sectors targeted by a producer. The section **focusses on the**
 10571 **drivers that can be expected to affect sales prices for use in conventional agriculture.**
 10572

10573 Values are presented for Cost and Freight (CFR) **agreements** to downstream users, and thus
10574 include the shipment costs to **the downstream processor or user**. For the producer of
10575 STRUBIAS materials the potential revenues will be lower, as any distribution costs will need
10576 to be deducted. Particularly with regard to materials of low economic valuation (e.g.
10577 incineration ashes as an intermediate raw material within the P-fertiliser production chain), it
10578 is important to recognise that the indicated values are CFR.

10579
10580 In this assessment, an important distinction is made in estimated pricing **between products**
10581 **sold as raw materials for the fertiliser industry and products sold directly as fertilisers**.
10582 Importantly, it is generally not possible to isolate prices for each specific end-use when the
10583 same product can be used in various ways.

- 10584
- 10585 • **Raw materials for chemical processing**: This case mainly refers to mono-incineration
10586 ashes derived from P-rich input materials such as sewage sludge, meat and bone meal,
10587 and possibly manure fractions. Sewage sludge ashes are not useable as fertilisers directly
10588 due to the metals/metalloids contained, meaning that a lower price per tonne P₂O₅ can be
10589 expected than for finished fertiliser products as various additional costs need to be
10590 incurred before reaching the end point in the manufacturing chain. For ashes derived from
10591 meat and bone meal and manure, possible post-processing could further improve the plant
10592 availability of the P contained. As such manufacturing steps involve large-scale industrial
10593 manufacturing, the specific chemical composition of the product sold is crucial, as
10594 relatively small variations in material quality (e.g. P-content, Al/Fe content) can result in
10595 significant increases in operating costs for the consumers of these materials. The price
10596 setting for such materials is therefore largely **determined by the price setting of CFR**
10597 **phosphate rock** that is consumed as a source material by downstream manufacturers of
10598 complex P-fertilisers.
 - 10599 • **Fertilisers ready for sale**: this is the case of products such as **DAP, MAP or TSP**. In
10600 most cases, no further processing is required, meaning that higher prices per tonne P₂O₅
10601 can be expected compared to raw material prices; the expected sales price includes the
10602 manufacturing costs already occurred throughout the value chain, plus some profit margin
10603 of all actors involved within the value chain. Physical qualities like particle size or
10604 hardness, or the content of impurities, can play a role in pricing. The chemical
10605 composition of such products is, generally speaking, homogenised and standardised.
10606 Here, the **price setting occurs relative to finished fertiliser products already on the**
10607 **market**, and the value of P is likely to be linked to the value of P in a multinutrient
10608 fertiliser such as DAP.
 - 10609 • **P-materials for secondary compounds**: this is **somewhat in the middle between the**
10610 **previous two categories**. Some producers purchase products (e.g. DAP), grind it into
10611 smaller particles, and re-granulate a mix of various particles to obtain a product
10612 containing various nutrient grades. Contrary to bulk blends (which are just a physical mix
10613 of individual fertilisers), these re-granulated products have a uniform nutrient content in
10614 each granule. Since the raw materials for this process need to be ground, physical
10615 characteristics play almost no role in price-setting, and **the nutrient content is by far**

10616 **and large the main determinant of traded value.** A condition is, however, that the
 10617 materials have characteristics that make them suitable for blending. **Buyers of such**
 10618 **products often are able to obtain a relatively lower price per tonne P₂O₅ compared**
 10619 **to products sold as finished fertilisers, mainly by targeting material with poorer**
 10620 **physical characteristics.** A relevant example for such a case could be powdered
 10621 struvites. Hence, for STRUBIAS materials that will be used as raw materials for
 10622 secondary compounders, the price setting for the P contained in the STRUBIAS materials
 10623 is likely to occur relative to P-fertiliser products used by blending companies. After the
 10624 application of a discount, the price for such materials could mirror the price of finished
 10625 fertilisers on the market.

10626
 10627 **The value of STRUBIAS materials that will be brought on the market as P-fertilisers is**
 10628 **likely** to be determined to a significant extent by the P content contained in the material. The
 10629 benchmark for the valuation of incineration ashes that will be used as intermediates in the P-
 10630 fertiliser production chain is **phosphate rock** (P_{intermediate} in Table 18), whereas end materials
 10631 of STRUBIAS production processes (i.e. the CMC material) will be benchmarked relative to
 10632 materials for blending or finished fertilisers, or **DAP** (P_{final} in Table 18). The current CFR
 10633 market prices for DAP and phosphate rock, expressed as Euro per tonne P contained in the
 10634 material, are given in for different EU Member States.

10636 **Table 17: Value of P present in DAP and phosphate rock from Morocco (32% P₂O₅, Euro per**
 10637 **tonne P, CFR Morocco) assessed for different EU Member States for the year 2017 based on**
 10638 **import prices (Source: Fertecon; exchange rate of 1.2 Euro/US dollar applied by JRC).**

	France	Germany	Italy	UK	Poland	Romania	Average
DAP	1213	1397	1213	1234	1198	1256	1252
phosphate rock	558	685	594	852	539	665	649

10639
 10640 The price as estimated based on the P content is further expected to be modified by price
 10641 premiums and price discounts.

10642 • **Price premiums** could possibly apply to materials that are low in metals/metalloids,
 10643 mainly precipitated phosphate salts & derivates. The use of precipitated phosphate
 10644 salts & derivates in fertiliser blends could effectively reduce the Cd content in P-
 10645 fertilisers, and avoid as such the need for decadmiation (a cost estimated of about 27 –
 10646 68 Euro per tonne P) or the reliance on possibly more expensive phosphate rocks, low
 10647 in Cd content. Supplementary nutrients in STRUBIAS fertilisers are valued for
 10648 fertilisers ready for sale and raw materials for secondary compounds used by
 10649 compounders or blenders who would be able to fully monetise the nutrient values in
 10650 the formulation. **Magnesium** is valued at 130 Euro per tonne Mg. An additional Mg
 10651 value for STRUBIAS materials containing Mg (e.g. struvite) will be added. **Nitrogen**
 10652 is valued at around 320 Euro per tonne across EU Member States. The value of N is
 10653 based on price of ammonia as a source of N. An additional N value for STRUBIAS

10654 materials containing N (e.g. struvite) will be added. For struvites, the combined
 10655 monetary value for Mg and N will, however, be relatively lower than the monetary
 10656 value for P (<20%).

- 10657 • **Price discounts** are expected to apply for STRUBIAS materials that i) have a reduced
 10658 or unknown relative agronomic efficiency compared to mined rock phosphate and
 10659 processed P-fertilisers, ii) are non-granulated, iii) have a lower nutrient and P-density
 10660 that increases fertiliser distribution and application costs, iv) show a reduced
 10661 suitability for its use in fertiliser blends, and v) are generally associated to a reduced
 10662 degree of consumer confidence.

10663
 10664 Examples of possible benchmark CFR prices based on their P content for selected
 10665 STRUBIAS materials in conventional agriculture are given in Table 18.

10666
 10667 **Table 18: Benchmark CFR prices for the valuation of incineration ashes and STRUBIAS**
 10668 **materials based on the P contained and other relevant price setting factors (Euro per tonne**
 10669 **material).**

material	basic price		price premium	price discount
	P _{inter-} mediate	P _{final}		
granulated struvite (12.6% P, 9.9% Mg, 5.7% N)	-	158	low in metals, N & Mg value of 28 Euro/t, granulated material	not applicable
powdered struvite (12.6% P, 9.9% Mg, 5.7% N)	-	158	low in metals, N & Mg value of 28 Euro/t	not granulated
sewage sludge ashes (9% P, low in Al/Fe content)	58	-	not applicable	not applicable
poultry litter ashes (5.5% P,)	-	69	PK fertiliser	low nutrient density, agronomic efficiency tested on limited soil and plant types
TSP derived from sewage sludge ash (20% P)	-	250	low in metals, granulated material	not applicable
Thomasphosphate-like ashes (e.g. AshDec, 7.5% P)	-	94	low in Cd	low nutrient density, agronomic efficiency tested on limited soil and plant types

10670
 10671 For some STRUBIAS materials, the target market for pyrolysis & gasification materials may
 10672 not be the conventional agricultural market. Specific materials of all STRUBIAS material
 10673 groups could possibly make a market entry niche markets where fertilising products are
 10674 traded at higher prices (e.g. organic farming, horticulture, and growing media). Also, the
 10675 marketing of STRUBIAS materials as part of the circular economy could drive sales process

10676 upwards in some markets. In organic farming, the absence of competition from mined rock
10677 phosphate and processed P-fertilisers could positively impact upon the sales prices of the
10678 STRUBIAS materials. Hence, in niche markets, **the specificity of the source materials and**
10679 **the possible environmental impacts of STRUBIAS production processes on natural**
10680 **resources can be expected to impact upon the sales prices of the STRUBIAS materials.**

10681 It is expected that the future evolution in sales prices will closely reflect the expected price
10682 evolution for phosphate rock (intermediate raw materials) and P value in finished fertilisers
10683 (DAP) as given in section 9.1.2. For these materials, a negligible increase for the period 2016
10684 - 2025 is expected. The future **prices for STRUBIAS materials are therefore expected to**
10685 **remain stable.** Nonetheless, the consumers' confidence in STRUBIAS materials and the field
10686 verification of the presumed agronomic efficiency in the relevant agricultural sectors could
10687 further impact the future prices for STRUBIAS materials.

10688 Based on this assessment, it is clear that **STRUBIAS materials can vary largely in pricing,**
10689 **depending on the STRUBIAS material group, the characteristics of the output material,**
10690 **and target markets.**

10691

10692 **9.2 Compliance costs for STRUBIAS materials**

10693 The compliance cost of producing fertilising products containing precipitated phosphate salts
10694 & derivatives, thermal oxidation materials & derivatives, and pyrolysis & gasification materials
10695 is dependent on the identity of the contaminant as proposed in the STRUBIAS recovery rules.
10696 The cost data is given for testing as performed according to the international standards
10697 indicated in section 9.2.

10698 The assessment on the compliance cost indicates the costs associated to the testing of the
10699 parameters included in the recovery rules for the corresponding CMC. Some of the
10700 parameters included in the compliance scheme should anyhow be measured because they are
10701 directly included as part of the testing requirements at PFC level (e.g. organic C), or are
10702 measured concomitantly with PFC level parameters (e.g. metals as Cr, Th, and V; which are
10703 measured in the same sample run as other metals and metalloids such as As, Cd, Pb, etc.).
10704 The cost assessment will take into consideration the testing requirements that are specific to
10705 the CMC (as indicated in red). **This cost corresponds to the supplementary testing costs**
10706 **relative to equivalent fertilising products produced from primary raw materials for**
10707 **which no CMC testing requirements other than REACH registration have been**
10708 **proposed (i.e. CMC 1 in the proposal for the Revised Fertiliser Regulation).**

10709

10710 Table 19: Price estimates for the different parameters included in the proposals for the
 10711 STRUBIAS recovery rules for the three candidate material groups; the total compliance cost is
 10712 the sum of the different analyses that are exclusively required for testing at CMC level
 10713 (parameters depicted in black colour are included in the measurements to test compliance with
 10714 parameters at PFC level; parameters depicted in red colour are exclusively required to test
 10715 compliance with the proposed STRUBIAS recovery rules).

STRUBIAS material group		Price estimate in EURO mean (range)	Comment
Precipitated phosphate salts & derivates			
	Nutrients, including Total P, total Al, total Fe	76 (38-112)	PFC testing requirement for testing on nutrients, metals and metalloids – no additional cost
	Organic carbon	36 (17-80)	PFC testing requirement
	Macroscopic impurities	69 (50-90)	
	<i>Salmonella, Escherichia coli, Enterococcaceae</i>	74 (36-170)	
	PAH (only required for some input materials)	65 (45-100)	
	<i>Clostridium perfringens</i>	35 (20-50)	
	<i>Ascaris</i> sp. eggs	60	
	Dry matter content	10 (5-30)	
Total cost		244	
Thermal oxidation materials & derivates			
	Organic carbon	36 (17-80)	PFC testing requirement
	PAH	65 (45-100)	
	PCDD/F	404 (200-660)	
	Cr, Tl, V (individual measurement)	30 (25-37), per element	Usually measured together with other metals and metalloids (see next row)
	Cr, Tl, V (at times including also other elements not included in CMC testing scheme, e.g. Ca, K, Mg, As, Cd, Cu, Hg, Pb, Ni, Zn, Cu, etc.)	200 (85-525)	PFC testing requirement for testing on metals and metalloids – no additional cost

	Cl-	43 (20-69)	
	pH	9 (2 – 30)	
Total cost		521	
Pyrolysis & gasification materials			
	Organic carbon	36 (17-80)	PFC testing requirement
	H	31 (20-45)	
	PAH	65 (45-100)	
	PCDD/F	404 (200-660)	
	PCB	81 (60-120)	
	Cl-	43 (20-69)	
	pH	9 (2 – 30)	
Total cost		633	
Labelling requirements			
	Neutralising value	30 (20-40)	

10716

10717 Additionally, CE marked fertilising products, regardless of whether these are produced from
10718 primary or secondary raw materials, should comply with REACH Regulation (EC) No
10719 1907/2006. The REACH Regulation addresses the manufacture, use and placing on the
10720 market of chemical substances and mixture, and their potential impacts on both human health
10721 and the environment. For full guidelines on the links of recovered substances to the REACH
10722 Regulation, reference is made to the documents "ECHA – Guidance on waste and recovered
10723 substances" (ECHA, 2010), "Guidance for identification and naming of substances under
10724 REACH and CLP" (ECHA, 2016) and "Guidance on the interpretation of key provisions of
10725 Directive 2008/98/EC on waste" (European Commission, 2012). For **STRUBIAS materials**
10726 **that will be placed on the market**, Article 2(7)(d) of REACH could possibly provide an
10727 **exemption for the registration of STRUBIAS substances that are already REACH**
10728 **registered**. Once the type (substance on its own or in a mixture) and composition of the
10729 recovered STRUBIAS material have been established, identified and documented, the
10730 recovery operator is therefore in a position to examine whether the **exemption criteria** under
10731 Article 2(7)d of REACH are fulfilled.

10732

10733 **9.3 Possible economic benefits and drawbacks of producing fertilising products** 10734 **containing STRUBIAS materials**

10735 9.3.1 Effects on costs for producers of eligible input materials for STRUBIAS pathways

10736 The incorporation of STRUBIAS materials in the Revised Fertiliser Regulation might
10737 **prevent additional costs** for producers of eligible input materials for STRUBIAS pathways,
10738 through reducing costs for the management and/or disposal of the specific materials, and
10739 reduced compliance costs (sensu Wijnands and Linders, 2013). Benefits might, for instance,
10740 ensue for operators of incineration facilities that sell sewage sludge ashes to a P-recovery
10741 operator instead of sending them to a landfill, or for farming cooperation's that locally
10742 process their excess manure fractions to nutrient concentrated STRUBIAS materials instead
10743 of exporting it to other EU Member States. As observed in section 15, the STRUBIAS
10744 pathways might become an additional chain of a material recycling cascade. Therefore, they
10745 might contribute to the economic valorisation of entire recycling cascades by further
10746 exploiting currently unused residues of such cascades.

10747

10748 9.3.2 Effects on the competitiveness of the European agricultural sector

10749 The average expenditures of fertilisers on EU level range between 1% and 12% of total farm
10750 costs (Wijnands and Linders, 2013). The costs are relatively high for crop-producing farms:
10751 for specialised field crops almost 12%. The addition of STRUBIAS materials as possible
10752 ingredients for CE marked fertiliser products will **stimulate innovation to possibly develop**
10753 **new fertilising products**, for example with different nutrient release dynamics than
10754 conventional water-soluble P-fertilisers or through combining STRUBIAS materials with
10755 other CMCs in a single product (e.g. pyrolysis materials as additives to compost). Those new
10756 products can be **placed on the market without administrative burdens** due to lengthy
10757 procedures. Hence, creating a level playing field in the EU will promote enhanced market
10758 integration and **improved competition** between fertilising manufacturers and fertiliser
10759 blending companies with **possible effects on farmers purchase prices for fertilising**
10760 **materials**. Finally, producing P-fertilisers from secondary raw materials produced locally in
10761 Europe will **reduce the susceptibility of the European agronomic sector on P-fertiliser**
10762 **price volatility** due to possible geo-political tensions and the depletion of easily available
10763 high quality phosphate rock.

10764

10765 9.3.3 Effects on the transparency and competitiveness of the European fertiliser sector

10766 At present, some actors on the internal fertilising product market are sceptical about the
10767 mutual recognition Regulation (Regulation (EC) No 764/2008), as it has created disruption
10768 on the market resulting in unfair competition because viewpoints on safety regulation
10769 between National Competent Authorities differ. This is especially an issue of concern for new
10770 fertilising products that are derived from secondary raw materials, such as STRUBIAS. If
10771 already existent, the different national regulations related to these fertilising materials create
10772 market fragmentation and generate substantial administrative burdens for companies and
10773 national competent authorities. **Harmonisation of the legislation concerning all fertilising**
10774 **materials at EU level will increase the transparency within the EU and thus decrease**
10775 **transaction costs** (Wijnands and Linders, 2013). Actors producing, trading or using these
10776 fertilising materials can rely on the same framework, and make use of the principle of free
10777 movement of goods in the EU. Information on the composition, tolerance levels and

10778 maximum level of contamination is available in the same legislation, **ensuring transparency**
10779 **to downstream users**, including retailers, fertilising blending companies, and farmers.

10780 STRUBIAS production pathways mainly depart from biogenic organic materials that are
10781 currently spread on land as an input material, especially manure and to a smaller extent
10782 sewage sludge. Some of the STRUBIAS production processes, particularly the thermal
10783 oxidation pathway, result in the destruction of other valuable agronomic resources, such as
10784 nitrogen or organic matter. In such case, these elements will have to **be replaced by**
10785 **alternative materials, such as N fertilisers, or compost**. If those specific pathways develop
10786 substantially, increased demands for those alternative materials can equally be expected.

10787

10788 9.3.4 Restructuring of fertiliser production and distribution systems

10789 STRUBIAS materials are often part of a material transformation cascade that generates a set
10790 of co-products (e.g. clean water, renewable energy, STRUBIAS materials, etc.). Different
10791 operators are active in this cascade, and STRUBIAS material manufacturers will have to
10792 collect eligible input materials for their production process at facilities of upstream operators
10793 in the material transformation chain. Hence, **actors belonging to different sectors are active**
10794 **in the material transformation cascade (e.g. agriculture, waste water treatment, waste**
10795 **management, food processing industry, etc.) and will have to establish agreements in**
10796 **order to synchronise material streams, considering quantitative and qualitative aspects,**
10797 **amongst the different sectors involved**. Efficient business models are needed to turn the
10798 various benefits of P-recovery into a market success. Accordingly, new multi-stakeholder
10799 business models that create synergies between waste management actors and the fertilising
10800 industry should emerge to harness economic opportunities in value creation from the
10801 recovery and reuse of resources that would otherwise be irretrievably lost (and paid for to be
10802 disposed).

10803 Manufacturers that place on the market CE marked fertilising products containing
10804 STRUBIAS materials shall perform the **quality assessment procedures** as described in
10805 section 5.7. Companies that have an internal production or product quality control system in
10806 place will have fewer costs than companies that do not yet have such a system. In the first
10807 case a new regulation might incur some cost for amendments (Wijnands and Linders, 2013).
10808 In the second case a control system has to be put in place and that will involve investment
10809 costs. These procedures and inspections will create a certain administrative burden, and
10810 adverse impacts will be relatively higher for small and medium enterprises than for large
10811 companies.

10812

10813 9.3.5 Technical adaptations for downstream users of STRUBIAS materials

10814 Fertiliser **blending companies** will be given the opportunity to manufacture innovative
10815 fertilising products with a tailored chemical and physical composition that include
10816 STRUBIAS materials (see section 9.3.2). This may, however, **require additional testing**
10817 **and possibly the implementation of novel techniques to ensure physical and chemical**
10818 **compatibility of the different input materials**. The extent to which blending companies

10819 will undertake process modifications will be dependent on the market potential of these
10820 investments in blending procedures and the market acceptance and confidence in STRUBIAS
10821 materials. It should, however, be noted that further efforts related to blending are not required
10822 as STRUBIAS materials can be placed on the market without industrial processing.

10823 It is expected that STRUBIAS materials will be incorporated into CE marked fertilising
10824 products that have the same physical form as those currently available on the market.
10825 Therefore, **no additional costs for farmers owing to equipment adaptation requirements**
10826 **for fertiliser application on land are expected.**

10827

10828 9.3.6 Externalities and soil degradation

10829 Phosphorus and nitrogen fertilisers applied to the soil in quantities that exceed the uptake
10830 capacity of plants can result in P accretion in soils, N and P leaching and run-off, and may
10831 result in environmental impacts. Such externalities constitute the increasing costs to be borne
10832 by society (Vollaro et al., 2016). A persistent surplus of N and P in the soil leads to
10833 environmental impacts on water (nitrate pollution, eutrophication, acidification, etc.), air (air
10834 quality and acid rain), climate (GHG emissions contributing to global warming), soil
10835 (acidification and accumulation of heavy metals) and biodiversity (loss of species) (Sarteel et
10836 al., 2016). A consequence is that nutrient surpluses impact upon externalities: **human health**
10837 **costs, additional costs for drinking water treatment**, etc. All impacts depend on what
10838 practices are implemented and on local conditions in terms of climate and soil but also on the
10839 possible magnitude of nutrient overload in environmental compartments. For the EU-27 in
10840 2008, the total social cost of eutrophication was estimated between 75 and 485 billion euro
10841 per year (Van Grinsven et al., 2013). Although the used willingness-to-pay approach in that
10842 study recognises considerable uncertainties and conceptual challenges in such a monetised
10843 valuation of non-commensurable issues, the cost estimate provides a general idea on the
10844 externalities and the need to address those from an economic perspective. As outlined in
10845 section 8.9.2, STRUBIAS production processes can, in some occasions, provide solutions to
10846 improve nutrient efficiency. **STRUBIAS processes can thus reduce externalities** through
10847 promoting processing techniques to reduce the dissipation of nutrients, and providing options
10848 for the fine-tuning of fertilisation management by providing a more balanced nutrient ratio in
10849 fertilising materials.

10850 Land degradation costs an estimated US\$ 40 billion US dollars annually worldwide (The
10851 Ellen MacArthur Foundation, 2014). Soil degradation might contribute to food shortages,
10852 higher commodity prices, desertification and ecosystem destruction in the EU (Jones et al.,
10853 2010). Society has a duty to ensure that the soil resources within their territories are managed
10854 appropriately and sustainably. There is plentiful information demonstrating the benefits of
10855 maintaining and increasing soil organic C stocks to mitigate soil degradation across a range
10856 of different soils, agro-ecosystems and climatic zones (Chabbi et al., 2017). On average, soils
10857 in Europe are most likely to be accumulating carbon. Soils under grassland and forests are a
10858 carbon sink (estimated up to 80 million tonnes of carbon per year) whereas soils under arable
10859 land are a smaller carbon source (estimated from 10 to 40 million tonnes of carbon per year)
10860 (European Environment Agency, 2012). STRUBIAS production process might impact soil

10861 organic carbon through different mechanisms. The first mechanism applies to all STRUBIAS
10862 processes that help to reduce excess N in the soil, as the latter may cause an increase in
10863 mineralisation of organic C which, in turn, leads to an increased loss of organic C from soils.
10864 The second group of mechanisms is specific to the STRUBIAS material groups that might
10865 increase or decrease the return of soil organic matter to soils:

- 10866 • The effect for precipitated phosphate salts & derivatives is **neutral** as this technology
10867 involves only a separation of the predominantly inorganic fraction (the precipitate)
10868 from an organic rich stream that can be further applied on land as a soil improver or
10869 N fertilising material.
- 10870 • The thermal oxidation process effectively destroys the organic matter present in the
10871 feedstock. The net effect for thermal oxidation materials & derivatives is thus
10872 **dependent on the counterfactual use of this material**, with **negative** effects on soil
10873 organic C expected for materials that are otherwise returned to land (e.g. poultry
10874 litter) and **neutral** effects for materials that are otherwise (co-)incinerated (e.g.
10875 sewage sludge in some EU regions).
- 10876 • Pyrolysis & gasification materials with a low H:C_{org} are often C-rich materials with a
10877 claimed long turnover time in soils. Lehmann et al. (2015) indicated that more than
10878 90% of the initial C present in the biochar will remain in the soil after 100 years.
10879 Given that on average 50% of the C from the feedstock material is lost during the
10880 pyrolysis process (Enders et al., 2012), this would imply a potential long-term
10881 sequestration of 45% of the C present in the feedstock material. That value is higher
10882 than the typical long-term C sequestration from raw, digested or composted
10883 feedstocks (on average 11%; Bruun et al., 2006). The **effect for pyrolysis &**
10884 **gasification materials on the soil organic C balance is thus evaluated as positive**
10885 (Lal, 2009; Beesley et al., 2011; Wu et al., 2017).

10886

GENERAL CONCLUSION

10887

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10888 **10 Concluding assessment for STRUBIAS materials**

10889 As outlined in section 3.1, the STRUBIAS material groups are assessed against three
10890 different criteria. Based on the techno-scientific data collection and analyses, following
10891 conclusions could be derived:

10892 I. *The use of the materials will not lead to overall adverse environmental or*
10893 *human health impacts;*

10894 The potential negative health impacts identified relate to risks in the recycling of
10895 contaminants contained in the eligible STRUBIAS input materials and the *de novo*
10896 production of specific contaminants. Therefore, the eligible input material list was restricted
10897 for all three STRUBIAS material groups, excluding for instance mixed municipal waste as
10898 starting material for STRUBIAS production processes. Moreover, specific requirements were
10899 proposed on, for example, conditions for thermal oxidation. Still, particular contaminants of
10900 concern were identified that could be transferred to the STRUBIAS materials. This refers
10901 specifically to biological pathogens and some organo-chemical compounds (pharmaceutical
10902 compounds, polycyclic aromatic hydrocarbons, etc.) for precipitated phosphate salts &
10903 derivatives, metals for thermal oxidation materials & derivatives, and volatile organic carbon for
10904 pyrolysis & gasification materials. Therefore, direct and indirect product quality requirements
10905 to restrict those contaminants in the STRUBIAS materials were proposed. Altogether, the
10906 technical requirements for the different Component Material Categories should ensure that
10907 the use of the STRUBIAS materials does not lead to overall adverse environmental or human
10908 health impacts, thus ensuring food safety. This was confirmed using life cycle analyses that
10909 indicated that assessed STRUBIAS production options provide savings for one or more of the
10910 impact categories assessed (i.e. global warming potential, eutrophication potential, or human
10911 health cancer toxicity) relative to mined phosphate rock and processed P-fertilisers.

10912

10913 II. *The material shall provide plants with nutrients or improve their nutrition*
10914 *efficiency, either on its own or mixed with another material [following the*
10915 *definition of fertilising products in the proposal for the Revised EC Fertiliser*
10916 *Regulation];*

10917 A detailed analysis of this criterion using meta-analyses approaches indicated that
10918 precipitated phosphate salts & derivatives and thermal oxidation materials & derivatives that
10919 meet the proposed STRUBIAS recovery rules generally provide plants with nutrients,
10920 especially P, with a similar agronomic efficiency to mined phosphate rock and processed P-
10921 fertilisers. For pyrolysis & gasification materials, it was indicated that plant responses for P-
10922 rich pyrolysis & gasification materials can vary widely depending on the feedstock and
10923 production conditions of the pyrolysis & gasification materials, with some materials showing
10924 similar efficiencies to mined phosphate rock and processed P-fertilisers. It is observed that
10925 not all these organic P-fertilisers are effective within every agronomic setting. However,
10926 responsible use practices for those fertilisers can also contribute to reducing the reliance on
10927 primary raw materials under specific situations, in line with the principles of precision and
10928 targeted agriculture to increase nutrient use efficiency in the EU. STRUBIAS materials that

10929 show a low nutrient content can serve other fertilising functions (e.g. soil improver, liming
10930 material, growing media, plant biostimulant, etc.), thus contributing to improving plant
10931 nutrient uptake efficiency in the short or long-term under specific situations. It is concluded
10932 that all three STRUBIAS materials provide plants with nutrients or improve their nutrition
10933 efficiency, although the latter may only hold true under specific European settings for some
10934 pyrolysis & gasification materials.

10935

10936 III. *Trade on the internal market can be expected for such a fertilising material,*
10937 *based on the current market and the future market and trade forecasts.*

10938 The internal market for STRUBIAS materials is a recently emerging market, for which at
10939 present no EU-wide legal framework exists. Therefore, assessing the expected trade of
10940 STRUBIAS materials on the internal market is challenging. Further market developments,
10941 technological progress and economic benefits due to scale effects might develop. The
10942 materialisation of STRUBIAS production pathways does not only depend on the feedstock
10943 availability and production cost, but also subject to other decisions that impact on the need to
10944 process eligible input materials for STRUBIAS materials in a different manner relative to the
10945 current business-as-usual practices. With the intention to promote a more circular and
10946 resource-efficient economy, policy targets, financial incentives or financial disincentives for
10947 the handling of biogenic materials will thus impact upon the STRUBIAS market outlook.
10948 Market demand and trade is expected for all three STRUBIAS material groups in different
10949 segments of the EU agricultural sector. The most important share of the STRUBIAS
10950 materials will be used as fertiliser that can be used to provide nutrient, mostly phosphorus,
10951 inputs to European agriculture. As a best estimate, the opening of the P-fertiliser market to
10952 STRUBIAS materials is expected to result in a substitution effect of phosphate rock mined
10953 and processed P-fertilisers by fertilising products containing precipitated phosphate salts &
10954 derivatives and thermal oxidation materials & derivatives of 17 to 31%. Market demand for
10955 STRUBIAS materials is also expected for those used in liming materials, soil improvers or
10956 growing media.

10957

10958 Overall, it is concluded that precipitated phosphate salts & derivatives, thermal oxidation
10959 materials & derivatives, and pyrolysis & gasification materials meet all three criteria against
10960 which they were assessed. STRUBIAS materials offer an avenue to enhanced food security
10961 and sustainable fertilisation, while conserving the environment and its natural resources in
10962 Europe and elsewhere. A stable legal framework for all three STRUBIAS material groups is
10963 therefore desirable to promote trade and use of these materials in the EU agricultural sector
10964 and to provide a material quality benchmark for producers and consumers of P-fertilising
10965 materials containing STRUBIAS.

10966

10967
10968

QUESTIONNAIRE

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10969 **11 Feedback from STRUBIAS sub-group members – DEADLINE 14/09/2018**

10970 **11.1 Objective of the questionnaire**

10971 The objective of the questionnaire is three-fold:

- 10972 ○ To **validate and, if necessary, correct the techno-scientific knowledge base** that
10973 provides the foundation for the proposed STRUBIAS material requirements and
10974 market aspects as outlined in this pre-final Report;
- 10975 ○ To **highlight and propose discussion items for discussion at the final STRUBIAS**
10976 **meeting**, as well as relevant alternatively proposals.
- 10977 ○ To provide **credible and relevant techno-scientific information to support the**
10978 **requirement for the re-evaluation of certain conclusions of the STRUBIAS work**
10979 in view of the preparation of the final STRUBIAS meeting by the JRC and other
10980 STRUBIAS sub-group members.

10981

10982 **11.2 Information exchange**

10983 The information laid down in this document has been collated and assessed by the European
10984 Commission's Joint Research Centre who led the work on the STRUBIAS project, **guided by**
10985 **the principles of technical expertise, transparency and neutrality**. The work of the
10986 **STRUBIAS sub-group and all other contributors is gratefully acknowledged**.

10987 STRUBIAS sub-group members have already had the opportunity to comment on most parts
10988 of the report, with the exception of the sections on quality management (section 5.7),
10989 environmental and human health impacts materials (section 8), compliance costs (section 9.2)
10990 and possible economic benefits and drawbacks (section 9.3). Detailed questionnaires and
10991 opportunities to provide feedback were included as part of:

- 10992 ○ the STRUBIAS background document for the Kick-off Meeting (May 2016);
- 10993 ○ the STRUBIAS Interim report on recovery rules (June 2017); and
- 10994 ○ the STRUBIAS Interim report on market aspects (December 2017).

10995

10996 Each of these comments has been assessed by the JRC, and **credible and relevant**
10997 **information** has been taken into consideration during the writing of the pre-final STRUBIAS
10998 report. Expert judgement by the JRC and the STRUBIAS sub-group has played a key role in
10999 each of these steps and the way in which the information is presented.

11000

11001 **11.3 Procedure**

11002 It is imperative that **STRUBIAS sub-group member representatives provide a**
11003 **consolidated opinion that is in line with the views of the member organisations and**
11004 **stakeholders they represent**. Unfortunately, the JRC is not able to accept responses and
11005 opinions from organisations and individual persons that do not form part of an official
11006 STRUBIAS member organisation. The JRC recommends any third party organisations or
11007 persons interested in contributing to this work to contact one of the member organisations of

11008 the STRUBIAS sub-group²⁶. These STRUBIAS members carry the full responsibility for the
11009 quality of the information sent to the JRC and may therefore decide to take any external input
11010 on board in their reply, or not, after careful consideration and thorough quality-checking.

11011
11012 In order to safeguard time efficiency and the timely finishing of the STRUBIAS project, **the**
11013 **JRC kindly requests not to reiterate comments on the sections of the previous reports**
11014 **that were distributed for review in previous written consultation rounds.** As outlined in
11015 section 11.2, the STRUBIAS sub-group has already had the possibility to comment on the
11016 overall share of the data collected in the report. Previous comments from the STRUBIAS
11017 sub-group have been assessed and incorporated if the information has been considered
11018 credible and relevant by the JRC.

11019
11020 The STRUBIAS sub-group members shall provide any feedback in a **concise, constructive**
11021 **and structured form** to enable the rapid understanding of the key messages. Especially at
11022 this stage in the process, STRUBIAS sub-group members are kindly requested to provide
11023 feedback that is **task-focused, clear, to the point**, and does not contain redundant or
11024 marginal information to safeguard time efficiency. Feedback should provide information that
11025 is **credible and relevant**, and STRUBIAS sub-group members should support their opinions
11026 **with objective and evidence based arguments.**

11027
11028 Sub-group members shall use the channels provided by the Commission for discussion and
11029 information exchange. The preferential route for submitting non-confidential information is
11030 via the **CIRCABC platform** as this will facilitate a structured information exchange amid
11031 STRUBIAS members. Detailed instructions on how to access the CIRCABC STRUBIAS
11032 Interest Group were distributed to sub-group members via e-mail. Please upload any
11033 information in the folder/space entitled "Pre-final STRUBIAS report", and then select the
11034 matching sub-folders: "Written feedback from sub-group". Please note that all information
11035 that is uploaded on CIRCABC is publically available. The document name should start with
11036 the acronym of the member organisation. The JRC prefers to receive publically available
11037 information in order to support a transparent information exchange process. Nevertheless, it
11038 is accepted that some data cannot be made public and should be handled in a **confidential**
11039 **manner**. If only the data provider or data source is confidential, but not the data itself, it is
11040 desirable that member organisations anonymise the data provider/source and upload the
11041 document on CIRCABC as indicated above. Confidential data that cannot be publicly shared
11042 in any form should be sent via e-mail to JRC-B5-FERTILISERS@EC.EUROPA.EU. The
11043 document name should include the acronym of the organisation followed by the word
11044 "confidential".

11045

²⁶ The list of Members of the STRUBIAS sub-group can be found in the Register of Commission Expert Groups
→ Fertilisers Working Group (E01320)
(<http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetail&groupID=1320>)
→ Tab "Subgroups" → Subgroup of the Commission expert group on Recovery Rules for Fertilising
Products

11046 The JRC is pleased to take into account any feedback on the questionnaire received from the
 11047 STRUBIAS sub-group members **until the deadline of Friday 14 September 2018.**

11048
 11049 **11.4 Questions**

11050 The pre-final report has assessed STRUBIAS materials incorporated into CE fertilising
 11051 products against following criteria:

- 11052 I. *The material shall provide plants with nutrients or improve their nutrition*
 11053 *efficiency, either on its own or mixed with another material [following the*
 11054 *definition of fertilising products in the proposal for the Revised EC Fertiliser*
 11055 *Regulation];*
- 11056 II. *The use of the materials will not lead to overall adverse environmental or*
 11057 *human health impacts;*
- 11058 III. *Trade on the internal market can be expected for such a fertilising material,*
 11059 *based on the current market and the future market and trade forecasts.*

11060
 11061 1. Have you noticed any **incorrect or obsolete techno-scientific information** in the pre-final
 11062 STRUBIAS report that has an important influence on the proposed STRUBIAS material
 11063 requirements or market assessment?

11064
 11065 2. Should the **proposed technical requirements be modified** in order to ensure compliance
 11066 with those criteria as given in section 3.1?

11067
 11068 3. Would you light **discuss other items of interest at the final STRUBIAS meeting?**

11069
 11070 If your observation involves an alternative proposal for the STRUBIAS material
 11071 requirements, please indicate, substantiate and upload supporting techno-scientific
 11072 information.

11073
 11074 Provide your feedback in a structured, tabular format with following headings: observation,
 11075 page/line numbers and section in the document, correction and/or alternative proposal,
 11076 techno-scientific rationale that supports the comment raised, reference to techno-scientific
 11077 data.

11078

observation	location in document	correction/ alternative proposal	techno-scientific rationale that supports the comment raised	reference to techno-scientific data
e.g. sales prices for mineral P-fertilisers are underestimated by 30%.	e.g. section 2.3.7.2 (line 2864)	e.g. sales prices vary from X to Y EUR	The data found in IFA report (2017).	e.g. IFA. (2017) has been uploaded on CIRCABC

11079

APPENDIX

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11081 **12 Glossary**

AOX	Adsorbable Organic halides - a measure of the organic halogen load of a material
BSE	Bovine Spongiform Encephalopathy, commonly known as mad cow disease - a transmissible spongiform encephalopathy and fatal neurodegenerative disease in cattle that causes a spongiform degeneration of the brain and spinal cord
BTEX + S	Benzene, Toluene, Ethylbenzene, the ortho-, para- & meta-Xylenes and Styrene - the most abundant volatile organic compounds that can occur in petroleum-derived and biomass ash as a result of incomplete combustion
ChemP	The chemical precipitation of phosphorus with metal salts in a waste water treatment configuration
CMC	Component Material Category in the proposed Revised Fertiliser Regulation ²⁷ . A CE marked fertilising product shall consist solely of component materials complying with the requirements for one or more of the CMCs. This project evaluates techno-scientific evidence in view of a possible inclusion of STRUBIAS as CMC in the Revised EC Fertiliser Regulation.
DAP	Di-Ammonium Phosphate, a water-soluble mineral fertiliser that contains nitrogen and phosphorus
DG GROW	The Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs is the European Commission service that is leading the process of laying down rules on the making available on the market of CE marked fertilising products
DG SANTE	The Directorate-General for Health and Food Safety is a Directorate-General of the European Commission, responsible for the implementation of European Union laws on the safety of food and other products, on consumers' rights and on the protection of people's health
EBC	European Biochar Certificate - a voluntary European industrial standard for pyrolysis & gasification materials
EBPR	Enhanced Biological Phosphorus Removal - a waste water treatment configuration applied to activated sludge systems for the removal of phosphate based on the action of polyphosphate-accumulating organisms.
EC	European Commission
EU	European Union
FAO	Food and Agricultural Organisation of the United Nations
IBI	International Biochar Initiative – an international platform that groups stakeholders that have an interest in using pyrolysis & gasification materials as fertilising products
IED	Industrial Emissions Directive (Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control).

²⁷ More information on: http://europa.eu/rapid/press-release_IP-16-827_en.htm

JRC	Joint Research Centre of the European Commission
MAP	Mono-Ammonium Phosphate - a water-soluble mineral fertiliser that contains nitrogen and phosphorus
MBM	Meat and bone meal
NAC	Neutral Ammonium Citrate - a chemical extractant used as a proxy for plant-available phosphorus
NDA	Nutrient deficient areas; areas characterised by low nutrient levels in soils
NPK fertilisers	Mineral fertilisers that contains nitrogen (N), phosphorus (P) and potassium (K)
NSA	Nutrient surplus areas; areas characterised by high nutrient levels in soils
OECD	Organisation for Economic Co-operation and Development - an intergovernmental economic organisation founded to stimulate economic progress and world trade
P₂O₅	Phosphorus pentoxide (see section 13 for chemical conversion factor to phosphorus pentoxide)
PAH	Polycyclic Aromatic Hydrocarbons (also polyaromatic hydrocarbons or polynuclear aromatic hydrocarbons)
PCB	PolyChlorinated Biphenyl - an organic chlorine compound with the formula C ₁₂ H _{10-x} Cl _x
PCDD/F	PolyChlorinated DibenzoDioxins (PCDDs) and PolyChlorinated DibenzoFurans (PCDFs)
PFC	Product Function Category to which CE marked fertilising products shall belong in the proposed Revised Fertiliser Regulation ²⁸ in line with their intended function (i.e. fertiliser, liming material, soil improver, growing medium, agronomic additive, plant biostimulant, fertilising product blend).
POP	Persistent Organic Pollutants - organic compounds that are resistant to environmental degradation through chemical, biological, and photolytic processes
RAE	Relative agronomic efficiency; the term expresses the agronomic efficiency in terms of plant yields and/or plant nutrient uptake for fertilisers derived from STRUBIAS materials relative to mined rock phosphate and processed P-fertilisers
REACH	Registration, Evaluation, Authorisation and restriction of Chemicals, Regulation (EC) No 1907/2006 of the European Parliament and of the Council. The Regulation was adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals.
SSP	Single Super Phosphate - a water-soluble mineral phosphorus fertiliser that contains calcium dihydrogen phosphate and gypsum
STRUBIAS	STRUvite, Biochar and ASH-based materials. The acronym STRUBIAS, has been chosen as working title and does not necessarily reflect the final

²⁸ More information on: http://europa.eu/rapid/press-release_IP-16-827_en.htm

materials	scope of any possible proposals for CMC categories
STRUBIAS group	sub- A technical working group that constitutes a sub-group of the Commission expert group on Fertilisers. The STRUBIAS sub-group participates in the process of sharing knowledge and provides non-binding expert advice to the European Commission on possible recovery rules for nutrients from eligible input materials into STRUBIAS materials.
TRL	Technology readiness level
TSP	Triple Super Phosphate - a water-soluble mineral phosphorus fertiliser, also known as calcium dihydrogen phosphate with the chemical formula $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$
WHO	World Health Organization - a specialised agency of the United Nations that is concerned with international public health.

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11083 **13 Chemical conversion factors**

11084 The table below provides a number of conversion factors to quickly convert a fertiliser's
 11085 nutrient content expressed as one chemical form into the content expressed as another
 11086 chemical form.

11087 For example, a material with a phosphorus content of 30%, expressed as P₂O₅, has a
 11088 phosphorus content of 30% x 0.44 = 13.2% expressed as elemental phosphorus P.

11089

P ₂ O ₅	x	0.44	=	P
K ₂ O	x	0.83	=	K
Na ₂ O	x	0.74	=	Na
CaO	x	0.71	=	Ca
MgO	x	0.6	=	Mg
NH ₃	x	0.82	=	N
SO ₃	x	0.4	=	S
CaO	x	1.78	=	CaCO ₃
P	x	2.29	=	P ₂ O ₅
K	x	1.2	=	K ₂ O
Na	x	1.35	=	Na ₂ O
Ca	x	1.4	=	CaO
Mg	x	1.66	=	MgO
N	x	1.23	=	NH ₃
S	x	2.5	=	SO ₃
CaCO ₃	x	0.56	=	CaO

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11092 **14 Potential input materials for fertilising products containing STRUBIAS materials**

11093 **14.1 Introduction**

11094 **Potential input materials** for the production of STRUBIAS materials include waste and by-
11095 products within the meaning of Directive 2008/98/EC, animal by-products within the
11096 meaning of Regulation (EC) No 1069/2009, and biological materials. Each of these input
11097 materials have **specific properties**, including nutrient and contaminant contents, that impact
11098 upon their suitability to be used as input materials for a specific STRUBIAS production
11099 stream. This section aims at providing an overview of the characteristics for input materials
11100 that have a high potential for nutrient recovery with a specific emphasis on P-recovery.

11101
11102 The works of van Dijk et al. (2016) and Buckwell and Nadeau (2016) provide an excellent
11103 overview of the P-flows within the food and non-food production–consumption–waste chain
11104 for the EU-27 (Figure 28). Although the work provides an overview for streams within the
11105 year 2005, it provides a starting point for **designating material streams and core sectors**
11106 **that are dominantly responsible for the dissipation of P into the environment**. In section
11107 7.3, best estimates on the potential for P-recovery from the streams and sectors of interest for
11108 the year 2030 through STRUBIAS will be provided.

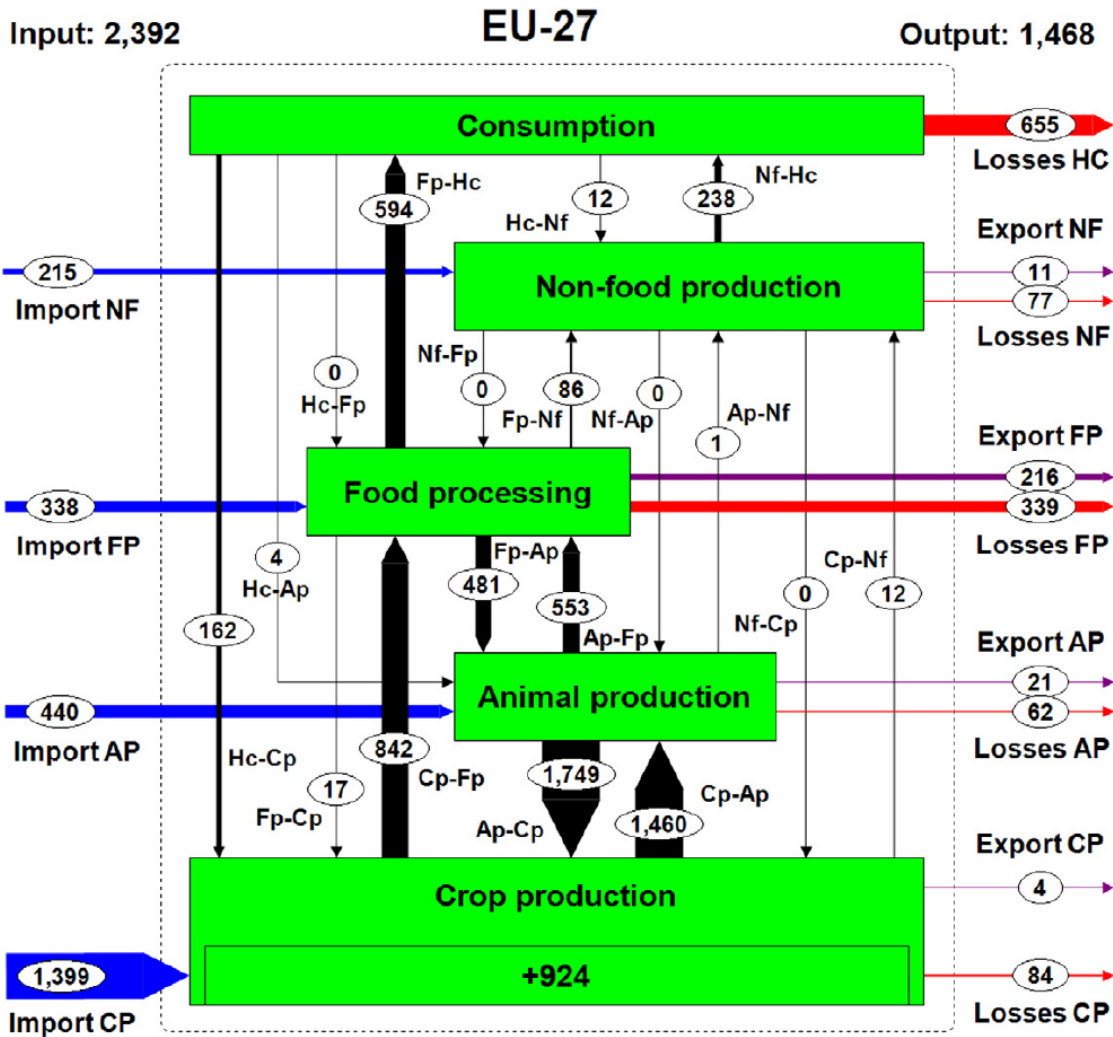
11109
11110 It is indicated that the P-dissipation into the environment mainly takes place through losses
11111 from crop production, food processing, and human consumption (Figure 28). Animal
11112 production and non-food production are associated to lower losses (Figure 28) (van Dijk et
11113 al., 2016).

11114 Losses from **crop production** mainly occur due to P accumulation in soils (924 kt P yr⁻¹),
11115 run-off and erosion (45 kt P yr⁻¹), and leaching and drainage to water bodies (40 kt P yr⁻¹).
11116 Additional losses from the agricultural sector are observed due to diffuse losses from stables
11117 (63 kt P yr⁻¹) (van Dijk et al., 2016).

11118 Losses from **food processing** mainly originate from the slaughtering of animals and the
11119 subsequent removal of P-rich rest materials (e.g. animal bones) from the biogeochemical P
11120 cycles. This loss flow equals 294 kt P yr⁻¹ (van Dijk et al., 2016). Other loss streams for the
11121 sector indicated by van Dijk et al. (2016) include food processing solid wastes (36 kt P yr⁻¹)
11122 and wastewaters (9 kt P yr⁻¹).

11123 Losses from **human consumption** are dominated by materials that are lost from waste water
11124 treatment plants (van Dijk et al., 2016). About 227 kt P yr⁻¹ ends up in communal sewage
11125 sludge, and an additional 74 kt P yr⁻¹ is lost as effluents from urban and decentralised waste
11126 water treatment plants. Untreated and uncollected waste waters sum up a total of about 59 kt
11127 P yr⁻¹. Other significant sources of P-dissipation from human consumption include food
11128 waste from households, retail and food service (175 kt P yr⁻¹), pet excreta (69 kt P yr⁻¹) and
11129 paper and wood waste (30 kt P yr⁻¹) (van Dijk et al., 2016).

11130 The losses from **non-food production**, as designated by van Dijk et al. (2016), relate to
11131 losses from forest-based industries (woodworking, furniture industry, pulp and paper
11132 industry). The total losses equal 77 kt P yr⁻¹, with wood industry waste being the dominant
11133 fraction (65 kt P yr⁻¹).



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Figure 28. Phosphorus (P) use for the EU-27 in 2005 [kt P yr⁻¹] aggregated at the food and non-food production–consumption–waste chain; showing the imports (blue), exports (purple), losses (red) and internal upward/downward flows (black) for crop production (CP), animal production (AP), food processing (FP), non-food production (NF) and human consumption (HC) sectors (indicated with square blocks); the arrow thickness shows the relative flow sizes; the positive balance of +924 in CP represents annual net accumulation of P in agricultural soils in 2005 (adopted from van Dijk et al., 2016).

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In the following sections, the characteristics of the designated potential input material streams by van Dijk (2016) and Buckwell and Nadeu (2016) will be reviewed in view of their potential to be used as an eligible input material for STRUBIAS production processes. Furthermore, the STRUBIAS sub-group pointed towards additional input materials that are suitable and already used for STRUBIAS production processes. Often, these input materials are used for a process aimed at the production of a different primary product (e.g. energy, clean water, steel) and STRUBIAS materials are produced or can be manufactured from residues from the process.

11155
11156

14.2 Crop residues

11157 **Cereals** (283 Mt yr⁻¹ harvested wet material, averaged over the period 2005-2012, expressed
11158 as wet matter) and **root crops** (173 Mt yr⁻¹ harvested, averaged over the same period) are the
11159 most important types of crops in the EU-27, both **in terms of area cultivated (data not**
11160 **shown) and production amounts** (Table 20) (Eurostat, 2016). Crop harvest of oil seeds (26
11161 Mt yr⁻¹) and rice (3 Mt yr⁻¹) make up a smaller contribution to the overall total of 350 Mt yr⁻¹
11162 for the EU (Table 20). Other crop types (e.g. other vegetables, nuts and non-food crops) were
11163 not considered in this analysis as they make up a very small contribution to the EU overall
11164 total crop production (Eurostat, 2016). Large differences exist between EU Member States,
11165 due to the climate conditions, specific soil condition and farming practices (data not shown;
11166 Eurostat, 2016).

11167
11168 The **residue-to-harvest ratio** varies widely across crop types, with the highest values
11169 observed for oil seeds (1.5 – 2.1), followed by cereals (1.0 – 1.6) (Table 20) (Energy
11170 Information Administration of the United States, 2001; Scarlat et al., 2010; Kremer, 2013).
11171 Root crops generally produce minor amounts of residues relative to the harvested crop
11172 biomass as the harvested tubers make up the dominant weight fraction of the plant biomass
11173 (residue-harvest ratio varying from 0.2-0.4) (Table 20). **Root crops and oil seeds have**
11174 **significantly higher N and P concentrations in their residues than cereals**, although large
11175 differences in nutrient concentrations were observed among the different cereal crops (Table
11176 20) (Kremer, 2013; Plants Database, 2016). Grain maize has, for instance, a nutrient content
11177 that is about 3 to 4 times higher than that of wheat straw.

11178
11179 Regarding nutrient content, **cereals produce about half of the crop residue nutrients**
11180 **present** (1353 kt N yr⁻¹, 279 kt P yr⁻¹), with the **other half split roughly equally between**
11181 **root crops** (676 kt N yr⁻¹, 126 kt P yr⁻¹) and **oil seeds** (743 kt N yr⁻¹, 150 kt P yr⁻¹). Five crop
11182 types (wheat and spelt, grain maize and corn-cob mixtures, sugar beet, sunflower seeds and
11183 rape and turnip rape seeds), contribute for 71%-73% of the nutrients generated as crop
11184 residues (Table 20).

11185
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11187 **Table 20: Production, characteristics and nutrient contents of agricultural crop residues in the**
 11188 **EU-27, averaged for the period 2005-2012 (Sources: Energy Information Administration of the**
 11189 **United States (2001); Eurostat (2016); Kremer (2013); Plants Database (2016); Scarlat et al.**
 11190 **(2010))**

crop	harvest (Mt yr-1)	residue-to- harvest ratio (-)	residue dry matter content (Mt yr-1) ¹	residue nutrient concentration		residue nutrient content	
				N (%)	P (%)	N (kt yr-1)	P (kt yr-1)
cereal	283		292			1353	279
wheat and spelt	136	1.3	150	0.28	0.05	419	73
barley	57	1.2	58	0.43	0.09	248	50
grain maize and corn-cob-mix	61	1.0	47	0.81	0.20	384	96
oats and spring cereal mixtures	12	1.3	14	0.70	0.14	101	20
rye and winter cereal mixtures	8	1.6	12	0.48	0.11	57	13
triticale	10	1.3	11	1.30	0.24	144	27
rice	3	1.4	3	0.67	0.13	23	5
root crops	173		40			676	126
potatoes	59	0.4	20	1.10	0.18	224	36
sugar beet	115	0.2	20	2.28	0.45	452	89
oil seeds	26		38			743	150
sunflower seeds	7	2.1	12	2.84	0.58	351	71
rape and turnip rape seeds	19	1.5	26	1.53	0.31	392	78
overall total	350		374			2795	559

¹calculated based on residue-to-harvest ratio and residue dry matter content

11191
 11192
 11193 A distinction, however, has to be made between residues remaining in the field and those
 11194 generated after harvesting. The majority of the crop residue is not collected and removed, but
 11195 **ploughed back into soil as its collection is too expensive to be profitable.** Additionally,
 11196 agricultural residues play an important role in **maintaining or improving soil**
 11197 **characteristics**, protecting the soil from erosion, maintaining or increasing soil organic
 11198 matter, maintaining nutrients in the soil and improving water retention (Nelson, 2002 in
 11199 Scarlat, 2010). Therefore, it is recommended to leave a significant share of the crop residues
 11200 on the field for agricultural sustainability, dependent on crop type, farming practices, site
 11201 conditions, and climate. The current best practice of incorporation for the EU is of one-third
 11202 of total residues (Joint Research Centre, 2009), although other studies have reported even
 11203 higher values of 40%-50% (Scarlat et al., 2010).

11204
 11205 **Crop residues are only collected if there is an economic potential, for instance, for their**
 11206 **use as animal feed, bedding material or biofuel.** The economic viability increases if
 11207 fertilising materials from crop residues are produced as part of a cascading approach that
 11208 relies on the residues of the primary process of recovery of valuable organic substances from
 11209 crop residues (e.g. lactic acid, citric acid, ethanol, caffeine, yeast production, biogas
 11210 production, etc.).

11211 At present, harvested residues are used for many often **onsite-specific purposes**: food,
 11212 fodder, feedstock, fibre, and further use such as compost production. Some amount of crop
 11213 residues is also collected for mushroom cultivation and various horticultural uses. Scarlat et
 11214 al. (2010) estimated that about 26 Mt yr⁻¹ of residues are used in animal husbandry and

11215 another 1.6 Mt yr⁻¹ of residue for mushroom production over the whole of the EU. The uptake
11216 of crop residues by the animal husbandry sector largely depends on the farm ratio of livestock
11217 to crop, for which higher values were documented for countries with high relative livestock
11218 proportions (e.g. for the UK, Searle and Malins, 2013). Much of the residue consumption for
11219 livestock occurs on site, i.e., the same farmer who harvests cereals and collects the straw
11220 feeds it to his or her livestock. Wheat and barley straw are also traded in Europe for use in the
11221 livestock sector. Some residues are sold to other parties, and this amount is easier to track.
11222 Studies have estimated off-farm residue use to amount to 5% - 6% (Kim and Dale, 2004).

11223
11224 Crop residues are often cited and explored for **their energy recovery potential**, but at
11225 present, crop residues are only used to a very small extent throughout the EU. Available EU-
11226 level data indicate that dedicated energy cropping for biofuels and electricity and heat
11227 generation covered approximately 5.5 million hectares of agricultural land in 2008
11228 (ETC/SIA, 2013), or about 3% of the EU utilised agricultural area. Practically all of this land
11229 was used for dedicated biofuel cropping (bioethanol and biodiesel). The realistic potential
11230 derived from the technical-sustainable potential for agricultural crop residues to contribute to
11231 renewable energy production has been estimated at 75 million tonnes per year in the EU-28,
11232 with a dominant contribution of the cereals wheat (26%), maize (21%) and barley (16%)
11233 (Iqbal et al., 2016). Based on the P content as given in Table 20 and taking into consideration
11234 the recommended crop extraction rates, **the total P content in the crop residues that could**
11235 **be used in nutrient recovery processes is estimated at around 110 kt P yr⁻¹**. Nutrient
11236 recovery from crop residues used for renewable energy production could potentially be a
11237 value-adding life stage or end-of-life solution for materials subject to anaerobic digestion for
11238 biogas production, or other thermochemical energy recovery processes. Such pathways are
11239 compatible with the production of **precipitated phosphate salts & derivatives** (after anaerobic
11240 digestion, although concerns exist due to the low phosphate content of anaerobically digested
11241 crop residues), **thermal oxidation materials & derivatives** (Insam and Knapp, 2011), and
11242 **pyrolysis & gasification materials** (EBC, 2012).

11243

11244

11245 **14.3 Manure**

11246 The **EU farm livestock population** consists of 153 million pigs, 88 million cattle, 1.3 billion
11247 poultry, 83 million sheep and 10 million goats (FAOSTAT-Commodity Balances Livestock,
11248 2012). Together, the **livestock excretes around 1400 Mt of manure** (Table 21) (Gendebien
11249 et al., 2001; Foget et al., 2011; Agrotechnology Atlas, 2016; Buckwell and Nadeu, 2016).
11250 Cattle manure (1092 Mt) represents the dominant manure fraction, with amounts that are
11251 about one order of magnitude greater than for pig (177 Mt) and poultry (112 Mt) (Foget et al.,
11252 2011) (Table 21). The manure produced from other livestock groups is mostly deposited
11253 directly on land by grazing animals. Production and characteristics of manure on a farm are
11254 largely **affected by species and growth stages of animals, feed ratios, manure collection**
11255 **and handling methods, and the amount of water added into the manure collection**
11256 **systems** (Agrotechnology Atlas, 2016).

11257

11258 Animal manure contains complex organic compounds originated from the undigested and
11259 wasted feed and veterinary products as well as simple organic and inorganic compounds
11260 produced in the gastrointestinal tract of animals. Hence, **manure slurry** is a mix of faeces
11261 and urine from livestock, bedding material with small structure like sawdust or chopped
11262 straw, washing water, water spill, etc. and originating from stables with whole or partly
11263 slotted floors (Bicudo, 2009). **Solid-liquid separation**, possibly after anaerobic digestion, is
11264 often used as a treatment method from improving manure handling properties and producing
11265 manure solids for energy generation, compost production and animal feeding. Another goal
11266 for solid liquid separation is to produce fertiliser products with different ratios of nitrogen to
11267 P and N to potassium (K) serving a better tuning with crops requirements for nutrients.
11268 Manure is removed from the livestock stables on a frequent (for instance daily) basis, and
11269 placed in a manure pad with drains, enabling to collect liquid fractions such as urine, silage
11270 effluents, process water and alike, in separate stores, and vice versa with the solid fractions.
11271 A broad variety of solid-liquid separation techniques is, however, available (Hjorth et al.,
11272 2010). Effective solid-liquid separation that is capable of removing a substantial amount of
11273 organic solids from fresh liquid or slurries can potentially offer the benefits of production of
11274 nutrient-rich organic solids, odour reduction in the subsequent liquid manure storages, and
11275 improvement in the economics of **subsequent liquid manure treatment processes**. The
11276 separated **manure solids** can be utilized on farms near animal operations or can be exported
11277 to other areas at significant economic and environmental costs as fertiliser and soil
11278 conditioning products (Agrotechnology Atlas, 2016). Alternatively, livestock is kept in
11279 stables where on a bed of long straw or similar material, up to 1 metre thick. The bed, also
11280 referred to as **deep litter**, is only removed with intervals of up to one year, when the livestock
11281 is removed from the stable for slaughter or grazing (Agrotechnology Atlas, 2016).

11282
11283 In spite of the vast nutrient amounts present in manure, these are present in highly diluted
11284 form as manure has an **average dry matter content of only 19%** (Table 21). The dry matter
11285 content is lowest for pig manure, with values as low as 5% for the largest share of the pig
11286 manure (pig slurry, Table 21). The **nutrient content of manure stocks varies broadly with**
11287 **the origin of the manure (cattle, pig, and poultry) and the type and extent of separation**
11288 (Table 21). Across the different origins of manure, poultry and pig slurries have the highest N
11289 and P concentrations with values of 5.8% - 8.3% and 2.2% - 2.3%, for N and P, respectively
11290 (Table 21). The N/P ratios of most manure types vary between 2 and 5, with the exception of
11291 liquid cattle manure that has an N/P ratio of about 12 (Table 21). All manure types have
11292 generally high organic matter contents (range 57% - 82%) (Table 21).

11293
11294 Cattle is the dominant manure fraction when data are expressed on a nutrient content basis.
11295 **Cattle manure contributes for 61% and 54% of the N and P present in the total**
11296 **livestock manure**, respectively (Table 21). **Poultry** manure is another significant nutrient
11297 stream, especially for P (36% of the total manure, up to 883 kt P yr⁻¹) and to a slightly lesser
11298 extent for N (30% of the total manure) (Table 21). **Pig** manure contributes for 9% (for N) and
11299 10% (for P) to the total nutrients presents in manure (Table 21). Poultry and pig are often
11300 kept inside year-round, for which reasons their manure can be easily collected.

11301

Table 21: Amount of manure in the EU-27 and its composition (sources: Agrotechnology Atlas (2016); Foget et al. (2011); Gendebien et al. (2001))

	Amount	Dry matter	Organic matter	N/P	K			N			P		
					concentration	content	relative contribution	concentration	content	relative contribution	concentration	content	relative contribution
	(Mt yr ⁻¹)	(%)	(% of dry matter)	(-)	(% of DM)	(kt K yr ⁻¹)	(%)	(% of DM)	(kt N yr ⁻¹)	(%)	(% of DM)	(kt P yr ⁻¹)	(%)
Pig slurry	148.6	5	69	3.7	4.6	373	4.7	8.3	673	7.2	2.2	181	7.3
Source separated pig manure							0.0			0.0			0.0
Solid	14.2	24	80	2.4	2.0	71	0.9	3.2	113	1.2	1.4	48	1.9
Liquid	8.8	2	n.a.	5.4	9.1	14	0.2	17.1	27	0.3	3.2	5	0.2
Pig deep litter	5.3	28	75	2.5	4.0	59	0.7	2.3	35	0.4	0.9	14	0.6
Total pig	176.9	7				517	6.5		847	9.1		248	10.0
Cattle slurry	447.8	9	66	4.6	4.7	1899	23.9	4.5	1818	19.6	1.0	399	16.1
Source separated cattle manure													
Solid	294.9	22	64	3.3	2.1	1371	17.2	2.4	1557	16.8	0.7	475	19.2
Liquid	54.6	3	57	12.5	29.4	447	5.6	12.2	185	2.0	1.0	15	0.6
Cattle deep litter	294.9	25	77	4.7	3.2	2397	30.2	2.9	2135	23.0	0.6	454	18.4
Total cattle	1092.1	17				6114	76.9		5694	61.3		1342	54.3
Poultry slurry	3.4	14	82	3.0	2.6	13	0.2	6.8	33	0.4	2.3	11	0.5
Poultry deep litter	109.5	57	74	3.1	2.1	1307	16.4	4.4	2713	29.2	1.4	872	35.3
Total poultry	112.9	55				1319	16.6		2746	29.6		883	35.7
Overall total	1381.9	19	69	4.4		7950			9287			2473	

11302

11303 It should be noted that the numbers for P presented in Table 2 differ from the ones presented
11304 in van Dijk et al. (2016). In their study, a total manure flux of 1.75 Mt P yr⁻¹ was observed for
11305 the reference year 2005, in contrast to the number of 2.47 Mt P yr⁻¹ as presented in Table 21.
11306 The reasons for this discrepancy relate to the different reference years that are used in the
11307 studies, and the uncertainty in average values for the nutrient concentrations and dry matter
11308 contents of the diverse manure fractions. Hence, estimating manure nutrient inputs is
11309 associated to a significant degree of uncertainty, and the absolute numbers given should be
11310 interpreted with the necessary caution.

11311
11312 **The main fate of manure in the EU-28 is currently land application.** At present, more
11313 than 90% of the manure produced in the EU is returned to agricultural land either through the
11314 spreading of the collected manure or directly by outside grazing activities (Buckwell and
11315 Nadeu, 2016). Only 7.8% of the produced manure, or 139 kt P, was processed in the year
11316 2010 (Foget et al., 2011).

11317
11318 **Landspreading of manure involves a risk for the accumulation of potentially toxic**
11319 **elements, pathogen recycling, and odour nuisance** (Gendebien et al., 2001). Manure may
11320 contain significant amounts of metals/metalloids due to the use of mineral supplements and
11321 veterinary products. This is particularly true for pig slurry, which can contain up to 600 mg
11322 kg⁻¹ dry matter of Cu, and up to 900 mg kg⁻¹ dry matter of Zn. Also, cattle slurries contain
11323 high amounts of Zn (up to 750 mg kg⁻¹ dry matter) (Gendebien et al., 2001). Considering the
11324 large volumes of manure applied, metals/metalloids may accumulate as a result of long-term
11325 agricultural use. Accumulation of metals/metalloids could not only affect the soil fertility, but
11326 also promote metal migration through leaching and runoff. Additionally, there is also
11327 growing concern regarding the environmental fate and potential impacts of the veterinary
11328 pharmaceuticals on human and ecosystem health as animal feeding pharmaceuticals are
11329 excreted into manure either as parent compounds or as bioactive metabolites (Song et al.,
11330 2010). Finally, animal manures contain pathogenic elements in variable quantities depending
11331 on the animal health. Manures applied without treatment and restriction on the application to
11332 land represent a risk for possible re-infection of resident animal population and the
11333 contamination of meat, dairy products, vegetables and water resources. There have been
11334 reports on cases of drinking water supplies contaminated by cattle slurry resulting in
11335 outbreaks of human diseases (Gendebien et al., 2001; Spellman and Whiting, 2007). The
11336 sources of ammonia emissions and odour nuisance from livestock production are from animal
11337 housing, waste handling, storage and landspreading. The storage of pig and poultry manure
11338 may cause odour problems if wastes turn anaerobic and give rise to strong odour when the
11339 crust is broken.

11340
11341 While nutrient recovery has **an enormous, positive role in well-adjusted agricultural**
11342 **systems**, much of the recycled manure is often **applied according to non-sustainable**
11343 **practices** due to spatial constraints associated to high transport costs of the large-volume
11344 material and unbalanced nutrient supply stoichiometry. This may lead to P accumulation in
11345 soil and water eutrophication after the leaching of nutrients from the soil.

11346

11347 In the legal sense, the animal by-products regulation (EC/1069/2009) classifies manure as an
11348 animal by-product of category 2. According to this regulation, **manure can be applied on**
11349 **land without further processing**. Possible manure **use restrictions** are, however, defined in
11350 other EU legislation.

11351
11352 The **Water Framework Directive** (WFD, 2000/60/EC) establishes an integrated and co-
11353 ordinated framework for the sustainable management of water, including prevention of
11354 deterioration of water bodies (lakes, rivers, coastal and transitional, groundwater), promotion
11355 of sustainable water use, and ensuring “enhanced protection and improvement of the aquatic
11356 environment”. The **Nitrates Directives** (91/676/EEC) indirectly limits the return of P to land
11357 by limiting the amount of N in manure that can be applied on land. However, the
11358 stoichiometric N/P ratios documented for soil microbes and plants (around 6 - 8; Cleveland
11359 and Liptzin, 2007) are higher than the N/P ratios of most types of manure (on average 4.4,
11360 Table 21). This indicates that **even manure applied to land in line with the Nitrates**
11361 **Directive contributes significantly to the observed P accumulations** in agricultural
11362 ecosystems that receive high manure loads (Figure 1; van Dijk et al., 2016). Member states
11363 (Belgium (Flanders, Wallonia), Denmark, the Netherlands, UK, Northern Ireland, Ireland)
11364 who have or had (Germany, Austria) an derogation for the use of N from animal manures
11365 (Nitrates directive) have to meet requirements of sound fertilisation practices which already
11366 leads to a more balanced nutrient management. In the Netherlands, for instance, manure
11367 processing is obligatory in case a farm has insufficient land to apply animal manure
11368 according the regulatory application standard. It is estimated that in 2015 about 8.9 kT P yr⁻¹
11369 from animal manure was processed in the Netherlands (BMA, 2015), with an additional 4.9
11370 kT P yr⁻¹ being planned. **Integrated pollution control**, as a principle of environmental
11371 protection and management, aims to minimize the overall environmental impact of human
11372 activities by taking into account pollution of air, water, land and the human environment, and
11373 identifying the action that causes on balance the least damage. As a legal system, integrated
11374 pollution control has been adopted by the European Union and, with an extended remit, been
11375 put in force as integrated pollution prevention and control (IPPC). IPPC covers intensive
11376 animal rearing for farms with a capacity of greater than 40,000 animal places for poultry,
11377 2000 for fattening pigs and 750 for sows. New farms and those with extensive modifications
11378 have to comply immediately whereas existing farms had to do so by 2007. Following inter-
11379 institutional negotiations, the Directive on industrial emissions 2010/75/EU (IED) was
11380 adopted on 24 November 2010. The IED repeals the IPPC Directive and the sectoral
11381 directives as of 7 January 2014. The IED requires ‘**best available techniques**’ to be applied
11382 in the operation of an installation. This will include measures for the management of
11383 manure/slurry within the installation (e.g. its removal from animal houses) and methods for
11384 its storage so as to prevent or minimise environmental impacts.

11385
11386 Eurostat monitors the risk of P pollution from agriculture based on the indicator "**gross P**
11387 **balance**", indicative for the potential surplus of P. The P balance lists all inputs and outputs
11388 into and out of the soil and calculates the gross P surplus as the difference between total
11389 inputs and total outputs. The gross P surplus per ha is derived by dividing the total gross
11390 phosphorus surplus by the reference area.

- 11391 The inputs of the phosphorus balance are:
- 11392 • Fertilisers, which consist of:
- 11393 • inorganic fertilisers;
- 11394 • organic fertilisers (excluding manure).
- 11395 • Gross manure input, which is calculated from:
- 11396 • manure production (phosphorus excretion);
- 11397 • manure withdrawals (manure export, manure processed as industrial waste,
- 11398 non-agricultural use of manure, other withdrawals);
- 11399 • change in manure stocks;
- 11400 • manure import.
- 11401 • Other phosphorus inputs, which consist of:
- 11402 • seeds and planting material;
- 11403 • atmospheric deposition.
- 11404

11405 The outputs of the gross phosphorus balance are:

- 11406 • Total removal of P with the harvest of crops (cereals, dried pulses, root crops,
- 11407 industrial crops, vegetables, fruit, ornamental plants, other harvested crops).
- 11408 • Total removal of P with the harvest and grazing of fodder (fodder from arable land,
- 11409 permanent and temporary pasture consumption).
- 11410 • Crop residues and soil of (root) crops removed from the field.
- 11411

11412 The indicator provides an indication of the potential surplus P on agricultural land (kg P per

11413 ha per year). The quality and accuracy of the estimated gross P surplus per ha depends on the

11414 quality and accuracy of underlying data and coefficients used. As methodologies (especially

11415 with regards to the coefficients) and data sources used in countries vary, the balances are only

11416 consistent within a country across time. The gross P balances are not consistent across

11417 countries implying that data cannot be compared between countries. It should be noted that

11418 data on **manure withdrawals, manure stocks and imports** were not **available in most**

11419 **countries**. Available data on manure withdrawals for non-agricultural use show that this

11420 input is significant (more than 5% of total manure input) in some countries (Belgium, the

11421 Czech Republic, the Netherlands), while non-significant in other countries (the United

11422 Kingdom, Switzerland).

11423

11424 The gross P balance can only indicate the **potential risk** to the environment while the **actual**

11425 **risk for water eutrophication depends on many factors including climate conditions, soil**

11426 **type and soil characteristics, management practices such as drainage, tillage, irrigation,**

11427 etc. The risk of P pollution is only partially determined by the P balance of a particular year.

11428 It is often more strongly determined by the cumulative P balance of the past.

11429

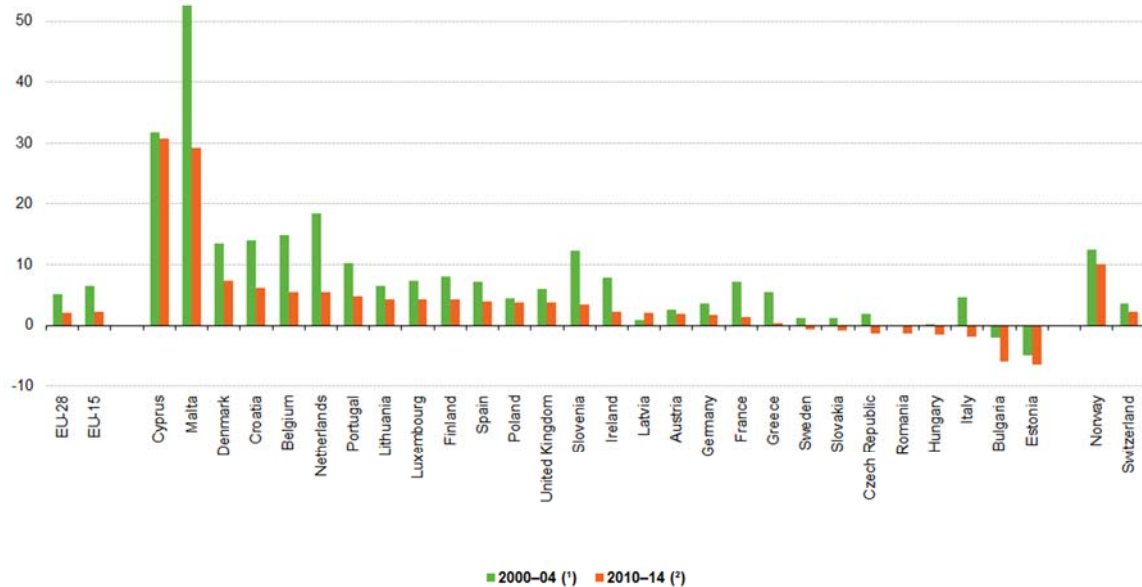
11430 The **potential P surplus for the EU-28 decreased from an estimated average of 5.2 kg P**

11431 **per ha per year in the period 2000-2004 to 1.9 kg P per ha per year in the period 2010-**

11432 **2014**. For the EU-15 the potential P surplus dropped from on average 6.4 kg P per ha per year

11433 in 2000-2004 to an average of 2.3 kg P per ha per year in 2010-2014. The average potential P

11434 surplus per ha in 2010-2014 was highest in the Mediterranean islands Cyprus and Malta,
 11435 above the EU average in Norway, Denmark, Croatia, Belgium, the Netherlands, Portugal,
 11436 Lithuania, Luxembourg, Finland, Spain, Poland, the United Kingdom, Slovenia, Switzerland,
 11437 Ireland and Latvia while the balance was negative for Sweden, Slovakia, the Czech Republic,
 11438 Romania, Hungary, Italy, Bulgaria and Estonia (Figure 29). In all Member States, with the
 11439 exception of Latvia, the potential P surplus between 2010 and 2014 was lower than between
 11440 2000 and 2004.



Note: Eurostat estimates for EU-28, EU-15, Belgium, Bulgaria, Denmark, Greece, Spain, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Malta, Austria, Romania and Slovakia.
 (*) Estonia: 2004
 (*) Germany, Ireland, Sweden and Switzerland: 2010-13

11441
 11442 **Figure 29: Gross phosphorus balance, averages 2000–04 and 2010–14 (Source: Eurostat - Agri-**
 11443 **environmental indicator - risk of pollution by phosphorus)**
 11444

11445 Nonetheless, **there is still a clear scope to increase the efficiency of nutrient recycling in**
 11446 **the agricultural sector. One option is through manure treatment options** that aim at
 11447 producing a safer, lower volume, and more targeted fertiliser that better matches crop needs.
 11448 For the year 2010, **7.8% of the manure (108 Mt, 556 kt N, 139 kt P) was being collected**
 11449 **for treatment** in the EU (Foget et al., 2011; Flotats et al., 2013). Distributed on livestock
 11450 manure treatments, pig slurry is a major focal area for treatment due to the high transport
 11451 costs for the highly diluted manure and the small surface area to dispose the slurry produced
 11452 (Foget et al., 2011). Two major routes are applied individually or combined to process
 11453 manure with the objective to change the physical and chemical manure properties, to recover
 11454 energy or to prepare for nutrient removal from the stream (Foget et al., 2011).
 11455

11456 **Separation via mechanical, chemical or other technologies** is applied to treat 49 Mt of
 11457 livestock manure, while anaerobic digestion is applied for 88 Mt of material (Buckwell and
 11458 Nadeu, 2016). In almost all types of separation, organic and inorganic coagulants and
 11459 flocculants are applied to achieve a good separation between the solid and liquid phase,
 11460 resulting in the precipitation of suspended solids and the concentration of the phosphates in

11461 the solid fraction. The use of coagulants and flocculants results in an increase of the costs of
11462 the mechanical separation process, and some flocculants might have adverse environmental
11463 effects, e.g. on soil and aquatic organisms (Buczek et al., 2017). Their use also has a strong
11464 effect on the further treatment potential of the solid and liquid fraction (Schoumans et al.,
11465 2010), although new technologies are emerging. Usual coagulants and flocculants are
11466 polyelectrolytes, aluminum and iron sulphate, aluminum and iron chloride, calcium oxides
11467 and calcium hydroxides, and also magnesium oxide and magnesium hydroxides. In case of
11468 targeting P-recovery in agriculture, the use of metal-containing salts might potentially impact
11469 upon the adeptness for P-recycling.

11470 Recovery of biogas during **anaerobic digestion** is advantageous as it can be used for electric
11471 energy generation or for the heating and drying during the further processing of manure.
11472 Additionally, anaerobic digestion increases the dewatering properties of the slurry as more
11473 components end up in the solid fraction following separation of the slurry, and the drying of
11474 the solid fraction proceeds more rapidly (Schoumans et al., 2010). The solid fraction can then
11475 be dried before pelletising or following incineration, or alternatively, composting is used. For
11476 0.7% of the manure production in the EU, the liquid fraction is further processed, mostly
11477 through biological treatment via conventional nitrification – denitrification systems and
11478 concentration through evaporation or filtration methods to produce a mineral concentrate
11479 (Foget et al., 2011; Buckwell and Nadeu, 2016). In the Netherlands, reverse osmosis
11480 techniques are used to produce NK fertilisers from liquid fractions of separation of animal
11481 manure or digestates. Substantial variations in the extent of manure processing and the
11482 different manure processing techniques are observed across EU member states (Foget et al.,
11483 2011).

11484
11485 Manure and stable livestock slurries are used as inputs for operational STRUBIAS processes.
11486 Stichting Mestverwerking Gelderland produces **K-struvite** from veal manure in the
11487 Netherlands. Also the EU funded BioEcoSim project aims at producing a mixture of
11488 precipitated phosphate salts & derivatives (from pig manure). Different companies in the
11489 Netherlands and the UK (e.g. BMC Moerdijk, Fibrophos, etc.) produce (mono- or co-
11490 incineration) **poultry litter ashes** from a combination of slaughtered animals and poultry
11491 beds. Finally, Hitachi-Zosen is evaluating the possibility of establishing **pig and poultry**
11492 **manure pyrolysis facilities** in Europe based on experience obtained from their pilot plant in
11493 Japan. Also, the BioEcoSim project and their partners are evaluating suchlike facilities in
11494 Western Europe.

11495
11496

11497 **14.4 Animal by-products other than manure**

11498 14.4.1 Food waste from households, retail and food services

11499 Food waste in the household sector involves **waste associated to meal preparation,**
11500 **leftovers, and purchased food not used in time.** Causes for this waste are diverse and relate
11501 to a lack of awareness and cooking skills, personal preferences, improper planning, labelling
11502 issues, storage and inappropriate portion sizes. In **wholesale/retail**, waste accumulates as a

11503 result of damage and expiry of products or surplus due to supply chain inefficiencies,
11504 improper stock management and deficient storage. Finally, additional aspects that cause
11505 waste from the **food services** include the single portion size, overstocking and meeting
11506 specific customer wishes (e.g. school children, etc.) (Bio Intelligence Service -
11507 Umweltbundesamt - AEA, 2010). Legally, waste from households, retail and food service
11508 waste containing products of animal origin is **category 3 animal by-product material**.

11509
11510 The amount of food waste generated from households, retail and food services is estimated at
11511 **62 Mt fresh material yr⁻¹, of which about three quarters (73%) is household waste, 17%**
11512 **is food services and 8% is retail** (Stenmark et al., 2016). The **nutrient content** of food
11513 waste is largely dependent on the exact composition (fraction animal and plant origin), but
11514 generally ranges from **1.6% - 2.3% for N and 0.26 - 0.54% P**. The dry matter content varies
11515 in the range 15% - 29% of the fresh weight (Brink, 1993; Widen, 1993). Hence, it is
11516 estimated that food waste from households, retail and food service could contain around **25-**
11517 **100 kt P per year**.

11518
11519 The current fate of the separately collected food waste is highly Member State specific.
11520 Currently, there is **no direct obligation at the EU level to recycle biodegradable waste**
11521 resulting in great differences across Member States. The Landfill Directive (1999/31/EC)
11522 obliges Member States, however, to reduce the amount of biodegradable municipal waste that
11523 they landfill to 35% of 1995 levels by 2016 (for some countries by 2020). On 2 July 2014, the
11524 European Commission adopted a legislative proposal to review waste-related targets in the
11525 Landfill Directive as well as recycling and other waste-related targets in Directive
11526 2008/98/EC on waste and Directive 94/62/EC on Packaging and Packaging Waste. The
11527 proposal aims at phasing out landfilling by 2025 for recyclable waste (including plastics,
11528 paper, metals, glass and bio-waste) in non-hazardous waste landfills, corresponding to a
11529 maximum landfilling rate of 25%.

11530
11531 Biodegradable waste is a **suitable input material for nutrient recycling options, such as**
11532 **composting and anaerobic digestion**, thanks to the low heavy metal content and high bio-
11533 availability of the nutrients. A critical aspect is, however, to what extent the separate
11534 collection and processing of food waste can be achieved.

11535
11536 In the **legal sense**, food waste is treated in the same way as normal waste that is non-
11537 hazardous if and only if it does not exhibit any properties that may render it hazardous.
11538 **Products of animal origin, or foodstuffs containing products of animal origin, and**
11539 **catering waste are, however, classified as category 3 Animal By-products**. Stringent
11540 controls are applied to its transport, handling and storage, treatment and disposal through
11541 Animal By-Products Regulation (EC) No 1069/2009. **Therefore, a share of the food waste**
11542 **is processed together with slaughter residues by the rendering industry** (see paragraph
11543 14.4.4).

11544
11545 14.4.2 Materials from the fish industry

11546 In 2012 the fish processing sector in the EU comprised approximately 3,500 firms with fish
11547 processing as their main activity (Doring and Borrello, 2014). Italy possessed the largest fish
11548 processing industry in 2012 in terms of number of firms (16% of the total) and the United
11549 Kingdom in terms of people employed (16% of the total), followed by Spain and France
11550 (Doring and Borrello, 2014). This sector includes activities such as the processing of white or
11551 pelagic fish; fatty fish; shellfish, i.e. crustaceans and molluscs, and fresh water fish. Fish
11552 processing is very widespread and varied. Many species of fish are mass processed, including
11553 cod, tuna, herring, mackerel, pollock, hake, haddock, salmon, anchovy and pilchards
11554 (European Commission, 2006b). Post-harvest loss occurs during pre-processing, processing,
11555 storage and transportation of fishery and aquaculture products. Post-harvest fish losses are,
11556 for instance, caused by fish scrap generation during fileting, curing and smoking processes
11557 and discarding of bycatch at sea because fish is too small or not valuable enough to bring to
11558 land for sale. At the global scale, up to **70% of total processed raw fish (on weight basis)**
11559 **ends up as solid waste in processing plants** (UNEP, 2000).

11560
11561 In the EU-28, about 5000 kt of fresh fish is processed on a yearly basis (Eurostat, 2017).
11562 Moreover, the EU-28 had a stable output of aquaculture products during the period 2004–
11563 2014, with a production quantity fluctuating around 1200 – 1300 kt live weight. Assuming a
11564 P content of 0.43% (Hjerne and Hansson, 2002), **the P content of fish residues from**
11565 **catches and aquaculture for the EU-28 could amount of up to 27 kt P yr⁻¹**. Moreover,
11566 fish excreta and non-digested feed from land-based aquaculture also form a P-source that can
11567 potentially be recovered as STRUBIAS materials. Fish residues generated during the
11568 processing of raw fish is a great source of minerals, proteins and fat, but if discarded, they
11569 can represent a major P loss. Treated fish waste has found many applications among which
11570 the most important are animal feed, biodiesel/biogas, dietetic products (chitosan), natural
11571 pigments (after extraction) and cosmetics (collagen). Residues from the sector are thus
11572 majorly used for the production of value-added products, and off-shore P losses from the
11573 sector are estimated relatively small (Hamilton et al., 2016).

11574
11575 Legally, residues from the fish industry are classified **as animal by-products and derived**
11576 **products**. The materials show similarity to animal by-products from the meat and dairy
11577 industry, for which reason P-recovery in the form of recovered phosphates, ashes and
11578 pyrolysis & gasification materials is in theory possible. No industrial STRUBIAS processes
11579 of high TRL level have so far been documented by the STRUBIAS sub-group, but similar
11580 recovery processes as documented for materials from the meat industry could potentially
11581 apply (see paragraph 14.4.3 and 14.4.4).

11582
11583 14.4.3 Materials from the meat industries

11584 **The cattle and poultry industries** are the largest source of animal food industry waste
11585 (Jayathilakan et al., 2012; EFPRA, 2017), with numbers largely exceeding those for fish
11586 scrap (Hamilton et al., 2016). In recent years there has been a change in the terminology used
11587 to describe outputs from slaughterhouses. The term “by-product” is being used increasingly;
11588 in this document, the term "**slaughter residues**" will be used in order to make a clear
11589 distinction with other animal by-products, such as manure. Slaughter residues produced in

11590 abattoirs consist of the portion of **slaughtered animals that cannot be sold as meat or used**
11591 **in meat products**. The consumer has a preference for lean meat, and only limited amounts of
11592 organ meats such as brain, kidney, sweetbread, tongue, etc. are consumed. As a result,
11593 basically the following residues become available in the slaughter process: (1) edible
11594 products such as blood and liver; (2) inedible products such as hair, bones, feathers; (3)
11595 manure, contents of rumen and intestines, (4) wastewater, and (5) fat (recovered from the
11596 wastewater by means of fat-separators). A complete overview is given in the Reference
11597 Document on Best Available Techniques in the Slaughterhouses and Animal By-products
11598 Industries (European Commission, 2005).

11599
11600 Slaughter residues are classified with other **animal by-products according to Regulation**
11601 **(EC) 1069/2009**. Slaughter residues are animal derived, and can contain different bacterial,
11602 viral, prion and parasitic **pathogens** and cannot be discharged into the environment without
11603 proper treatment. Therefore, the use of unprocessed slaughter residues for animal feed has
11604 been banned in the EU since 2000 due to fear of Bovine Spongiform Encephalopathy (BSE).
11605 Determinate category-specific product **treatment options** should now be undertaken prior to
11606 further utilization (Table 22). The rendering industry handles slaughter residues, fallen stock
11607 taken from farms, catering waste and unsold animal products that have the potential to
11608 become a health risk (EFPPRA, 2017). Through applying the prescribed procedures, rendering
11609 makes the material safe and **suitable for reuse** as outlined in the animal by-products
11610 Regulation (EC No 1069/2009). The material as obtained after the application of heat and
11611 pressure to sterilise and stabilise animal material is rich in fat and protein, for which reason it
11612 is suitable for a number of application as outlined in Figure 30. At present, specific animal
11613 by-products of category 2 and 3 can be processed and put to further use as feed, organic
11614 fertilisers and soil improvers (Article 32 of EC Regulation (EC) 1069/2009 on animal by-
11615 products).

11616

11617 **Table 22: Classification of substrates according to Regulation (EC) 1069/2009, and their**
 11618 **respective main treatment routes (adopted from Moller, 2015)**

Category 1	Category 2	Category 3
By-products of animals suspected of being infected by TSE (transmissible spongiform encephalopathy) and specified risk materials, including bovine brain and spinal cord.	By-products of animals presenting a risk of infection other than TSE, animals that have died in ways other than being slaughtered, animals killed to eradicate an epizootic disease, and contents of digestive tracts from slaughtering.	By-products arising from the production of goods intended for human consumption using slaughtered animals not affected by any sign of diseases transmissible to humans or other animals. These may also include leftovers from canteens, food processing industry etc.
Material shall optionally be (a) disposed of as waste by incineration (b) recovered or disposed of by co-incineration (c) used as fuel. Very often, the material is incinerated in cement kilns, meaning an irreversible removal of the remaining nutrients P, K, Mg and Ca from the nutrient cycle.	Material can be (a) treated as category 1 material, (b) used for the manufacturing of organic fertilizers following processing by pressure sterilization (e.g. > 133 °C and > 3 bars of pressure for > 20 minutes), and permanent marking of the resulting material, or (c) composted or transformed to biogas following processing by pressure sterilization.	Material shall be treated (a) as category 1 or 2 material (b) used for manufacturing animal feed after pasteurization (>70 °C, > 1 h), or (c) used for manufacturing organic fertilizers following processing by pasteurization.

11619
 11620
 11621 **Poultry** (23 Mt yr⁻¹) and **pig** (21 Mt yr⁻¹) constitute the greatest fractions of animal carcasses
 11622 expressed on a weight basis, followed by bovine meat (8 Mt yr⁻¹) (Table 23) (Eurostat, 2016).
 11623 Sheep and goat meat do not make up a substantial amount of the slaughtered animals. The
 11624 waste fraction is highest for cattle (0.42), than for pig (0.34) and poultry (0.25) (Table 23). **A**
 11625 **total amount of >17 Mt of slaughter residues** is generated with poultry meat (55%) having
 11626 the highest relative contribution, followed by pig (25%) and bovine meat (20%). The data of
 11627 Table 5 are generally in agreement with the data as presented by Van Dijk et al. (2016), and
 11628 indicate a total P flow of about 281 kT P yr⁻¹ for the sector. Abattoir wastes are characterized
 11629 by **very high P contents**. The mean P content of bone for bovine and poultry bone is about
 11630 10.5% on a dry weight basis (Beighle et al., 1994; Hemme et al., 2005), and P contents for
 11631 blood and offal may reach up to 4.6% and 1.5%, respectively (Gendebien et al., 2001).
 11632

11633 **Table 23: Overview of the slaughtered animals and the amounts of slaughter residues generated**
 11634 **in EU-28 for the year 2005**

	absolute weight of slaughtered animals ^{a,b} (kt yr ⁻¹)	Inedible fraction ^{c,d} (-)	slaughter refuse (kt yr ⁻¹)	relative contribution (%)
bovine meat	8136	0.42	3417	25
calve	946			
adult cattle	6819			
pigmeat	21781	0.34	7405	53
sheep and goat meat	809	0.48	388	3
poultry meat	10797	0.25	2699	19
overall sum	49289		13910	

^abased on Eurostat values for slaughtering in slaughterhouses for the year 2005 (cattle, pig and poultry) and 2015 (sheep and goat)

^bdata for poultry meat are underestimated because data for specific EU Member States are referred to as confidential in the Eurostat database, and could thus not be included

^cincludes the sum of animal fractions that are not transferred to the consumer and food-processing industry

^dbased on EFPR (2017)

11635
 11636
 11637 Eleven percent of pork carcasses, 15% of beef carcasses and 16% of lamb carcasses are **bone**.
 11638 With a P content of about 10% (Beighle et al., 1994; Hemme et al., 2005), **this material**
 11639 **represents a dominant proportion based of the P present in the non-edible animal by-**
 11640 **products**. As a matter of fact, the majority of P (85-88%) exists as bone P in the body of
 11641 vertebrates (Hua et al., 2005).

11642
 11643 Also, significant volumes of **waste waters** are produced at the slaughterhouse. This category
 11644 contains dung and urine from animal holding areas, washings from distribution vehicles, and
 11645 waste water generated during the process of meat and bone meal production (European
 11646 Commission, 2005). These waste waters are either treated on-site or discharged to municipal
 11647 waste water treatment (European Commission, 2005). The on-site generated waste waters
 11648 may have been in contact with category 1 animal by-products. Therefore, the P-recovery
 11649 from these waste waters may be legally impeded as the category 1 materials may not be used
 11650 for the production of fertilisers according to Regulation (EC) 1069/2009.

11651
 11652
 11653 14.4.4 Rendering industry

11654 Rendering transforms the non-edible materials discarded by the meat and other industries into
 11655 stable, value-added materials. Rendering can be carried out on an industrial, farm, or kitchen
 11656 scale. The majority of tissue processed comes from slaughterhouses, but also includes
 11657 restaurant grease and butcher shop trimmings and expired meat from grocery stores. This
 11658 material can include the fatty tissue, bones, and offal, as well as entire carcasses of animals
 11659 condemned at slaughterhouses, and those that have died on farms, in transit, etc. The most
 11660 common animal sources are beef, pork, sheep, and poultry. The rendering process

11661 simultaneously dries the material and separates the fat from the bone and protein. A rendering
11662 process yields a fat commodity (yellow grease, choice white grease, bleachable fancy tallow,
11663 etc.) and a protein meal (meat and bone meal, poultry byproduct meal, etc.). Rendering plants
11664 often also handle other materials, such as slaughterhouse blood, feathers and hair, but do so
11665 using processes distinct from true rendering. The mono feed animal bone processing industry
11666 is a specific rendering industrial operation, which is processing food grade category 3 animal
11667 bones only or category 3 and 2, and having specific output products, such as food grade
11668 gelatine, China Bone for porcelain industry, processed bone grist (bone meal) and organic
11669 ingredients including hydrolysate for pet food.

11670

11671 The work of van Dijk et al. (2016) indicates significant P losses of 294 kt P yr⁻¹ from the
11672 slaughter residues for the reference year. It should be noted that **these numbers might be**
11673 **outdated at present because the entry into force of the EC Animal By-Products**
11674 **Regulation** (Regulation (EC) No 1069/2009). Following the crises related to the outbreak of
11675 foot-and-mouth disease, the spread of transmissible spongiform encephalopathies such as
11676 bovine spongiform encephalopathy (BSE), the further use of animal by-products was largely
11677 restricted. The disposal of all animal by-products was, however, not a realistic option as it
11678 would lead to unsustainable costs and risks for the environment, and contradicts with the
11679 sustainable management of these materials. The clear interest of EU Member States to use
11680 animal by-products for a wide range of applications in sustainable manner was reflected in
11681 EC Regulation No 1069/2009 as outlined in Figure 30.

11682

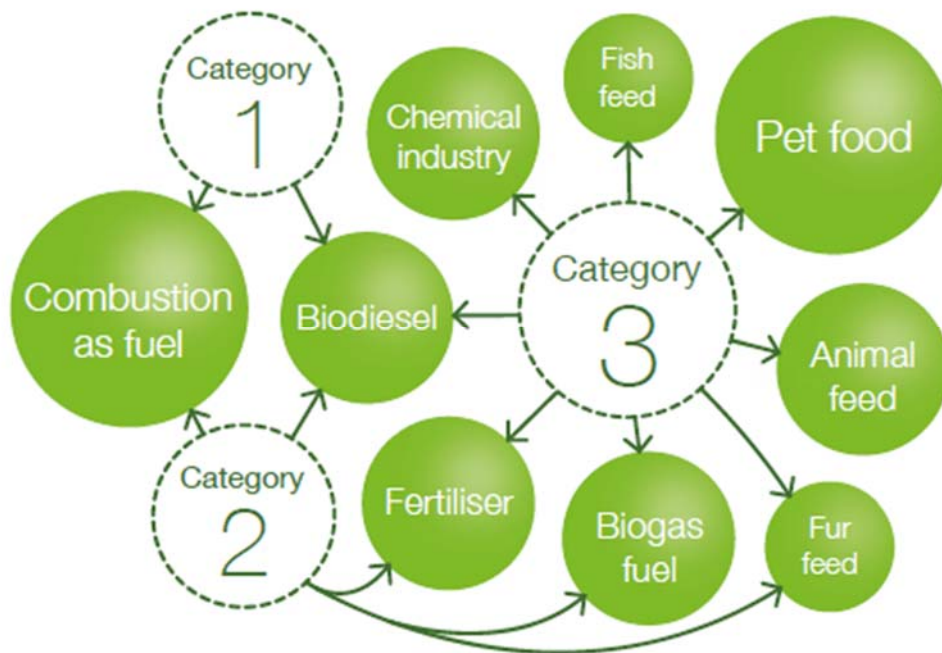
11683 Altogether, the European Fat Processors and Renderers Association (EFPRA) process
11684 annually about 17 Mt of material in Europe. **From this 17 Mt, about 12 Mt is classified as**
11685 **category 3 materials, about 0.8 Mt as category 2 materials and 4.6 Mt as category 1**
11686 **material** (EFPRA, 2017). Given the limited treatment disposal options for category 1 animal
11687 by-products, these materials are almost exclusively used for renewable energy production
11688 (Dobbelare, 2017) (Figure 30). Category 2 material is mainly used for the production of
11689 biodiesel (fat fraction), and fertilisers (protein fraction) (Dobbelare, 2017) (Figure 30). About
11690 180 kt of category 2 protein material is used for the production of (organic) fertilisers in the
11691 year 2016 (Dobbelare, 2017). The fat fraction of Category 3 animal by-products are typically
11692 processed to produce Processed Animal Proteins (PAP), that can be used for pet food, animal
11693 feed including and fish feed, oleochemicals, edible fats and biodiesel (EFPRA, 2017). The
11694 protein fraction for category 3 material equalled 2.7 Mt of material in 2016, and was
11695 dominantly used for the production of pet food (~70%), (organic) fertilisers (18%), and to a
11696 smaller extent for fish feed, human food (gelatin) and fur feed (EFPRA, 2017) (Figure 30).
11697 About 510 kt of (organic) fertilisers were produced from category 3 material in the year 2016.
11698 **Assuming a P content of 5.3% for the protein fraction (Moller, 2015), the current**
11699 **fertiliser volumes of category 2 and 3 category animal by-products would equal about**
11700 **27 kt P yr⁻¹.**

11701

11702 Time series of the fate of animal by-products for France confirm that the fraction of category
11703 3 animal by-products that is incinerated for energy recovery has significantly decreased over
11704 the last decade (2006 – 2015), and that the relative share used for pet food production

11705 significantly increased (SIFCO, 2017). **It is concluded that the entry into force of**
 11706 **Regulation (EC) No 1069/2009 effective increased the re-utilisation of animal by-**
 11707 **products of category 3.** Therefore, the pet food sector is a significant competing industry for
 11708 the fertiliser industry that produces plant nutrition products from category 3 animal by-
 11709 products.

11710
 11711 Therefore, the current P fraction that is dissipated is largely restricted to P present in category
 11712 1 (4.6 Mt material yr⁻¹) that is incinerated for energy recovery or used as biodiesel after prior
 11713 processing steps.



11714
 11715 **Figure 30: Potential application of processed animal by-products of category 1, 2 and 3 (source:**
 11716 **EFPPRA (2017))**
 11717

11718 Animal by-products other than manure and derived products not intended for human
 11719 consumption are currently already used for the manufacturing of STRUBIAS materials. The
 11720 mono-incineration of 1 tonne of animal derived meal and grist generates about 100-300 kg of
 11721 **ash** (Coutand et al., 2008). During the incineration process, all organic matter in the material,
 11722 including proteins, is transformed to CO₂, H₂O and nitrous and sulphur oxides, etc. Minerals
 11723 like Ca, Mg and P are relatively stable in response to heating (Deydier et al., 2005a; Zheng et
 11724 al., 2013). As a result, meat and bone meal ashes have high P (average 14.0%, range 6.1% -
 11725 18.9%) and Ca contents (20.9%), but low N contents (average 0.17%) (Deydier et al., 2005a;
 11726 Wopenka and Pasteris, 2005; Czaja and Hermann, 2011). The combustion induces a wide
 11727 range of structural modifications, such as crystallization of calcium phosphate, substitution
 11728 reactions, etc. These processes reduce the P-solubility and therefore the value of the meat and
 11729 bone meal ashes as P fertiliser in comparison to the original substrate (Moller, 2015). At
 11730 present, however, co-incineration is the dominant thermochemical pathway due to the ease of
 11731 operation and increased energy revenues. Mono-incineration is only applied at specific
 11732 facilities (e.g. Kalfos – SARIA) that produce Kalfos fertiliser based on meat and bone meal
 11733 ashes. Bone grist is also the input material for the **production of Animal Bone biochar** (3R

11734 AgroCarbon, 2016), a fertiliser material with a P content of 13%. **Calcium phosphates can**
11735 **be precipitated** when degreasing animal residues (bone) during the demineralisation of the
11736 liquor during **gelatine manufacturing**.

11737

11738 **14.5 Effluents and residues from municipal waste water treatment plants**

11739 **Waste water treatment plants** process grey/black water from households and industrial
11740 waste water produced. The dominant share of P from **industrial waste waters** present in
11741 **industrial sewage** is found in the sludge from the meat industry, potato industry, dairy
11742 industries, vegetable industry, and pulp and paper industry (Geertjes et al., 2016), and will be
11743 covered in the respective sections.

11744

11745 Municipal sewage is used water mainly coming from domestic activities and sometimes
11746 combined with used water from industrial activities and/or with surface run-off. The Urban
11747 Waste Water Treatment Directive (91/271/EEC) defines an **agglomeration** as an area where
11748 the population and/or economic activities are sufficiently concentrated for urban waste water
11749 to be collected and conducted to an urban waste water treatment plant or to a final discharge
11750 point. The size of an agglomeration in terms of generated pollution load is measured in
11751 **“population equivalent”** (p.e.). This is the organic biodegradable load that has a five-day
11752 biochemical oxygen demand (BOD5) of 60 g of oxygen per day, or in more popular terms –
11753 the organic biodegradable load generated by one person per day.

11754

11755 **Sewage treatment** is the process of removing contaminants from wastewater. It includes
11756 physical, chemical, and biological processes to remove these contaminants and produce
11757 environmentally safe treated wastewater (or treated effluent). **Primary** treatment removes
11758 part of the suspended solids, while **secondary** (biological) treatment uses aerobic or
11759 anaerobic micro-organisms to decompose most of the organic matter and nutrients (mostly
11760 N). **Tertiary** (advanced) treatment removes the organic matter and nutrients even more
11761 efficiently. It generally includes P retention and in some cases enhanced N removal. Nitrogen
11762 removal is regularly achieved through biological N removal through N reducing pathways
11763 (denitrification, possibly Anammox) that **remove the N from the system** as gaseous
11764 compounds, although specific recovery options are available (e.g. ammonia stripping).

11765

11766 The main objective of the **Urban Waste Water Treatment Directive** (91/271/EEC) defines
11767 in which conditions the waste water should be collected and treated before being released in
11768 the environment according to the quality of the receiving waters. The directive includes
11769 **requirements for collection and treatment of wastewater** in all settlements
11770 (agglomerations) and areas of economic activity with a population equivalent (p.e.) larger
11771 than 2000. The connection rate in Central European countries is even higher, and exceeds
11772 90%. About 80% of the population is connected to waste water treatment in Northern and
11773 Southern European countries. On the basis of data reported in 2010, about 67% of the total
11774 population is connected to wastewater treatment in the countries of Eastern Europe.
11775 **Advanced (secondary or tertiary) treatments for nutrient and organic matter removal**
11776 **are required for populations larger than 10 000 p.e.** The current population connected to

11777 plants with tertiary treatment is in the order of 70% in Northern and Central Europe, and
 11778 about 50% for Southern and Eastern Europe (European Environment Agency, 2013b).
 11779 Average connection rate in South-East Europe (Turkey, Bulgaria and Romania) is about 40%.
 11780 About a quarter of the population in South Eastern countries is connected to collecting
 11781 systems without treatment (European Environment Agency, 2013b).

11782
 11783 Table 24 shows the generated organic pollution load that agglomerations discharge as a
 11784 function of size class (European Commission, 2017a).

11785
 11786 **Table 24: The generated organic pollution load of urban waste water treatment agglomerations**
 11787 **as a function of size class (European Commission, 2017a)**

	Total load discharged from agglomerations 2000-10000 p.e. (million p.e.)	Total load discharged from agglomerations >10000 p.e. (million p.e.)	Total load discharged from big cities discharging >150 000 pe (million p.e.)
EU15	51	457	230
EU13	17	62	47
EU28	68	519	277

11788
 11789 Different configurations exist for P removal in waste water treatment plants, with the most
 11790 popular techniques being **enhanced biological phosphorus removal (EBPR)** and **chemical**
 11791 **phosphorus removal (Chem-P)** using Fe or Al salts.

11792
 11793 The major feature of the **EBPR process** is that organic matter uptake and P release take place
 11794 under anaerobic condition and P uptake takes place under subsequent aerobic zone (Zhang et
 11795 al., 2013). The enhanced phosphorus removal is attributed mainly to a group of selectively
 11796 enriched heterotrophic bacteria, i.e., **P-accumulating organisms (PAOs)**. PAOs store carbon
 11797 sources as intracellular polymers [i.e., poly- β -hydroxyalkanoates] using the energy of
 11798 polyphosphate (polyP) and glycogen degradation and then release orthophosphate (orthoP)
 11799 into the outside under anaerobic conditions. In the subsequent aerobic phase, PAOs use the
 11800 stored poly- β -hydroxyalkanoates as an energy source, transforming orthoP to polyP,
 11801 replenishing glycogen and self-growth. Phosphorus is accumulated in the sludge and is
 11802 removed by sedimentation and discharging the P-rich excess sludge.

11803
 11804 Chemical treatment for phosphorus removal involves **the addition of metal salts** to react
 11805 with soluble phosphate to form solid precipitates that are removed by solids separation
 11806 processes including clarification and filtration. The most common metal salts used are in the
 11807 form of alum (aluminum sulfate), sodium aluminate, ferric chloride, ferric sulfate, ferrous
 11808 sulfate, and ferrous chloride. The chemicals can be added before the primary settling, during
 11809 secondary treatment or as part of a tertiary treatment process. Iron salts are usually preferred
 11810 over Al salts due to their lower cost (Wilfert et al., 2015). Apart from P removal, Fe plays an

11811 important role to prevent hydrogen sulfide emissions during anaerobic digestion and acts as a
 11812 coagulant to improve sludge dewatering (Charles et al., 2006; Ge et al., 2013).

11813
 11814 Chem-P is more prevalent than EBPR in municipal waste water treatment plants in Europe
 11815 (Paul et al., 2001; DWA, 2005; Korving, 2012; Carliell-Marquet and Cooper, 2014; Wilfert et
 11816 al., 2015).

11817
 11818 **Table 25: Configurations used in enhanced phosphorus removal methods used in selected EU**
 11819 **Member States (adopted from Wilfert et al., 2015)**

Country	Type of weighting	No tertiary treatment	Mostly EBPR	EBPR with		Reference
				ChemP support	ChemP	
Germany	People equivalents	2%	6%	31%	61%	DWA, 2015
	Number of plants	20%	16%	21%	43%	
The Netherlands	Sludge production	4%	13%	51%	32%	Korving, 2012
United Kingdom	People equivalents	no data	5%	no data	95%	Carliell-Marquet and Cooper, 2014
	Number of plants	no data	23%	no data	77%	
Germany	Number of plants	no data	17%	36%	47%	Paul et al., 2001

11820
 11821
 11822 Although removal of phosphorus from waste water is a requirement under Article 5 of the
 11823 Urban Waste Water Treatment Directive (91/271/EEC), **this directive does not require**
 11824 **extraction of the P in a useable form**. One particular feature of the Directive is that it allows
 11825 the flocculation of the phosphorus using aluminium and iron, which produces a strongly
 11826 bound compound from which the P is not easily commercially recoverable and which may
 11827 not be fully available to plants (Wilfert et al., 2015).

11828
 11829 **Sewage sludge** is the semi-solid material or slurry that remains after the treatment. Sewage
 11830 sludge is an organic substrate relatively **rich in nutrients, but also might contain a**
 11831 **substantial amount of organic and inorganic contaminants**. The material has to undergo
 11832 further treatment before being suitable for disposal or land application. According to the CEN
 11833 (European Committee for Standardization), sludge is defined as "*a mixture of water and*
 11834 *solids separated from various types of water as a result of natural or artificial processes*". In
 11835 sewage treatment works, **sludge is further treated** to reduce its water content (thickening,
 11836 dewatering, drying, or a combination thereof) and to increase its stability (anaerobic
 11837 digestion, aerobic stabilization, lime stabilization, composting, or a combination thereof).

11838
 11839 The current **fate of treated sludge** includes disposal in landfills, application to land,
 11840 incineration, or composting (Figure 31). Existing national and EU regulation also set
 11841 progressive limits on disposing sludge in landfill and its direct application to land, especially
 11842 in densely populated EU regions (Buckwell and Nadeu, 2016). This has caused an increase
 11843 and interest for **the importance of alternative disposal and recycling routes for growing**
 11844 **amounts of sewage sludge**.

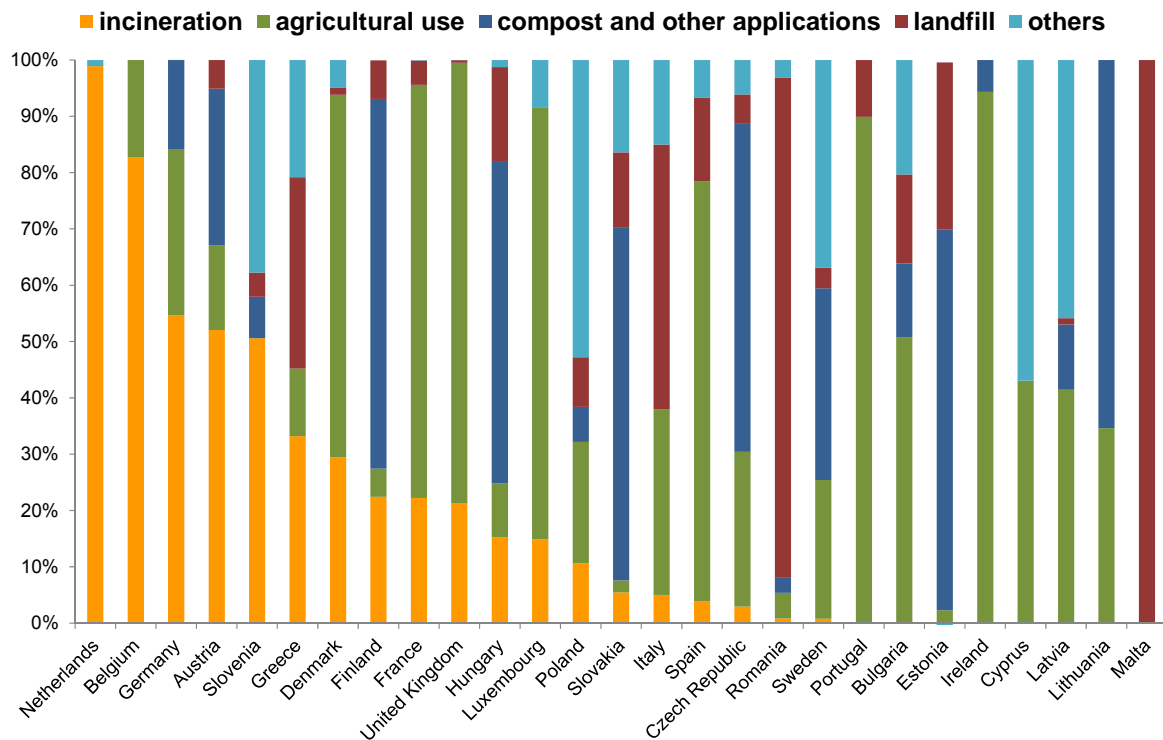


Figure 31: Routes for sewage sludge disposal in the year 2012 in EU-27 (year 2010 data for Italy) (data available from Eurostat).

11846
11847
11848
11849

11850 In 2012, about **23% of the sludge is incinerated** in Europe (2.3 Mt dry sludge yr⁻¹),
11851 meanwhile **49%** (5.0 Mt dry sludge yr⁻¹) of the sludge is directly **returned to land for**
11852 **agricultural use** (Eurostat, 2012). Nevertheless, large differences in the proportional
11853 contribution of sewage sludge disposal routes exist among Member States for the fate of
11854 sewage sludge (Figure 31). Countries with a high population and animal density, and strict
11855 restrictions on landfilling, incinerate high proportions of their sewage sludge (e.g.
11856 Netherlands, Belgium, Germany and Austria) (Figure 31). Other Member States (Denmark,
11857 France, United Kingdom, Luxembourg, Spain, and Portugal) apply large amounts of the
11858 sewage sludge directly on land. Finally, Member States as Greece, Italy, Romania, Estonia
11859 and Malta landfill significant amounts of sludge (Figure 31).

11860

11861 Although the Sewage Sludge Directive (91/271/EEC) has established the conditions for safe
11862 use of sludge on agricultural land, but concerns exist, notably as regards the maximum limit
11863 values for cadmium and other contaminants are considered to be too high (European
11864 Commission, 2013a). Sixteen Member States have adopted more stringent standards than
11865 those set out in the Directive. **Therefore, direct sewage sludge application on agricultural**
11866 **land is progressively decreasing in Europe.** Harmonisation of higher quality standards
11867 would encourage greater confidence amongst farmers and consumers on the safe use of
11868 sludge in the EU. In order to encourage more efficient resource use in the future, these issues
11869 will need to be addressed so that standards for sewage sludge-derived products inspire
11870 confidence right across the chain of end users: namely farmers, retailers and ultimately
11871 consumers.

11872
11873 A **detailed description of the sewage sludge mono-incineration process** is given in
11874 Donatello and Cheeseman (2013). Sludge and hot compressed air (ca. 500–600°C) are fed to
11875 the combustion chamber. The sand bed temperature is typically 750°C and the overhead
11876 freeboard zone at 800–900°C. Temperatures can be finely controlled by the injection of water
11877 or liquefied gas oil. The sand bed acts as a “thermal fly wheel” and helps stabilise
11878 temperature fluctuations in the incinerator. Particle residence times in the combustion
11879 chamber are typically only 1–2 s and during this time water is evaporated, volatile metals
11880 vapourise and organic compounds are combusted completely to gases, either directly or via
11881 the formation of an intermediate char. The remaining inorganic material is carried out of the
11882 chamber as fine particulates with the exhaust gases. During incineration, **most of the N is**
11883 **released into the atmosphere while much of the P and K, and heavy metals are retained**
11884 **in the fly ash** (Deydier et al., 2005a; Zheng et al., 2013). Sulphur (S) is retained in the air
11885 pollution system, and can possibly be recycled as Na₂SO₄ from the alkaline scrubber. The fly
11886 ash is generally removed by bag filters, electrostatic precipitators or cyclones after passing
11887 through a heat exchanger. The flue gas is then treated using a wet scrubber with acid, alkali
11888 and possibly activated carbon dosing to comply with emission limits, as required by
11889 Industrial Emissions Directive (2010/75/EU). The scrubbing process produces an additional
11890 waste sludge, which is dewatered and normally disposed of in hazardous waste landfill.
11891 **Mono-incineration produces fly ash with high P contents (2-12%).** The average P content
11892 in sewage sludge ashes is 10.8 % in the Netherlands (CBS Statistics Netherlands, 2015) and
11893 8.9% in Germany (Krüger and Adam, 2015). In Germany, about half of the generated
11894 municipal sewage sludge is currently already processed within mono-incineration plants
11895 (Adam et al., 2015).
11896
11897 Sludge can also be **co-incinerated with municipal solid waste or industrial waste** in
11898 existing general purpose incineration plants that produce energy. The ash produced has a
11899 lower P concentration (e.g. on average 4.9% in Germany), and potentially a higher amount of
11900 impurities and contaminants.
11901
11902 In the EU-28, it is estimated that annually generated municipal waste waters contain **2.3-3.1**
11903 **Mt of N and around 0.50 Mt of P** (Sutton et al., 2011; Leip et al., 2014; van Dijk et al.,
11904 2016). About 227 kt P yr⁻¹ ends up in communal sewage sludge, and an additional 74 kt P yr⁻¹
11905 is lost as effluents from urban and decentralised waste water treatment plants. Untreated and
11906 uncollected waste waters sum up a total of about 59 kt P yr⁻¹. The remainder 140 kt P is
11907 contained in sewage sludge that is directly applied on agricultural land.
11908
11909 **STRUBIAS materials can be produced from (processed) wastewaters and sludges at**
11910 **municipal waste water treatments plants, as well from the incinerated sewage sludges**
11911 (see section 15).
11912
11913

11914 **14.6 Food processing industry residues other than animal by-products**

11915 Three different food processing sectors, other than the meat and fish industry, have been
11916 identified that show a discernible potential for P-recovery. Losses from food processing
11917 industries correspond to **44 kt P and 157 kt N per year** (Sutton et al., 2011; van Dijk et al.,
11918 2016). The share of P can be split up in losses in solid forms (e.g. sludges: 36 kt P) and losses
11919 as wastewaters (9.2 kt P). Currently, **P is recovered in the form of precipitated phosphate**
11920 **salts & derivates from the wastewaters from the potato and dairy industry**. Given that
11921 the sludges are characterised by high moisture but low P contents, supplementary
11922 STRUBIAS recovery from the sludges will most likely be in the form of precipitated
11923 phosphate salts & derivates, eventually after anaerobic digestion of the residues.

11924

11925 14.6.1 Potato crisps and chips industry

11926 Two of the main potato-based products are crisps and chips. The manufacturing of both
11927 essentially consists of peeling the raw material, slicing to an appropriate size and blanching,
11928 followed by frying to achieve the desired sensory properties. To prevent colourisation of the
11929 potato, a substance **called pyrophosphate** ($\text{Na}_2\text{H}_2\text{P}_2\text{O}_7$) is used to complex iron (Fe^{2+}). In
11930 this way sodium acid pyrophosphate prevents that iron in the potato reacts with chlorogenic
11931 acid during the heating processes (Rossell, 2001). The oxidation of the Fe^{2+} -chlorogenic acid
11932 complex by oxygen from the air would otherwise result into a grayish-colored substance that
11933 causes the after-cooking gray discoloration (Rossell, 2001). This is a very significant P-
11934 source in the waste water from potato processing installations. The waste water have a typical
11935 PO_4^{3-}P concentration of about 200 mg L^{-1} (European Commission, 2017b). **Average P-**
11936 **recovery efficiencies of 80–90% have been reported**. The cost of recovery is lower
11937 compared to phosphorus removal by chemical precipitation using, for example, FeCl_3
11938 (European Commission, 2017b). At present, more than 4 t of struvite per year is produced by
11939 the potato-processing in Italy, Belgium and the Netherlands (STRUBIAS sub-group
11940 comments; Dewaele, 2015).

11941

11942 14.6.2 Waste waters from the dairy, brewery, grain, fruit and vegetable industry

11943 Plant-derived waste arises from cultivated grains, fruits, and vegetables. A determined
11944 fraction of the plant materials are not edible and are thus treated as agrowaste. Spillage,
11945 spoilage and storage loss or outgrading, pest infestation, and loss of quality during storage
11946 can be the main reasons for loss of agricultural produce after harvesting. Additional waste is
11947 generated during processing stages such as peeling, washing, boiling, and slicing. Finally,
11948 byproducts such as pomace and spent grain are formed, and wastes from plant shutdowns or
11949 washing occur (de las Fuentes et al., 2003).

11950

11951 **Water consumption** is one of the key environmental issues for the food processing sector.
11952 Dairy and brewery industries are major water consumers, producing waste waters that are
11953 generally not dangerous but are heavily loaded with organic matter (Gendebien et al., 2001).
11954 The composition of the effluents is quite variable in composition. Compared to effluents from

11955 the chips and crisp industry, dairy, brewery and starch manufacturing industries have –
11956 generally speaking - less P in their waste waters.

11957

11958 A significant proportion of the waste waters are originating from the washing of installations.

11959 Typical **cleaning agents** used in the food-processing industry sector are (European
11960 commission, 2006a):

- 11961 • alkalis, e.g. sodium and potassium hydroxide, metasilicate, sodium carbonate;
- 11962 • acids, e.g. nitric acid, phosphoric acid, citric acid, gluconic acid;
- 11963 • pre-prepared cleaning agents containing chelating agents such as EDTA, NTA,
11964 phosphates, polyphosphates, phosphonates or surface-active agents;
- 11965 • oxidising and non-oxidising biocides.

11966 The use of chelating agents and biocides may hamper nutrient recovery as the contaminants
11967 may be transferred to the recovered material.

11968

11969 Many **dairies** use large amounts of water, mainly for cleaning. The PO_4^{3-}P concentration in
11970 the waste water varies between 20 and 200 mg L^{-1} (European commission, 2006a). Many
11971 dairies have built their own effluent treatment plant and produce large amounts of sludges
11972 rich in P and organic matter. Humana Milchunion E.G. has installed a struvite reactor to
11973 recover P from dairy wastewater effluents (PO_4^{3-}P concentration in the waste water: 60 – 65
11974 mg P L^{-1} ; P-recovery efficiency of about 75%).

11975 In the **brewery**, waste water from the anaerobic reactor is driven to a reservoir where it is
11976 mixed with aerobic sludge (from the second sedimentation) and with untreated neutralised
11977 waste water (taken before anaerobic digestion). The PO_4^{3-}P concentration in the waste water
11978 varies between 0 and 200 mg L^{-1} (Gendebien et al., 2001). All these flows are recirculating
11979 and, in these conditions, the aerobic sludge encourages the growth of P-assimilating bacteria.
11980 Phosphorus could then be recovered after the bacterial release of orthophosphates.

11981 **Sugar mills** produce wastewater, emissions and solid waste from plant matter and sludge
11982 washed from the sugar beet (Hess et al., 2014). Sugar beet is 75% water, and the extraction
11983 process, by definition, aims to release a high proportion of water contained in the beets. The
11984 technique applied for sugar extraction from plant tissues has an impact on the volumes of
11985 water used (consumed and polluted) to produce sugar (Bio Intelligence Service -
11986 Umweltbundesamt - AEA, 2010). Considering the high nutrient contents of the sugar beet,
11987 the waste generated during the sugar beet processing is also rich in N and P (Buckwell and
11988 Nadeu, 2016). Gendebien et al. (2001) indicated, for instance, effluent P concentrations of >
11989 100 mg P L^{-1} .

11990

11991 Moreover, **materials from other food industry sectors can be used for the production of**
11992 **STRUBIAS materials, mostly thermal oxidation materials and pyrolysis materials of**
11993 **lower P-content.**

11994

11995

11996 **14.7 Chemical industry waste waters**

11997 The EU chemical industry sector provides a significant contribution to the EU economy. It is
11998 one of its most international and competitive industries, connected to a wide field of
11999 processing and manufacturing activities (European commission, 2014). **Specific chemical**
12000 **industry subsectors are responsible for the most significant emissions of macronutrients**
12001 **to water, especially P** (E-PRTR, 2013; European commission, 2014). Emissions of P to
12002 water by the chemical industry sector equal a total of **10.3 kt P** for the year 2010. The
12003 dominant contribution originates from **manufacture and formulation of pharmaceutical**
12004 **products** (9.41 kt P), with only a minor share from other chemical industries such as basic
12005 organic chemicals (0.45 kt P), basic inorganic chemical (0.32 kt P) and fertilisers (0.12 kt P)
12006 (E-PRTR, 2013; European commission, 2014).

12007
12008 Pharmaceuticals are produced using synthesis or fermentation. Organic wastes produced in
12009 the pharmaceutical industry are mainly **biomass** (cells from the fermentation process),
12010 **synthesis residues, alcohol and organic solvents** from the cleaning process, product
12011 residues and dust from reprocessing (Gendebien et al., 2001). Care has to be taken where
12012 residues originate from the pharmaceutical industry as it is very **difficult to fully remove**
12013 **traces of the pharmaceutical end product and hazardous solvents from the waste**
12014 **waters**. Aqueous wastes from the manufacture, formulation, supply and use (MFSU) of
12015 pharmaceuticals is classified as hazardous waste according to the European List of Waste
12016 pursuant to Directive 2008/98/EC.

12017
12018 At present, Genzyme bvba makes use of a struvite reactor for P-recovery in the form of
12019 precipitated phosphate salts & derivatives from their pharmaceuticals production plant in Geel,
12020 Belgium. The P-rich wastewaters (55 mg PO₄³⁻-P) are used for the production of 220 kg of
12021 struvite (Dewaele, 2015).

12022

12023

12024 **14.8 Iron and steel industry residues**

12025 **Blast furnace slag** is a by-product of the manufacture of iron by thermochemical reduction in
12026 a blast furnace. It is formed in a continuous process by the fusion of limestone (and/or
12027 dolomite) and other fluxes with the residues from the carbon source and non-metallic
12028 components of the iron ore. Oil, tar, natural gas, powdered coal and oxygen can also be
12029 injected into the furnace to combine with the coke to release additional energy which is
12030 necessary to increase productivity. Silicate and aluminate impurities in the ore and coke are
12031 chemically bound to lime (CaO), and then removed as a molten slag with a complex Ca-Mg-
12032 Al-silicate composition. Blast furnace slag is generated at temperatures above 1500°C.
12033 Dependent on the way of cooling of the liquid slag it can be distinguished between crystalline
12034 air-cooled blast furnace slag and glassy granulated blast furnace slag.

12035

12036 Steelmaking slags are residues of processing molten iron into a specific type or grade of steel
12037 (Reijonen, 2017). Today there are two major commercial processes for making steel, namely
12038 basic oxygen steelmaking, which has liquid pig-iron from the blast furnace and lower amount

12039 of scrap steel as the main feed materials, and electric arc furnace steelmaking, which uses
12040 scrap steel or direct reduced iron as the main feed materials.

12041

12042 **Basic oxygen furnace slag** is formed during the conversion of liquid iron (hot metal) into
12043 crude steel during a batch process in a basic oxygen furnace. The slag is generated by the
12044 addition of fluxes, such as limestone and/or dolomite, during blowing oxygen into the melt.
12045 Due to the oxidising conditions, some elements (like Fe and Mn) are partly oxidised and
12046 contribute to the formation of the slag. Furthermore some components are either oxidised to
12047 gas (like carbon) or are chemically bound in the slag (like silicon or phosphorus). The liquid
12048 slag which has tapping temperatures of around 1600°C is air-cooled under controlled
12049 conditions in pits forming crystalline slag. The main components of a basic oxygen furnace
12050 slag are complex Ca-Mg-Fe-Mn-silicates.

12051

12052 **Electric arc furnace slag** is produced when scrap metal and fluxes are oxidized by the use of
12053 an electric current. Chemical energy is supplied via several sources including oxy-fuel
12054 burners and oxygen injections. Oxy-fuel burners combust natural gas using oxygen or a blend
12055 of oxygen and air. In some operations, oxygen is injected via a consumable pipe lance to
12056 "cut" the scrap. The oxygen reacts with the hot scrap and burns iron to produce intense heat
12057 for cutting the scrap. Once a molten pool of steel is generated in the furnace, oxygen can be
12058 lanced directly into the bath. This oxygen will react with several components in the bath
12059 including, aluminum, silicon, manganese, phosphorus, carbon and iron. All of these reactions
12060 are exothermic and thus supply additional energy to aid in the melting of the scrap. The
12061 metallic oxides that are formed will end up in the slag. Electric arc furnace slags are
12062 crystalline materials with a complex Ca-Mg-Fe-Al-Mn-silicate composition.

12063

12064 Nowadays, basic oxygen steelmaking and electric arc furnaces account for virtually all steel
12065 production (Jewell and Kimball, 2014). On average the production of one tonne of steel
12066 results in 200 kg (via electric arc furnace) to 400 kg (via blast furnace and basic oxygen
12067 furnace) of residues. These include slags, dusts, sludges and other materials.

12068

12069 **Blast oxygen furnace slag** is formed in the basic oxygen converter during the conversion of
12070 pig iron into crude steel. In this process, molten metal from blast furnace is treated with
12071 oxygen to remove impurities via oxidation at 1400–1650 °C (Yildirim and Prezzi, 2011).
12072 Oxidation is followed by slag formation with burned lime. The principal components of both
12073 slags are silicates, aluminates and oxides of Ca, or to lesser extent of Mg (Waligora et al.,
12074 2010). **Granulated blast furnace slag** is formed in the smelting process of iron ore/pellets
12075 with coke and flux (limestone, burned lime or dolomite). Silicate and aluminate impurities in
12076 the ore and coke are chemically bound to lime (CaO), and then removed as a molten slag. Oil,
12077 tar, natural gas, powdered coal and oxygen can also be injected into the furnace to combine
12078 with the coke to release additional energy which is necessary to increase productivity.

12079 **Electric arc furnace slag** is produced when scrap metal and fluxes are oxidized by the use of
12080 an electric current. Chemical energy is supplied via several sources including oxy-fuel
12081 burners and oxygen injections. Oxy-fuel burners combust natural gas using oxygen or a blend
12082 of oxygen and air. In some operations, oxygen is injected via a consumable pipe lance to

12083 "cut" the scrap. The oxygen reacts with the hot scrap and burns iron to produce intense heat
12084 for cutting the scrap. Once a molten pool of steel is generated in the furnace, oxygen can be
12085 lanced directly into the bath. This oxygen will react with several components in the bath
12086 including, aluminum, silicon, manganese, phosphorus, carbon and iron. All of these reactions
12087 are exothermic and thus supply additional energy to aid in the melting of the scrap. The
12088 metallic oxides that are formed will end up in the slag.

12089
12090 Slags that have undergone a **thermal oxidation at high temperatures** could be considered
12091 **as thermal oxidation materials & derivatives in the STRUBIAS project**. The sTRUBIAS
12092 sub-group indicated that at present, approximately 800 000 tonnes of these slags are used as
12093 **fertilising products within the EU, mostly in the form of liming materials and P-rich**
12094 **slags that are used as fertilisers.**

12095 12096 **14.9 Forest-based industry residues and green waste**

12097 14.9.1 Woody residues

12098 This category includes woody residues that originates from (1) **sidestreams produced by the**
12099 **woodworking industry** for instance harvest slash, sawmill sidestreams and shavings from
12100 timber yards, materials from chipboard and other timber processing, reclaimed timber from
12101 buildings, pallets and packing crates, (2) currently **uncollected forest residues** and (3) the
12102 processing of plant materials other than residues **from households waste** classified as food
12103 waste (including parks and garden waste).

12104
12105 The **total amounts of wood residues** that are available within the EU for posterior use are
12106 **estimated at about 120 Mt per year**, with future predictions remaining more or less at the
12107 same level (Searle and Malins, 2013). This number is the sum of following fractions:

- 12108 • According to Manteau (2012), **26 million tonnes of post-consumer wood** (i.e. wood
12109 products such as furniture that are discarded) was generated in 2010. Of this, 7.8
12110 million tonnes was recycled into other materials and 10.3 million tonnes was burned
12111 for energy in power plants or households. About 8 million tonnes was permanently
12112 disposed of or combusted without energy recovery.
- 12113 • Forests and other wooded land occupy over 44% of the EU's surface and represent 5%
12114 of the world's forests. In the last 50 years, both their area and the standing timber
12115 volume (growing stock) have continued to grow. Nowadays, they gain almost 700 000
12116 ha annually. According to Searle and Malins (2013), it was estimated that the total
12117 production of **forestry residues in the EU was 80.7 million tonnes** in 2011. Some
12118 forestry residues are currently collected, but according to ECF (European Climate
12119 Foundation, 2013), the current usage of forestry residues in the EU is only about 3%,
12120 with activities mainly occurring in Scandinavia. Similar to crop residues, a share of
12121 the forestry residues should remain on land to protect soil carbon and sustainable
12122 ecosystem functioning. To be conservative and to avoid other unintended
12123 consequences, Searle and Malins (2013) assumed that **50% removal of forestry**
12124 **residues may be sustainable** if combined with good management practices.

12125 Assuming these values, a total of about 40 million tonnes of uncollected forestry
12126 residues might potentially be available for nutrient recovery.

- 12127 • Presumably much of the 19.7 million tonnes of **household vegetal waste are garden**
12128 **clippings and other wood residues** (Searle and Malins, 2013).

12129

12130 Wood **treated** with preservative chemicals such as pentachlorophenol, lindane or copper
12131 chrome arsenate **may hinder its posterior use**, including recycling and energy recovery.

12132 **Untreated wood waste is a material with high organic matter content, but with a**

12133 **relatively low nutrient content**, both in terms of N (often < 1%) and P (~0.1%). Gendebien

12134 et al. (2001) indicated an average P content of 0.09%, but no numbers were given for N.

12135 Wood N/P contents vary between 10 and 28 (Mooshammer et al., 2014; Sardans and

12136 Peñuelas, 2015), for which we estimate assume an N content of 1.5%. The high C/N ratio

12137 makes it an unsuitable material for direct fertiliser applications as it will promote microbial N

12138 immobilization and thus reduce the N availability in the soil. It may, nevertheless, be used as

12139 a mulch to discourage weed growth and conserve moisture or as an aggregate for compost.

12140 The total nutrient content of forest residues can then be calculated by multiplying

12141 abovementioned numbers on forest residue availability with the assumed nutrient contents.

12142 Assuming an estimated moisture content of 25-50%, 900 – 1350 kt N and 54-81 kt P yr⁻¹.

12143 These numbers are generally in line with the estimated P-content of **76 kt P as estimated by**

12144 Van Dijk et al. (2016).

12145

12146 Bark and wood residues from wood handling can be combusted **for energy recovery**. Wood

12147 ash from bark boilers contains nutrients taken from the forest with the wood raw material and

12148 this ash can be suitable as a fertiliser as long as the wood originated metals like Cd meet

12149 harmonised requirements for fertilisers. Wood biomass is used for energy production in many

12150 EU Member States, especially in northern Europe. Wood combustion in Denmark, Finland

12151 and Sweden generate >290 kT of biomass ashes, whereas the combined wood ashes of

12152 Austria, Germany, Ireland, Italy and the Netherlands add another 300 kT of wood ashes (van

12153 Eijk et al., 2012). Assuming a P content of 0.1%, the **wood bottom and fly ashes in these**

12154 **European countries thus contain only 0.3 kT of P**. Moreover, competing uses (concrete

12155 industry, fill and ground remediation) exist for these biomass ashes (van Eijk et al., 2012).

12156

12157 Given their high carbon content, wood residues are mainly used for energy production, but

12158 the combustion residues are often applied on (forested) land in north European countries

12159 (Insam and Knapp, 2011). Wood material is currently also the **dominant input materials for**

12160 **the production of pyrolysis & gasification materials** that are used as soil improver (EBC,

12161 2012).

12162

12163 14.9.2 Pulp and paper industry

12164 For a complete overview of the processing of woody material and recovered materials, it is

12165 referred to the Best Available Techniques (BAT) Reference Document for the Production of

12166 Pulp, Paper and Board (European Commission, 2015a).

12167

12168 The production process used in papermaking depends on the stock used to generate the fibre
12169 (Gendebien et al., 2001). When virgin wood fibre is used to produce **paper**, the pulp creates
12170 liquid effluent and the **sludge** mainly contains lignin and cellulose. When waste paper is used
12171 in the process, de-inking and bleaching is required, and the de-inking sludge will contain
12172 chemical residues. The process of reusing fibre from recycled paper produces large amounts
12173 of sludge (1 tonne of sludge for every tonne of paper produced) (Gendebien et al., 2001). De-
12174 inking sludge will also contain high levels of carbon, calcium carbonate and, generally,
12175 aluminium silicate (Gendebien et al., 2001). Within the paper industry, the most economic
12176 choice for sludge disposal can determine the process used (Gendebien et al., 2001).

12177
12178 Pulp and paper primary sludge comprises cellulose fibre (40 to 60% of dry solids). De-inking
12179 primary sludges also contain printing inks and mineral components (40 to 60% dry solids:
12180 kaolin, talc, and **calcium carbonate**). The abundance of metals in the sludges has
12181 significantly decreased over the last decades due to stricter legislation on metal/metalloid
12182 contents of the ink. The P content of the pulp and paper industry sludges is however
12183 relatively low (0.3% P on average; Gendebien et al., 2001).

12184
12185 The **incineration of the sludges** from the dissimilar paper and cardboard producing and pulp
12186 processes is commonly applied in the sector. The use of auxiliary fuel may be necessary to
12187 maintain good burning conditions unless the sludge is mixed with bark and other wood waste
12188 material. Burning reduces the volume of waste and the **inorganic content remains as ash**. It
12189 is noted that specific effluents cannot be sent for incineration as a consequence of the use of
12190 certain chemicals (e.g. chlorine dioxide).

12191
12192 The **sector BAT conclusions** indicate that the recovery of energy by incinerating wastes and
12193 residues from the production of pulp and paper that have high organic content and calorific
12194 value is permitted on condition that the recycling or reuse of wastes and residues from the
12195 production of pulp and paper is not possible (European Commission, 2015a).

12196
12197 14.9.3 Emissions to water

12198 Liquid effluents contain material in colloidal or suspended forms and dissolved substances.
12199 With few exceptions (eucalyptus pulping), **the original levels of N and P are low and are**
12200 **added to biological waste water treatment plants to feed the biomass.**

12201
12202 14.9.4 Conclusion

12203 From an economic point of view, **the cost of harvest, transport, and processing is**
12204 **disproportional in relation to the P quantities that can be recovered.** Therefore, it is more
12205 likely that any P-recovery from **wood will be formed as part of cascades where synergies**
12206 **exist between the manufacturing of other products (energy, paper) and nutrient**
12207 **recovery.**

12208
12209

12210 **14.10 Municipal solid waste**

12211 About **258 Mt of municipal solid waste** (MSW) is produced yearly in the EU-27 (Eurostat,
12212 2016). The N and P of the biodegradable waste fractions mainly originate **food waste and**
12213 **woody residues**. Also some N could be present in textile materials. The biodegradable
12214 fraction represents on average 37% of all municipal solid waste, although the fraction varies
12215 widely between EU countries (European Commission, 2010b).

12216
12217 Municipal solid waste raises problems since it is a **mixture of materials that are**
12218 **heterogeneous in nature and not segregated**. The composition of MSW varies regionally,
12219 but usually contains a mixture of organic waste, paper and cardboard, textile waste, plastics,
12220 metals, glass and potentially some biomedical waste and hazardous (battery, nail polish
12221 bottles, insecticides) compounds (Sokka et al., 2004; Chandrappa and Das, 2012).

12222
12223 A MSW can undergo a **mechanical sorting** of the waste into a biodegradable material
12224 containing fraction and a non-biodegradable material containing fraction. In the latter case,
12225 nutrient recovery from the biodegradable fraction is possible through composting and
12226 anaerobic digestion.

12227
12228 In the alternative scenarios, the MSW is not separated and may either be **landfilled** (resulting
12229 in a complete loss of the material, including its nutrients) **or incinerated**.

12230
12231 **The ashes from MSW** generally contain relatively **low amounts of P**, with values of
12232 approximately 0.4% P (Kalmykova and Fedje, 2013).

12233

12234

12235 **14.11 Others**

12236 Abovementioned input material represent the overall share of the nutrients present in waste
12237 and have therefore the greatest potential for nutrient recovery options. **The STRUBIAS sub-**
12238 **group did not identify waste materials, industrial residues or biological materials other**
12239 **than those mentioned in sections 14.2 - 14.9.**

12240

12241 Nevertheless, other streams originating from secondary raw materials are not de facto
12242 excluded as STRUBIAS input materials. Based on detailed information provided from EU
12243 Member States, Gendebien et al. (2001) provides an excellent, though somewhat out-dated,
12244 overview of the mass amounts, nutrient contents and environmental concerns and health
12245 issues for numerous other waste streams that are currently spread on agricultural land:
12246 **tannery sludge, decarbonation sludge, inorganic waste from chemical industry, textile**
12247 **waste, wool scourers waste, waste lime from cement manufacture or gas processing,**
12248 **waste gypsum, waste from energy production and dredgings.**

12249

12250 It should be noted that some of these streams (e.g dredgings, waste lime, and waste gypsum)
12251 may **contain large amounts of biological contaminants and high amounts of heavy**
12252 **metals** that may potentially hinder nutrient recovery processes. Therefore, treatment may

12253 require a potentially large chemical and electrical demand in order to recover a relatively
12254 small amount of nutrients from the waste stream. Others streams may be suitable for use as
12255 such, in case they are low in contaminants identified.

12256

12257

12258 **14.12 Conclusion**

12259 Understanding the **complex flow of nutrients throughout the food and non-food**
12260 **production and consumption chains** in Europe is needed **to assess the feasibility and**
12261 **impact potential of different streams as input material** for fertilisers derived from
12262 secondary raw materials. The overview presented in this document builds further upon the
12263 information presented by the scientific community, multi-stakeholder research platforms,
12264 think tanks and international and non-governmental organizations (Sutton et al., 2011; Leip et
12265 al., 2014; Buckwell and Nadeu, 2016; van Dijk et al., 2016), complemented by own estimates
12266 as described in each of the input material sections.

12267

12268 STRUBIAS materials are currently produced from all listed input materials, but the
12269 deliberateness of nutrient recovery varies between the different materials. A nutrient recovery
12270 system can specifically be designed for nutrient recovery, with the aim:

- 12271 • to produce **plant nutrition materials from secondary raw materials**: all processes;
- 12272 • **to avoid the loss or spillage of nutrients into the environment**: manure, effluents
12273 and residues from municipal waste waters, food processing residues, residues from
12274 gelatin production process;
- 12275 • to **remove nutrients for improved functioning of biological waste water treatment**
12276 **plants**;

12277 Note that some STRUBIAS materials can be listed under different items because the
12278 production process can serve different goals and benefits at a time.

12279

12280 STRUBIAS materials can also be produced – with or without process adaptation - as a
12281 primary product or residue of a production process **aimed at the production of a different**
12282 **primary output**: energy, **clean water effluents**, poultry litter ashes, forest-based industry
12283 residues, iron and steel industry residues. In many occasions, STRUBIAS materials form part
12284 of a cascade that transforms secondary raw materials in a set of added value materials, and to
12285 reduce as such the burden on primary raw materials.

12286 **15 Production processes and techniques**

12287 The following section aims to give a general overview of different production processes and
12288 techniques of each of the three STRUBIAS material groups, as well as on the general
12289 principles applied in production processes. Note, however, that STRUBIAS materials are
12290 only recently becoming available on the market, and that there are many ongoing technical
12291 developments in the progressively emerging market sector. Therefore, the production
12292 processes are, by no means, exhaustive or complete.

12293

12294 **15.1 Precipitated phosphate salts & derivates**

12295 15.1.1 Waste water treatment plants

12296 In **conventional wastewater treatment** plants, **P** is mainly **eliminated** by **enhanced**
12297 **biological phosphorus removal (EBPR)** or by **chemical precipitation with metal salts**
12298 **(ChemP)** or a combination of both. With EBPR, microorganisms (P accumulating organisms,
12299 PAOs) incorporate P in a cell biomass compound called polyphosphate and the P is removed
12300 from the process by sludge wasting. Chemical precipitation with metal salts can remove the P
12301 to low levels in the effluent. The commonly used chemicals are aluminum (Al(III)), ferric
12302 (Fe(III)), ferrous (Fe(II)), and calcium (Ca(II)) ions. The direct use of P-rich sludge as a
12303 fertiliser is associated to an increasing number of concerns due to concerns related to
12304 pathogens, and uncertainties related to P bioavailability (Cox et al., 1997; Vaneeckhaute et
12305 al., 2016).

12306

12307 Phosphate salts can be recovered from **sludge liquor** and from **digested sludge** when the
12308 PO_4^{3-} precipitates together with Mg^{2+} or Ca^{2+} , possibly also trapping NH_4^+ and/or K^+ in the
12309 molecular structure. Struvite, the most commonly recovered phosphate salt, forms from
12310 equimolar quantities of Mg^{2+} , PO_4^{3-} and NH_4^+ implying that the efficiency of NH_4^+ removal
12311 is relatively low and the excess N remains in soluble form. In most sewage treatment
12312 applications **Mg is the limiting element**, for which it is added to the process as MgCl_2 or
12313 MgO . The formation of precipitates is strongly influenced by pH, hence if the feed stream
12314 does not have sufficient alkalinity, NaOH is added and/or CO_2 is stripped from the solution.
12315 More detailed information on the crystallization dynamics and kinetics for the struvite
12316 crystallization process is given in Le Corre et al. (2009).

12317

12318 Phosphorus recovery from sludge liquor and from digested sludge is limited to the amount of
12319 **soluble PO_4^{3-}** . For most waste water treatment plants, the latter is in the range of **5-20% of**
12320 **total P** load of the sludge under normal pH conditions (Jossa and Remy, 2015). P content of
12321 the solid phase can be substantially mobilized into the liquid phase (e.g through the **addition**
12322 **of volatile fatty acids, acidification, or thermal hydrolysis**) so that total P recovery rates of
12323 **up to 50%** are achievable.

12324

12325 **Precipitation in the form of phosphate salts without those pre-treatments** is essentially
12326 **applicable to those wastewater treatment plants where EBPR is used.** Here, the

12327 polyphosphates stored in the bacterial cells are partly released again under anaerobic
 12328 conditions, thereby significantly increasing the $\text{PO}_4^{3-}\text{-P}$ content in the sludge system to levels
 12329 that support P recovery. The P content in wastewater treatment plants with EBPR and
 12330 anaerobic digestion can be $75\text{--}300 \text{ mg L}^{-1} \text{ PO}_4^{3-}\text{-P}$ after the anaerobic digester (García et al.,
 12331 2012). **P-recovery processes that include** pre-treatment step are in principal able to deal
 12332 with sludge that had been subjected to chemical removal and coagulation with Al and Fe
 12333 salts. Nevertheless, additional chemical or energy demand may be required when sludges rich
 12334 in chemical coagulants are applied (Kabbe et al., 2015).

12335
 12336 **Four types of recovered phosphate forming processes** are considered: (I) from the sludge
 12337 liquor, (II) from the digested sludge, (III) downstream from the digested sludge after a pH
 12338 regulating treatment, (IV) upstream from the digested sludge with thermal hydrolysis. The 4
 12339 types differ in their P-recovery rate, sludge input materials that be used, and energy and
 12340 chemical demand (Table 26). For phosphate salt formation from the **liquor** (type I), the
 12341 **concentrated side streams** after the anaerobic treatment or the dewatering unit after
 12342 anaerobic digestion are the best options for P recovery. The implementation of a P-recovery
 12343 system **before the anaerobic digester** (type II and type IV) reduces uncontrolled P
 12344 precipitation in the anaerobic digester or post-digestion processes and enhances P recovery
 12345 (Marti et al., 2008; Martí et al., 2010). Downstream P recovery from the **sludge phase** can
 12346 include recovery from both the digester sludge before and after the dewatering unit.

12347
 12348 **Table 26: Overview of the principles and properties of production process for precipitated**
 12349 **phosphate salts at waste water treatment plants or downstream sludge processing plants.**

	type I	type II	type III
	P- precipitation from liquor after sludge dewatering	P-precipitation upstream from the sludge dewatering unit	P-precipitation downstream from the sludge after dewatering
implementation status	mostly operating, some piloting	operating or piloting	operating or piloting
input material	sludge liquor from EBPR	non-dewatered sludge	dewatered sludge
phosphorus recovery	low to moderate (~ 10-15%)	variable (~ 10% - 50%)	high (up to 50%)
chemical demand	low	low to moderate	high
energy demand	low	variable energy demand and energy recovery potential	high
increased sludge dewaterability	no	yes	no

12350
 12351 ○ Type I: P- precipitation from liquor after sludge dewatering. Recovered
 12352 phosphates, mostly struvites, can be formed **from the sludge liquor (i.e. reject**
 12353 **water) in mixed stirred tanks.** The *PHOSPAQ*® and *ANPHOS*® processes
 12354 operate in a single and two separate stirred tank reactors. An increase in pH (CO_2
 12355 stripping) and mixing are obtained via aeration, and MgO is added to the
 12356 wastewater. The *NuReSys*® process differs from the *ANPHOS*® process since it is

12357 operated in continuous mode instead of batch, at a lower residence time. Another
12358 difference is the use of a different Mg source ($MgCl_2$) and the addition of a 29%
12359 NaOH solution to the crystallization reactor. The *Struvia*® process relies on the
12360 use of a continuous stirred tank reactor with integrated solid/liquid separation by
12361 calming zone and lamellar packing or with additional lamella settler. Also the
12362 *Phorwater*® and *Prisa*® technologies rely on the struvite crystallization in a
12363 continuous liquid flow system. In the PHORWater® process the elutriation of the
12364 mixed sludge (primary and EBPR sludge) allows reducing the P load entering the
12365 anaerobic digester and achieving a high P concentration in the supernatant of the
12366 sludge thickener (Martí et al., 2010; Bouzas et al., 2016). In the *Ekobalans*®
12367 (pilot) plant, struvite precipitation is a simple, low-cost process which produces
12368 microcrystals that are separated out using hydrocyclones. The struvite
12369 microcrystals are then formulated into dry, regular granules in combination with
12370 $(NH_4)_2SO_4$ and K salts, to give a NPK fertiliser adapted to agricultural use. Some
12371 processes (*PhosphoGreen*®, *Naskeo*®, *Crystalactor*®, *Rephos*®, and *Ostara*
12372 *Pearl*®) apply a controlled chemical crystallization in a **fluidized bed reactor to**
12373 **form struvite from the sludge liquor**. Fluidised bed reactors contain a bed of
12374 granulated struvite or fine sand, which acts as a seed material for crystal growth to
12375 facilitate the nucleation and separate crystals from the liquid phase. The process
12376 has the advantage of allowing large phosphate salt pellets to be kept in suspension
12377 in the bottom of the reactor without washing out fine crystal nuclei from the top of
12378 the reactor.

12379 ○ Type II: P-precipitation upstream from the sludge dewatering unit. In this
12380 configuration, phosphate salts are precipitated upstream to the dewatering unit,
12381 providing the benefit that the sludge volume and dry matter content is reduced,
12382 thus decreasing the costs for dewatering. The *AirPrex*® precipitates salts **directly**
12383 **from the outflow stream from the anaerobic digester**. In the process, the
12384 digested sludge is led through a cylindrical reactor, with an inner cylindrical zone
12385 mixed by air upflow and a settling zone between this inner cylinder and the outer
12386 cylinder. Internal sludge recycling allows the crystals to grow, until they reach a
12387 size at which they can escape from the recycle flow and settle (Desmidt et al.,
12388 2015). The recovered phosphate is crystallised within the wet sludge and can
12389 therefore show some organic and inorganic impurities. Washing and gentle drying
12390 of the mineral crystals improves the quality and provides a marketable fertiliser
12391 product (Ewert et al., 2014). The typical P-recovery from such processes is
12392 currently around 10-20%. Hydrothermal hydrolysis at typical temperatures
12393 between 150-200°C or other pre-treatments can be applied on the raw sludges to
12394 increase the fraction of phosphates in solution and the methane production
12395 potential of the sludges, and thus further increasing the potential for P and energy
12396 recovery from the sludges (e.g. Pondus, Eliquo-Stulz, TerraNova Ultra). Also the
12397 Ostara's Pearl process can be combined with the Waste Activated Sludge
12398 STRIPping process WASSTRIP (Baur, 2009). Here, the raw sludges (primary,
12399 secondary and/or tertiary) are sent to the WASSTRIP reactor where P and Mg are

12400 released (stripped) by the micro-organisms as a consequence of endogenous
12401 respiration and fermentation. A subsequent solid-liquid separation process
12402 separates a Mg and P-rich stream that is sent directly to the struvite reactor, thus
12403 by-passing the anaerobic digester and dewatering unit. Hence, only the C-rich
12404 solid fraction from the material leaving the WASSTRIP reactor is further
12405 processed in the anaerobic digester and dewatered. The advantage of this process
12406 that those units have to process a smaller sludge volume, significantly reducing
12407 the capital and operating costs for anaerobic digestion and sludge dewatering.
12408 Finally, the CalPrex™ process includes an acid phase digester to provide a low-
12409 oxygen and low pH environment to facilitate the rapid release of orthophosphates
12410 in EBPR sludge. Also, the Struvex® process relies on pre-treatment techniques
12411 installed prior to the dewatering unit, possibly in combination with hydrolysis to
12412 recover P from EBPR and ChemP sludges. If such pre-treatment units are placed
12413 upstream from the dewatering unit, phosphate salts can be precipitated as struvites
12414 or calcium phosphates from the digested sludge and significant reductions in
12415 sludge volumes and P-recovery rates (up to 50%) can be achieved.

12416 ○ Type III: P-precipitation downstream from the sludge after dewatering. A **wet-**
12417 **chemical extraction process** to process **digested sludge from waste water**
12418 **treatment plants**. These processes can use sludges produced in biological
12419 (EBPR) and chemical (precipitation with metal salts) waste water treatment
12420 processes, although the chemical and energy demand varies for both types of
12421 sludges. In contrast to the processes of type II, these processes enable higher P
12422 recovery efficiencies recovery by transferring (dissolving) P fixed in the solid
12423 sludge phase into the aqueous phase.

12424 ▪ In the *Seaborne*® process (or Gifhorn process), nutrients are separated
12425 from the sewage sludge using a **wet-chemical process** and processed into
12426 a marketed fertiliser containing acceptable levels of heavy metals or
12427 organic pollutants (Muller et al., 2005; Desmidt et al., 2015). In the first
12428 process step, an **acidification** of the sludge occurs by the addition of
12429 H₂SO₄ in order to dissolve the solids and to release heavy metals and
12430 nutrients. In case the sludge input material originates from a plant that uses
12431 chemical precipitation, an additional precipitation step between extraction
12432 and dewatering by addition of Na₂S is introduced in order to avoid that Fe
12433 phosphate compounds with low plant availability are transferred to the
12434 nutrient product (Muller et al., 2005; Desmidt et al., 2015). The remaining
12435 solids are separated from the flow by using a centrifuge and filter system,
12436 and are then dried and directed to the sludge incineration. In the next
12437 treatment step, sulphuric digester gas is used to precipitate heavy metals
12438 from the effluent liquor. In the following process step the nutrients are
12439 recycled. Phosphate is precipitated majorly as struvite by the addition of
12440 NaOH, to obtain an alkaline pH-value, and MgO as precipitant, but
12441 significant amounts of calcium phosphates can be formed likewise.
12442 Finally, the surplus N is recovered by air stripping of ammonia. Around

- 12443 90% of the nutrients (P, N) could be recovered by the Seaborne process,
 12444 the P as struvite, the N for just under a third in struvite and the remainder
 12445 in $(\text{NH}_4)_2\text{SO}_4$ (Günther et al., 2007).
- 12446 ■ The **Stuttgarter® process** relies on the same principle of wet chemical
 12447 treatment but differs from the Seaborne process by the fact that it uses a
 12448 **chamber-filter-press for solid-liquid separation**, and that complexation
 12449 of heavy metal ions to avoid co-precipitation is achieved by dosing of
 12450 citric acid (Ewert et al., 2014). Here, the recovery product is mainly
 12451 struvite (ca. 95%) (Ewert et al., 2014).
 - 12452 ■ In the **ExtraPhos (Budenheim®) process** the sewage sludge/water
 12453 suspension is aerated with carbon dioxide under pressure of approx. 10
 12454 bar. With this treatment, carbon dioxide becomes carbonic acid in the
 12455 sewage liquor, the pH decreases to a value of between 4.5 and 5.5 and a
 12456 part of the phosphates bound to the sewage sludge matrix is dissolved. In
 12457 the following solid/liquid separation, the sewage sludge particles are
 12458 separated from the liquid phase using Ca-based coagulants. The end
 12459 material recovered is dicalcium phosphate.
 - 12460 ■ The **TerraNova® process** applies a thermal hydrolysis treatment on
 12461 downstream EBPR or ChemP sludges in order to achieve the leaching of
 12462 the phosphates from the sludge, after which these are precipitated using Ca
 12463 ions. The process is at present in a pilot stage.
 - 12464 ○ Type IV: upstream sludge hydrolysis. Instead of releasing phosphorus by
 12465 acidification from digested sludge by applying chemicals, **thermal hydrolysis** at
 12466 temperatures between 150-200°C could be applied on secondary sludge from
 12467 waste water treatment plants applying **EBPR**. This releases P to a soluble form so
 12468 that higher recovery rates can be achieved by phosphate precipitation, and also
 12469 improves CH_4 production. The digested sludge firstly is thickened and then
 12470 subjected to hydrolysis and digestion. Digested sludge has a very high water
 12471 absorbing capacity, greatly reducing the degree of dewatering in proportion to its
 12472 share. Through thermal hydrolysis in a pre-treatment step, poorly degradable
 12473 substrates such as proteins and polysaccharides are modified such that micro-
 12474 organisms can easily degrade them. Hence, by deploying this procedure prior to
 12475 primary sedimentation, the good degradability and dewaterability rates of the
 12476 sludge liquor is increased (Ewert et al., 2014). Processes include thermal
 12477 hydrolysis (e.g. *Cambi*, *Eliquo Stulz (LysoGest)*, *Exelys*) or thermo-chemical
 12478 hydrolysis (e.g. *Pondus*). Thermal hydrolysis of the digested sludge upstream of
 12479 primary sedimentation is then followed by P recovery from the fully digested
 12480 sludge (e.g. AirPrex® procedure) (Ewert et al., 2014).
- 12481 There are specific processes (PASCH®, P-bac (INOCRE)®) that produce **struvite from**
 12482 **ashes as input material**. These products will be described in section 15.2 (thermal oxidation
 12483 materials & derivatives).

12484

12485 15.1.2 Precipitation from other input materials

12486 **Most** of the **techniques** that recover P in the form of phosphate salts (struvite, dicalcium
12487 phosphates, or a mixture of Ca- and Mg-salts) are developed for **municipal wastewater**
12488 (Desmidt et al., 2015). P-recovery techniques based on precipitation techniques can apply in
12489 principle to all phosphate rich liquids or slurries. Therefore, the techniques can also be
12490 applied on phosphate-rich industrial waste water (e.g. potato industry, dairy industry, type I
12491 processes) and anaerobically digested biowaste and manure fractions (mostly type I
12492 applications). Also other organic C-rich materials such as manure and sludges from the food
12493 industry could be subject to P-recovery techniques that increase the recovery efficiency (type
12494 III and IV processes).

12495

12496 15.1.3 Deliberateness of the nutrient recovery

12497 The production processes can be **specifically developed** for the P-removal through the
12498 precipitation of Ca- or Mg-phosphate from phosphate rich waste water streams (often from
12499 the food processing industry). Mostly, the P-recovery installation is **an integral part of a**
12500 **larger installation** as often pre-treatment is required (e.g. EBPR, anaerobic digestion).

12501 The P-precipitation process may provide important **benefits for the simplicity of operation**
12502 **of biological waste water treatment plants** and associated economic returns, even without
12503 retailing the recovered phosphate salt as a fertiliser.

12504 ○ Phosphate salt producing processes of Type II and IV may **increase the**
12505 **dewaterability** of the sludge, and thus the associated costs of sludge disposal and
12506 chemical demand associated to traditional sludge dewatering options (e.g. addition
12507 of flocculation agents, acid and alkaline, etc.). At present, costs for sludge
12508 treatment and sludge disposal account for around 29% of the total expenses of the
12509 whole wastewater treatment processes, of which sludge dewatering accounts for
12510 16% (STRUBIAS sub-group comments). The divalent cation bridging theory
12511 states that flocculation, which is strongly linked to dewaterability, is driven by the
12512 ratio of divalent cation concentrations (Ca^{2+} , Mg^{2+}) over monovalent cations (Na^+ ,
12513 K^+ , NH_4^+ , etc.). Divalent cation creates bridges between particles whereas
12514 monovalent cations tend to deteriorate flock structures. Therefore, an improved
12515 dewaterability can be expected if the addition of magnesium divalent cations
12516 surpasses the effect of sodium hydroxide dosing. Marchi et al. (2015) indicated
12517 the importance of a proper tuning of chemical additions in order to achieve
12518 progressive dewatering.

12519 ○ Waste water treatment costs are also reduced by the lower maintenance costs due
12520 to the **avoided pipe clogging and abrasion of centrifuges**.

12521 ○ The **reduction of the P and N load of the sludge liquor** has a direct effect on the
12522 treatment capacity of the whole waste water treatment plant as well as a cost

12523 factor, since the removal of nutrients from the wastewater requires energy,
12524 chemicals and tank volume (Ewert et al., 2014).

12525 The presence of some other species present in the stream or the purposeful addition of
12526 specific chemicals may cause the (co-)formation of materials other than struvite (K-struvite,
12527 calcium hydroxyl apatite, vivianite, etc.).

12528

12529 **15.2 Thermal oxidation materials & derivates**

12530 Whether ashes as obtained after the thermal oxidation processes can be suitable for direct use
12531 as a fertilising material is dependent on (1) the elemental composition of the ashes, (2) the
12532 presence of metals and metalloids in the input materials, and (3) the availability of the plant
12533 nutrients present in the ashes.

12534

12535 15.2.1 Raw ashes and melting/sintering materials

12536 *15.2.1.1 Thermal oxidation technology*

12537 Ashes obtained from the combustion of organic materials (e.g. wood residues, poultry
12538 manure, meat and bone meal, animal bones, sewage sludge) are used directly as a
12539 multinutrient fertiliser and/or liming material in many different EU Member States. Available
12540 technologies for the combustion of such organic biomass include (van Eijk et al., 2012):

- 12541 • **Bubbling fluidized bed boilers (BFB)** are often preferred in small-scale applications,
12542 with fuels having low heat value and high moisture content. The bed is fluidised by
12543 means of an arrangement of nozzles at the bottom of the furnace which create turbulence
12544 that enhance the mixing of the fuel, increasing the boiler's efficiency by converting
12545 unburned C remaining to usable energy. The bed is usually formed by sand and with a
12546 small amount of fuel. Solids fluidization occurs when a gaseous stream (primary air)
12547 passes through a bed of solid particles at enough velocity (above the minimum
12548 fluidization velocity) to overcome the particles gravity force. Limestone might be added
12549 to the bed to eliminate sulphur and/or chlorine. BFB operation range is between the
12550 minimum fluidisation velocity and the entrainment velocity on which the bed particles
12551 would be dragged by the passing gas, being usually 1.2 m/s at full load. Combustion
12552 temperature is typically between 800 and 950°C, being 850°C a usual bed temperature.
- 12553 • **Circulating Fluidized Bed (CFB)** technology boilers are normally used in larger
12554 applications, being similar in basic concept to the BFB. CFB has enhanced flexibility
12555 over BFBs for firing multi-fuels with high moisture content and significantly higher
12556 efficiency up to 95%. CFB configuration includes solid separators that separate the
12557 entrained particles from the flue gas stream and recycles them to the lower furnace. The
12558 collected particles are returned to the furnace via the loop seal. The addition of the solid
12559 separators allows CFB technology to reach the higher values regarding efficiency and
12560 availability and provides fuel flexibility. The entrainment velocity is the limit point that
12561 defines the transition from a BFB to a CFB. The CFB operation range is fixed over that
12562 entrainment velocity. Beyond this velocity the bed material becomes entrained and the

12563 solids are distributed throughout the furnace with a gradually decreasing density from the
12564 bottom to the top of the furnace. Fluidizing velocity is higher than in a BFB and can be
12565 between 4.5-6.7 m/s.

12566 • Similar to BFB, **grate boilers** are used in units below 100 MWe and normally for
12567 industrial uses. Grate technology can burn a range of fuels wider than a BFB, but worse
12568 emissions and efficiency as BFB. Grate boiler provides very good performance burning
12569 low moisture and high alkalis content fuels. Grate can burn difficult fuels as straw,
12570 poultry litter, high alkaline agro crops that are more challenging to combust using
12571 BFB/CFB due to high agglomeration tendency.

12572 • Organic residues can also be heated to temperatures between 800°C and 1500°C to
12573 achieve a transformation of solid materials through **melting** (e.g. in a rotary kiln or cupola
12574 furnace). Melting occurs in a non-oxygen limiting environment, resulting in the formation
12575 of ashes and P-slugs. Due to the addition of carbonates, soda (Na_2CO_3) and quartz sand, it
12576 is possible to separate P from many other elements and to influence the crystal structure
12577 of the P containing slags (e.g. isomorphic substitution of PO_4^{3-} ionic group by SiO_2^{2-} or
12578 CO_3^{2-}) affecting the reactivity of the final product and therefore the plant P availability.
12579 Metals/metalloids are partially volatilised (Zn, Cd, Hg, F), partially remain in the metal
12580 fraction (e.g. Fe, Cu, Cr, Ni) or remain in the slags (see post-processing). Therefore, this
12581 process can be applied on non-combusted organic materials or as a post-processing step
12582 on combustion ashes to improve the material quality (see section 15.2.1).

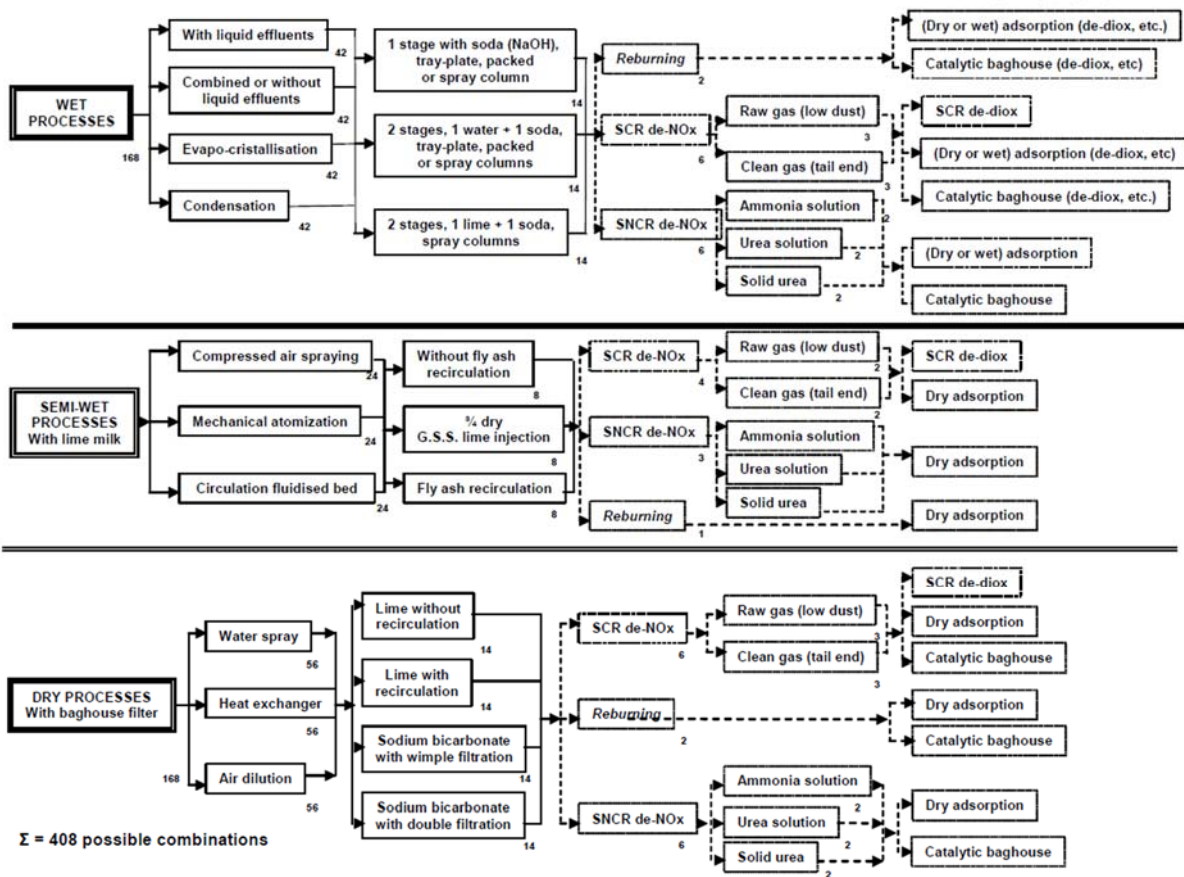
12583
12584 **Also steelmaking** processes make use of thermal oxidation melting processes in basic
12585 furnaces (converters) or electric arc furnace. Steel slag is produced as molten rock at around
12586 1650°C during the conversion of hot metal, sponge iron or steel scrap into crude steel. It
12587 consists of the oxidised accessory elements from hot metal, steel scrap and the other metallic
12588 substances, and of the slag-forming additives such as limestone, burnt lime or dolomite.
12589 Depending on how the crude steel is produced, a distinction is made between basic oxygen
12590 furnace slag from the basic oxygen furnace process, and electric arc furnace slag from the
12591 electric arc furnace process. A **blast furnace** is a type of metallurgical furnace that relies on
12592 thermal reduction for smelting to produce industrial metals. In a blast furnace, fuel, ores, and
12593 flux (limestone) are continuously supplied through the top of the furnace, while a hot blast of
12594 air (sometimes with oxygen enrichment) is blown into the lower section of the furnace
12595 through a series of pipes called tuyeres, so that the chemical reactions take place throughout
12596 the furnace as the material moves downward. An **electric arc furnace** is a furnace that heats
12597 charged material by means of an electric arc. Modern furnaces mount, however, oxygen-fuel
12598 burners in the sidewall and use them to provide chemical energy to the cold-spots, making the
12599 heating of the steel more uniform. Additional chemical energy is provided by injecting
12600 oxygen and carbon into the furnace. In specific metallurgic treatments under development
12601 (Bartsch et al., 2014), organic residues or their ashes are heated together with slags from
12602 basic oxygen furnaces to achieve a reconfiguration of the solid materials with the intention to
12603 improve the quality (e.g. increased plant availability through the formation of
12604 silicophosphates, reduced metal content) of the resulting P-rich fertilising material (see
12605 section 15.2.2).

12606

12607 15.2.1.2 Flue-gas treatment systems

12608 Flue-gas treatment (FGT) systems are constructed from a combination of individual process
 12609 units that together provide an overall treatment system for the flue-gases (European
 12610 Commission, 2006c). The individual components of a FGT system are combined to provide
 12611 **an effective overall system for the treatment of the pollutants that are found in the flue-**
 12612 **gases.** There are many individual components and designs, and they may be combined in
 12613 many ways. The diagram below shows an example of the options and their possible
 12614 combination (European Commission, 2006c). The FGT technology impacts upon the quality
 12615 of the combustion residues.

12616



12617

12618 **Figure 32: Overview of potential combinations of fluegas treatment systems (European**
 12619 **Commission, 2006c)**

12620

12621 15.2.2 Ash and slag derivates

12622 The use of **raw ashes** in agriculture can be associated to two major issues (Chandrajith and
 12623 Dissanayake, 2009; Herzel et al., 2016). At first, the conditions during thermal oxidation
 12624 induce a wide range of structural modifications that can **reduce the P-solubility and plant**
 12625 **availability.** Secondly, ashes produced of specific input materials (e.g. sewage sludge)
 12626 contain **high contents of metals/metalloids.** Hence, direct fertiliser use will return these

12627 potentially toxic elements into soil, water, air, food crops, and ultimately the human body
12628 tissues via the food chain.

12629 Ashes not suitable for direct recycling can be treated through two different routes that aim at
12630 P-recovery: (1) wet-chemical processes and (2) thermal processes (Table 27). Ashes from
12631 mono-incineration (i.e. not mixed with low-P wastes like industrial sludges, municipal solid
12632 refuse) are relevant for enhanced P-recovery strategies because of the high P content. These
12633 processes are especially relevant for P-rich ashes generated from sewage sludge, meat and
12634 bone meal, manure, etc. Phosphorus **recovery rates** from mono-incinerated ashes can reach
12635 **up to 90%** (Cornel and Schaum, 2009). For sewage sludge ashes, specific thermal as well as
12636 wet-chemical processes are able to process **ashes originating from EBPR as ChemP plants**
12637 (Kabbe et al., 2015).

12638 • Type I: wet-chemical processes

12639 ○ An almost complete **acidic dissolution of P at pH-values below 2** through the
12640 addition of chemicals is the principle of action to transform P into a bio-available
12641 form via wet-chemical extraction techniques. This process is unavoidably
12642 accompanied by a partial dissolution of metals or their compounds. The amount of
12643 dissolved metals depends on the composition of the raw input material (Fe- or Al-
12644 rich) as well as on the type and amount of the added acid (H₂SO₄ or HCl). Some
12645 processes effectively separate and remove toxic inorganic contaminants (e.g. Pb,
12646 Cd, Hg, etc.) in order to increase the quality of the P-recovery product.
12647 Additionally, it is desirable to separate especially Al and Fe as well, as these
12648 elements can reduce the quality and plant bio-availability of the recovery product.
12649 **For the removal of cations from the acidic leachate** different approaches are
12650 technically feasible to obtain satisfactory P-removal: sequential precipitation,
12651 liquid-liquid extraction, and ion exchange (Table 27).

12652 ■ P-rich ashes of specific characteristics can replace ground phosphate rock
12653 in the **acidulation process applied by the fertiliser industry**. The
12654 addition of sulphuric acid or nitric acid will result in the production of
12655 traditional P-fertilisers (e.g. DAP, MAP, TSP, nitrophosphate, etc.). The P-
12656 rich ashes should be consistent and the Fe/Al content should be relatively
12657 low in order to enable the partial substitution of phosphate rock by ashes in
12658 the process; typically ashes make up only 10-20% of the P in the mixture
12659 with the remaining P being added as phosphate rock (Langeveld and Ten
12660 Wolde, 2013). The metal removal rates are low as the P and other
12661 compounds in the ashes are dissolved in process, and end up together in
12662 the fertilising material.

12663 ■ The basis of the **SEPHOS process** is the **sequential precipitation** of P
12664 complexes with an alkaline treatment (Takahashi et al., 2001; Schaum,
12665 2007). The separation of dissolved P from heavy metals is achieved by
12666 raising the pH-value in the acidic leachate to induce the precipitation of
12667 Al-P while most heavy metals remain in solution (Takahashi et al., 2001).

12668 The heavy metal content of the Al-P product is then further decreased by
12669 precipitating heavy metals with sulphide (Schaum, 2007). Since the entire
12670 P has to be precipitated as Al-P, this process is especially suitable for Al-
12671 rich ashes coming from waste water treatment plants that employ chemical
12672 P-removal by addition of Al-salts. Since Al-P cannot be directly reused as
12673 fertiliser, the precipitated Al-P may be dissolved by alkaline treatment
12674 followed by precipitation as Ca-P. Altogether, this type of wet chemical P-
12675 recovery process results in a total chemical demand (at least 600 g H₂SO₄
12676 /kg ash and 300 g NaOH/kg ash) (Schaum, 2007). A P-recovery rate of
12677 90% is documented for the Sephos process. The **SESAL-Phos process**
12678 (Petzet et al., 2012) applies a softer acidification treatment (to a pH value
12679 of around 3 through HCl addition), followed by direct alkaline dissolution
12680 of P. In this case, only the low amounts of P dissolve, while most (heavy)
12681 metals remain in the ash. In a following process step, the dissolved P can
12682 be precipitated from the alkaline solution (pH > 13) as Ca-P with a very
12683 low impurity level, via the addition CaCl₂. The amount of Al-P directly
12684 leachable via alkaline treatment depends on both the Al content and the Ca
12685 content of the ashes (Schaum, 2007). In case of sewage sludge ash with
12686 very low Ca contents, a significant amount of P can be dissolved with low
12687 chemical demand, for which the process is more suitable for soft waters.
12688 Consequently, the SESAL-Phos process leads to a significantly reduced
12689 specific chemical demand, but the recovery rate of 74-78% is lower for the
12690 SEPHOS process (Petzet et al., 2012).

12691 The **Leachphos®** process is another **sequential process** with a leaching
12692 and a precipitation step to treat fly ash, amongst other from municipal
12693 solid waste incineration (Adam et al., 2015). The first step is leaching of
12694 sewage sludge ash with dilute H₂SO₄ that dissolves about 70-90 % of the P
12695 in the ashes, depending on acid concentration and reaction time. The
12696 leaching is followed by a solid/liquid separation step carried out on a
12697 vacuum belt filter or in a filter press. The leached sewage sludge ash filter
12698 cake is withdrawn from the process and must be disposed. The P
12699 containing liquid is pumped into a second stirred reactor, where dissolved
12700 P is precipitated by dosing of lime (CaO) or caustic soda (NaOH). A
12701 product with relatively high P content (13% P), considerable metal
12702 depletion and sufficient dewaterability is thereby produced (Adam et al.,
12703 2015). Depending on the precipitation agent, P is present in different
12704 mineral phases. If precipitated mainly with lime, P is present in the form of
12705 **calcium phosphate next to aluminium phosphate**. After precipitation
12706 and separation of the phosphorus product, the liquid waste stream requires
12707 additional treatment. Treatment consists of pH elevation to a pH of 9 by
12708 dosing of additional lime and of sulphidic precipitation of metals by an
12709 organosulphide precipitation agent (Adam et al., 2015). This is carried out
12710 in a third reactor followed by an additional solid/liquid separation step by a

12711 filter press. Thus the metals in the wastewater are removed almost
12712 completely. Thereafter, the pH in the waste water is adjusted to a pH of 7
12713 and is discharged either to a waste water treatment plant or directly to a
12714 receiving water body (Adam et al., 2015).

12715 ■ The **PASCH®** (Phosphorus recovery from Ash, developed at Aachen
12716 University) process utilizes **liquid-liquid extraction** for heavy metal and
12717 iron separation (Nieminen, 2010; Pinnekamp et al., 2010). Different acids
12718 were tested for P-dissolution by Montag and Pinnekamp (2009) with
12719 results of 25%, 50%, 80% and 90%, for NaOH, H₃PO₃, H₂SO₄ and HCl
12720 respectively. After the acid leaching, a lamella separator and filter separate
12721 the residue. The filtrate, containing phosphorus, calcium, and metal
12722 compounds, is treated in the extraction step with Alamine 336 and
12723 tributylphosphate (TBP). Reduction in the heavy metal concentrations is
12724 over 95% and iron over 99%. The final step precipitates the phosphate as
12725 calcium phosphate or struvite depending on precipitation chemical (i.e.
12726 lime or magnesium compounds).

12727 ■ The **BioCon® process** recovers P as H₃PO₄ from sewage sludge ashes
12728 (Balmér et al., 2002; Nieminen, 2010). The entire process consists of three
12729 phases: sludge drying, sludge incineration, and recovery unit with **ion**
12730 **exchangers**. The first step of the recovery process dissolves the P and
12731 heavy metal contents with H₂SO₄ at a pH value of 1 (Berg and Schaum,
12732 2005; Herrman, 2009). The solution passes through a series of ion
12733 exchangers. The first exchanger is cationic, separating Fe³⁺ ions. It is
12734 regenerated with HCl producing FeCl₃. The following exchanger is
12735 anionic, collecting K⁺ ions, and after regeneration with H₂SO₄ produces
12736 KHSO₄. In this step, NaOH is used for both pH adjustment and
12737 regeneration (Hultman et al., 2001). The final exchanger collects
12738 phosphates. Regeneration with HCl produces a stream of H₃PO₄ (Lundin et
12739 al., 2004). It should be emphasized that H₃PO₄ has no soil fertilising
12740 properties on its own; it is an intermediate in the production process of
12741 mineral P-fertilisers.

12742 ■ Additionally, there are different patented multi-modular approaches of
12743 which the process detail are kept confidential. The **EcoPhos®** process is
12744 already implemented at full-scale and relies on a multi-step approach to
12745 valorise low grade phosphate rock and also P-rich ashes to high quality
12746 market products as H₃PO₄ or dicalcium phosphate (DCP) (EcoPhos, 2016).
12747 First step is the leaching of the ash with HCl. Undergoing different
12748 modules (including ion exchange resins) which are kept confidential, a
12749 purified H₃PO₄ for fertiliser or food and feed industry is produced. At the
12750 same time most of the produced residues are sellable products as CaCl₂,
12751 gypsum, silicate as well as iron- and aluminum chlorides. With the
12752 **TetraPhos®** process, Remondis developed and implemented a similar

12753 approach in pilot scale (Hamburg) using H_3PO_4 instead of HCl to the leach
12754 the ash, and ending up with H_3PO_4 as a final product (Remondis Aqua,
12755 2016). A full-scale operational TetraPhos plant at the Hamburg waste
12756 water treatment plant will be opened in 2019. Also in the acid leaching
12757 **RecoPhos®** process (Weigand et al., 2013; RecoPhos, 2016), the plant-
12758 available phosphate fraction is increased by reacting the sewage sludge ash
12759 with H_3PO_4 . Thereby, the primary minerals are transformed into soluble
12760 calcium and magnesium dihydrogen phosphate, the primary nutrient
12761 components of the RecoPhos P 38 fertiliser. The piloting **Edask process**
12762 relies on semi-permeable membranes, under the influence of an electric
12763 potential, to separate phosphate ions (electrodialysis) (Thornberg, 2015).
12764 The P-recovery end product is H_3PO_4 . The **EasyMining Ash2Phos** relies
12765 on similar principles, including the acidulation of the ashes, followed by
12766 the separation of elements and removal of metals. Also here, the process
12767 produces various added value materials, including P-fertilisers, ferric and
12768 aluminium hydroxide. The process consists of several successive chemical
12769 reactions undertaken in room temperature, and can also use sludge ashes
12770 with lower P content than from mono-incineration. The heavy metals are
12771 separated as sulfide precipitate for disposal which will be disposed.
12772 **Phos4life** is a process for P recovery process from sewage sludge
12773 incineration ash, for which development is led by Zurich Kanton (AWEL)
12774 and ZAR (Zentrum für nachhaltige Abfall- und Ressourcennutzung. The
12775 process developed together with Técnicas Reunidas and successfully tested
12776 under micro-pilot plant operation in Madrid uses sulphuric acid (at 96%)
12777 to solubilise P and other elements in the ash, then hydrochloric acid and
12778 solvent extraction to separate phosphorus acid from iron chloride solution
12779 and heavy metals. The full scale process is planned to treat 30 000 t/year
12780 of sewage sludge incineration ashes, to produce 11 000 t/year of 74%
12781 phosphoric acid (after concentration using steam), 34 000 t/y of 40% iron
12782 chloride solution for recycling as coagulant agent in waste water treatment
12783 plants and 42 000 t/y of a residue which can be used by the cement
12784 industry. Heavy metal contaminants are nearly completely (>85%)
12785 transferred to a metal concentrate for metal recycling. The initial test
12786 results show the following recovering rates of the total potential in the
12787 SSIA: Phosphorus >95% (as H_3PO_4); iron: >90% (as iron-chloride
12788 solution).

- 12789
- 12790 ○ The **P-bac process®** offers selective recovery of P from sludge ash, bed ash and
12791 contaminated soils via a biotechnological route (Inocre Biotech, 2016). The P-bac
12792 process combines efficient and selective phosphate recovery with **bioleaching** and
12793 therefore is especially suitable for solids with high content of heavy metals. The
12794 selective recovery of phosphate with the P-bac process is realised in two phases.
12795 The first step is based on the “bioleaching principle”, which is applied worldwide
for the exploitation of metals (e.g. Cu, Zn, U, etc.) in the mining industry. By

12796 **microbial generation of H₂SO₄**, phosphate derivates and metals/metalloids are
12797 dissolved within few hours. The remaining solid matter is separated from the
12798 liquid matter and can be disposed for reduced costs. The phosphate-enriched
12799 biomass subsequently is separated from the liquid phase and can be precipitated as
12800 struvite after anaerobic dissolution. Up to 90% of the original phosphate can be
12801 recovered with the P-bac process.

12802 • Type II: Thermal processes

12803 ○ Nutrients can be recovered from ashes by high temperature treatments (Table 27).
12804 Processes were developed that transfer P into a metallurgical slag by reductive
12805 smelting at very high temperature temperatures in a shaft furnace (Scheidig, 2009)
12806 or that reduce P to elemental P that is separated via the gas phase in an inductively
12807 heated shaft furnace (Schönberg et al., 2014). The general principle is that volatile
12808 heavy metals such as Zn, Pb, Cd and Hg are separated from the product via the
12809 gas phase and further collected in the flue dust, and heavy metals with high
12810 boiling points such as Fe, Cu, Ni and Cr are separated in the form of a liquid alloy.

12811 ■ The **Mephrec** (Metallurgical Phosphorus Recovery) process was
12812 developed by the German company Ingitec. The process recovers P and
12813 energy from sludge and many other input materials of high calorific value
12814 such as meat and bone meal and/or wood ash. **Dried sludge** is briquetted
12815 with slag forming substances and coke. The mixture is treated in 2000°C
12816 transferring P into the mineral slag and heavy metals to liquid metal phase
12817 (Fe, Cu, Cr, Ni) or to gaseous phase (Hg, Cd, Pb, Zn). The silico
12818 phosphates containing slag is separated from metal phase after being
12819 tapped at 1450°C (Adam 2009). The final product contains, depending on
12820 the input materials used, 5-10% P with over 90% citric acid solubility. The
12821 P content can be varied by mixing sewage sludge with animal meal. The
12822 energy recovery from high-calorific raw off-gas can be realized either by
12823 directly combusting and using the heat in an Organic Rankine Cycle
12824 (ORC) process, or multi-stage gas cleaning and use in a combined heat and
12825 power (CHP) plant (Adam et al., 2015). With **sewage sludge ash**, the P
12826 content can reach up to 9%, but energy recovery is not possible.

12827 ■ The **FEhS/Salzgitter process** is a process to increase the P-content of
12828 liquid steel slag with phosphorus by blending it with ashes from the
12829 incineration of P-containing materials like sewage sludge and/or meat and
12830 bone meal. For the process, the slag is separated from the metal bath and
12831 transferred to an external slag pot, in which the cold ash is blown into the
12832 melt from the top together with oxygen or air. In the liquid slag the ash's
12833 phosphates are dissolved. After cooling and solidification, P₂O₅ is
12834 converted to plant-available Ca-Si-phosphate, similar to the phosphate in
12835 Thomas ground basic slag. The oxidation of residual metallic iron and
12836 bivalent iron in the steel slag produces the energy to maintain the

12837 necessary process temperatures of around 1500°C. The process has been
12838 tested in laboratory and in industrial scale.

12839 ▪ The melting process of the Japanese company **Kubota** has been developed
12840 for municipal solid waste, sewage sludge, landfill waste and ashes thereof.
12841 It enables the separation of P-slag through a temperature treatment of
12842 1250~1350°C. P is immobilized in the slag (~13% P) with a recovery rate
12843 of > 80% (Kubota, 2015).

12844 ○ The **ASH DEC** process (OutoTec) treats mono-incinerated sewage sludge ashes
12845 by a **sodium sulphate dosage and thermal treatment** below the melting point of
12846 sewage sludge ash in order to remove heavy metals making the product suitable
12847 for agricultural use by increasing the plant availability of P. An ASH DEC plant
12848 could stand alone and being operated as greenfield facility. For economic and
12849 ecological reasons it is planned to **combine the ASH DEC plant with mono-**
12850 **incineration**. The main advantage of the combination is the possibility of feeding
12851 hot ash directly from the mono-incineration plant to the ASH DEC facility, thus
12852 saving energy and equipment (Adam et al., 2015). In the first step, the ash is
12853 mixed with Na₂SO₄ in the thermally treated ash. Fresh Na₂SO₄ input could be
12854 partly replaced by recycled Na₂SO₄ from the mono-incineration. Alternatively
12855 (older process), MgCl₂ can be used for higher removal rates of heavy metals in the
12856 process, but this pathway results in reduced plant availability of the recovered
12857 phosphates. The dried sewage sludge (> 80 % dry matter) is charged in granules
12858 and is used as reducing agent in the ASH DEC process for the reduction of
12859 sulphate in the Na₂SO₄ and metal compounds. The thermal reaction is performed
12860 in a directly heated rotary kiln in counter flow having maximum temperatures of
12861 900-950°C. At this temperature, metals/metalloids react with the salts, become
12862 gaseous, and evaporate. After cooling, the P-rich ashes (P content of about 5-10%)
12863 are in the form of small granules and may be finished on site or in cooperation
12864 with a customer at the site to further increase agronomic values.

12865 ○ The **EuPhoRe®-Process** begins with application of additives into the dewatered
12866 or dried sewage sludge (Zepke and Klose, 2017). The following energy utilisation
12867 is characterised by volatile components degassing during a reduction period under
12868 application of medium temperature pyrolysis at 650 to 750 °C and is linked to an
12869 immediate subsequent post-combustion of the remaining fixed carbon at
12870 temperatures between 900 and 1.100 °C. During the first reductive process step,
12871 the heavy metal compounds contained in the sewage sludge are already partly
12872 transformed into the gas phase, although it is continued throughout the oxidative
12873 second process step, the carbon post-combustion. The metal compounds are being
12874 efficiency released and significantly improved through additive compounds of
12875 alkaline and/or earth alkali salts, such as MgCl₂. Magnesium remains into the
12876 phosphate-fertiliser and improves the plant availability. Chlorides take the reduced
12877 heavy metals into the gas stream. The generated phosphate fertiliser contains low-
12878 carbon (2 – 6% C) and the heavy metal compounds are to a large extent depleted

12879 (up to > 98%). The fertiliser contains nearly the entire phosphate load of the input
12880 material and after grinding as well as dust collection consequently allows for a
12881 direct agricultural utilisation. The energy content of dewatered sewage sludge
12882 (>25% dried matter) is sufficient for a complete thermic, self-sustaining
12883 production facility operation including the required drying process.

12884 ○ The **thermo-reductive RecoPhos** is a thermo-chemical process involving the
12885 fractioned extraction of P and heavy metals from sewage sludge, meat and bone
12886 meal and sewage sludge ashes at high temperatures under reducing conditions
12887 (Steppich, 2015). Thermal process uses **electro-magnetically induced heating** of
12888 a reactor bed consisting of coke or graphite. The induction heating systems serve
12889 alternating magnetic fields with high energy density and thus provide the reaction
12890 conditions required for the molten ash to react with the C. The reductive processes
12891 taking place within the reactor are based on the Whoëler reaction at a temperature
12892 of 1200-1400°C, which is the same chemical principle as the one used in the well-
12893 established submerged arc furnace, producing high grade elemental P as vapour,
12894 which can be either condensed and harvested as P₄ or subsequently oxidised to
12895 P₂O₅ or converted into H₃PO₄. The process enables the use of waste materials as
12896 heat sources, reducing agents or additives, including dried sewage sludge, foundry
12897 ash, waste salts or meat and bone meal, and low grade phosphate rock, with as
12898 advantage that in the RecoPhos process no pre-agglomeration of powder feedstock
12899 is needed and no dioxin emissions takes place. The Recophos process also claims
12900 to be able to recover P from raw materials containing significant levels of Fe from
12901 ChemP waste water treatment plants. The end product P₄ can then be used for
12902 production of flame retardants or lubrication additives while H₃PO₄ can then be
12903 further used for the production of inorganic P-fertilisers and other P-containing
12904 products. The thermo-reductive RecoPhos technology has been acquired by **ICL**
12905 (Israel Chemicals Ltd) for the industrial scale production of P-fertilisers derived
12906 from secondary raw materials.

12907 **Table 27: Overview of the principles and properties of P-recovery processes for thermal oxidation materials & derivatives.**

process name	status	route	P-separation	products	P-recovery	ref.
SEPHOS	unknown	wet-chemical	sequential precipitation	calcium phosphates	90%	(a)
SESAL-Phos	piloting at laboratory scale	wet-chemical	sequential precipitation	calcium phosphates	74-78%	(b)
LeachPhos	piloting/planned	wet-chemical	sequential precipitation	calcium phosphate, aluminium phosphate	70-90%	(c)
PASCH	unknown	wet-chemical	liquid-liquid extraction	calcium phosphate, struvite	90%	(d)
BioCon	unknown	wet-chemical	ion exchange	H ₃ PO ₄	60%	(e)
EcoPhos	piloting/constructing/operating	wet-chemical	confidential, including ion exchange	H ₃ PO ₄ , dicalciumphosphate	97%	(f)
TetraPhos	piloting	wet-chemical	confidential	H ₃ PO ₄	unknown	(g)
RecoPhos (P 38)	operating	wet-chemical	confidential	mostly calcium and magnesium phosphates	98%	(h)
Edask	piloting	wet-chemical	ion exchange (electrodialysis)	H ₃ PO ₄	unknown	(i)
P-bac	piloting	wet-chemical	bioleaching	struvite	90%	(j)
EasyMining Ash2Phos	piloting/constructing/operating	wet-chemical	unknown	MCP, DCP, MAP, DAP, SSP, etc.	>90%	
Phos4life	piloting/constructing/operating	wet-chemical	unknown	H ₃ PO ₄	>95%	
Mehprec	piloting/constructing/planned	thermal	not applicable	P-rich slag (5-10% P)	80%	(k)
Kubota	operating (Japan)	thermal	not applicable	P-rich slag (~13% P)	> 80%	(l)
Ash Dec	piloting/planned	thermal	not applicable	P-rich ashes (5-10% P)	98%	(m)
RecoPhos (ICL)	piloting/planned	thermal	not applicable	elemental P, P ₂ O ₅ and H ₃ PO ₄	89%	(n)
EuPhoRe	piloting/constructing/operating	thermal	not applicable	P-rich ashes (5-10% P)	98%	(o)

(a) Schaum et al., 2005; Schaum, 2007, (b) Petzet et al., 2012, (c) Adam et al., 2015, (d) Pinnekamp et al., 2010, (e) Balmer et al, 2002, (f) Adam et al., 2015; EcoPhos, 2016, (g) Remondis Aqua, 2016, (h) Weigand et al., 2013, RecoPhos, 2016, (i) Thornberg, 2015, (j) Inocre Biotech, 2016, (k) Adam et al., 2015, (l) Kubota, 2015, (m) Adam et al., 2015, (n) Steppich, 2015, (o) Zepke and Klose, 2017

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12909 15.2.3 Deliberateness of the nutrient recovery
12910 Thermal oxidation processes may be performed for sanitisation and volume reduction of
12911 waste-based materials. Synergies with energy recovery are possible for organic materials.
12912 The chemical or thermal post-incineration manufacturing processes target the **specific aim of**
12913 **P recovery and/or to improve material properties**. Finally, P-slags from the steel industry
12914 are produced as a residue from the steelmaking industry.

12915

12916 **15.3 Pyrolysis & gasification materials**

12917 15.3.1 Pyrolysis spectrum production techniques

12918 Pyrolysis spectrum techniques take place in an oxygen-deficit environment or with a
12919 controlled amount of oxygen and/or steam that limit the chemical reactions that transform
12920 input materials into chars. The extent to which pyrolysis & gasification materials burn
12921 depends on the ratio between the number of moles of oxygen admitted in the reactor and the
12922 moles of oxygen required for complete combustion. The less oxygen present in the reactor,
12923 the more solid pyrolysis material is produced. There are several available thermochemical
12924 technologies that operate in an oxygen-limited environment:

12925 • **Hydrothermal carbonisation** involves treatment in a closed system at moderate
12926 temperatures (~ 180°C - 300°C) and a pressure of approximately 10-30 bar over an
12927 aqueous solution of biomass for several hours (2h-10h), resulting in the production of
12928 char-type like materials as residues.

12929 • **The pyrolysis** process produces three different products that depend on the
12930 technology used, namely **biochar** (solid), **syngas** (non-condensable gases), and **bio-**
12931 **oil** (condensable liquid residue). The thermochemical decomposition of the organic
12932 materials takes place by heating in an oxygen-deficient environment at moderate to
12933 high temperatures (~ 300°C - 700°C). Pyrolysis systems use kilns or retorts, and
12934 exclude oxygen while allowing the pyrolysis gases, or “syngas” to escape and be
12935 captured for combustion.

12936 • **Gasification** is a process that converts organic feedstocks into carbon monoxide,
12937 hydrogen and carbon dioxide. The material is treated at high temperatures (> 700°C),
12938 with a controlled amount of oxygen and/or steam. Gasification generally produces
12939 less solid materials compared to pyrolysis, because some oxygen is intentionally
12940 introduced in the system.

12941 For simplicity, pyrolysis & gasification materials will refer to all three techniques as the
12942 critical factor for this CMC is that the chemical reactions that transform input materials are
12943 limited by the amount of oxygen and/or steam.

12944

12945 There are a number of different reactor configurations that can achieve this including ablative
12946 systems, fluidised beds, stirred or moving beds and vacuum pyrolysis systems. For a more
12947 detailed description, it is referred to Venderbosch and Prins (2010).

12948
12949 Pyrolysis can be an **endothermic or exothermic reaction** depending on the reactor
12950 temperature and the moisture content of the input materials, becoming increasingly
12951 exothermic as the reaction temperature decreases (Mok and Antal, 1983). The exothermicity
12952 of the slow pyrolysis reaction per unit of biochar yield is reported to range from 2.0 to 3.2 kJ
12953 g⁻¹ biochar (Mok and Antal, 1983; Milosavljevic et al., 1996).

12955 15.3.2 Spectrum of pyrolysis & gasification materials

12956 Materials produced by pyrolysis spectrum techniques largely reflect the elemental
12957 composition of the input material that was used for the process. The **organic carbon content**
12958 **of pyrolysed chars fluctuates between 5% and 95%** of the dry mass, dependent on the
12959 feedstock and process temperature used. Some pyrolysis & gasification materials made of
12960 plant-based materials often have a high organic C content, but low nutrient content. An
12961 important defining feature of these materials is a certain level of organic C forms, called
12962 fused aromatic ring structures that relate to many of the soil improving properties ascribed to
12963 the material. Such materials are typically defined as biochar, and have organic C contents >
12964 50%. Pyrolysis materials derived from mineral-rich input materials (e.g. manure, animal
12965 bones) are much lower in organic C. Therefore, the European Biochar Certificate refers to
12966 pyrolysed organic matter with a C content lower than 50% as pyrogenic carbonaceous
12967 materials, instead of biochar. In the STRUBIAS framework, the name pyrolysis &
12968 gasification materials has been proposed as a common name for all material produced in an
12969 oxygen-limiting environment, although a distinction has been made between C-rich (e.g.
12970 woody biomass) and nutrient-rich pyrolysis & gasification materials.

12971

12972 15.3.3 Deliberateness of the nutrient recovery

12973 Pyrolysis processes are mostly performed with the specific aim of producing a high-value
12974 product with a set of specific properties that relate to its function (e.g. soil improver, P-
12975 fertiliser). Pyrolysis can also be performed in order to enable a weight reduction of the input
12976 materials, facilitating its further handling, transport, and distribution. Also synergies with
12977 energy recovery is possible for organic materials, but the energy recovery potential in
12978 pyrolysis plants is largely dependent on the moisture content of the input materials.

12979 Pyrolysis & gasification materials can also be produced for objectives other than nutrient
12980 recovery. Biochar application to soil is described as a **climate change mitigation strategy**
12981 (Woolf et al., 2010). The transformation of labile to recalcitrant C compounds in the biochar
12982 production process has been suggested as a means of abating climate change. Apart from its
12983 application to the soil, **biochar can also be used for other applications** (Schmidt and
12984 Wilson, 2016):

- 12985 ○ The cascaded use of biochar in animal farming (silage agent, slurry treatment,
12986 feed additive);

- 12987 ○ Use as a soil conditioner (carbon amendment, compost additive, plant
- 12988 protection);
- 12989 ○ Use in the building sector (insulation, air decontamination, humidity regulation);
- 12990 ○ The treatment of waste water (active carbon filter, pre-rinsing additive);
- 12991 ○ The treatment of drinking water (micro filters);
- 12992 ○ Other uses (exhaust filters, carbon fibers, semiconductors, etc.).
- 12993
- 12994

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16 Chemical composition of STRUBIAS materials

16.1 Precipitated phosphate salts & derivatives

16.1.1 Macroelements

Table 28: Macronutrient and organic C content precipitated phosphate salts from different input materials.

input material	dry matter content (%, dried at 105°C)	P	N	Mg	Ca	K	organic C	Reference
				(% , dried at 40°C)				
urban wastewater -Pearl		13.4	5.7					(Kraus and Seis, 2015)
urban wastewater - Airpex		11.7	4.7					(Kraus and Seis, 2015)
urban wastewater - Stuttgart		10.1	5					(Kraus and Seis, 2015)
urban wastewater - Gifhorn								(Kraus and Seis, 2015)
urban wastewater	58.3	10.0	2.1	7.3	6.7		3.7	(STOWA, 2015)
urban wastewater	77.3	7.5	3.0	5.9	4.3		0.3	(STOWA, 2015)
urban wastewater	52.1	12.1	2.0	8.6	1.6		0.3	(STOWA, 2015)
urban wastewater	52.8	13.5	5.5	10.8	1.0		0.3	(STOWA, 2015)
urban wastewater		12.9	5.7	9.8				(Ueno and Fujii, 2001)
urban wastewater		12.4	5.1	9.1				(Münch and Barr, 2001)
urban wastewater		12.1	4.2	9.3	0.49	0.06		(Vogel et al., 2015)
urban wastewater	69.7	9.5	6.0	8.3	0.5	0.14		STRUBIAS - confidential data provider
urban wastewater	61.8	10.5	4.7	7.7	5.6	0.47		STRUBIAS - confidential data provider
urban wastewater	57.1	11.0	5.0	9.5			6.2	(ADEME - Naskeo Rittmo Timab, 2016)
urban wastewater	61.2	10.9	4.7				6.2	(ADEME - Naskeo Rittmo Timab, 2016)
manure (Stichting Mestverwerking Gelderland)		5.9	0.8	8.0	1.5	4.8	3.2	(Ehlert et al., 2016a)
manure		10.1	5.8	6.4		3.7		(Katanda et al., 2016)
urban wastewater		10.4	4.4	13.1	1.2	0.08		(Plaza et al., 2007)
dairy industry		11.3	3.3	8.64		0.73		(Uysal and Kuru, 2015)
dairy industry		12.4		4.2	17.9			(Massey et al., 2009)
potato industry		92	9.4	5.2			4.8	(Sigurnjak et al., 2016)

potato industry - Nuresys	56.1	12.8	5.1	9.7	0.25	(Vanhoof and Tirez, 2014)
food processing (vegetable oil) - Nuresys	55.9	12.6	5.2	9.7	0.1	(Vanhoof and Tirez, 2014)
urban wastewater - Nuresys	58.4	12.2	5.1	9.1	0.3	(Vanhoof and Tirez, 2014)
potato industry - Crustell	13.6	10.7	4.7	9.2	3.3	(Vanhoof and Tirez, 2014)
urban wastewater - Aquafin	56.8	11.5	5.4	9.2	0.4	(Vanhoof and Tirez, 2014)

16.1.2 Metals and metalloids

Table 29: Metal/metalloid contents (mg kg⁻¹ dry weight) for precipitated P-salts (confidential information received from the STRUBIAS subgroup is not included in this Table).

input material	As	Cd	Cu	Cr	Hg	Ni	Pb	Zn	Reference
	(mg kg ⁻¹ , dry matter)								
urban wastewater -Pearl	3	0.1	3	3	0	3	1	15	(Kraus and Seis, 2015)
urban wastewater - Airpex	1	0.3	42	16	0	16	13	90	(Kraus and Seis, 2015)
urban wastewater - Stuttgart	2	0.4	30	4	0	5	7	47	(Kraus and Seis, 2015)
urban wastewater - Gifhorn		0.2	12	2	0	2	1	24	(Kraus and Seis, 2015)
urban wastewater	<0.05	<0.01		<dl	<dl	<dl	<dl		(Ueno and Fujii, 2001)
urban wastewater		<0.4			0		5		(Münch and Barr, 2001)
urban wastewater		<0.4	2	2	0	<0.4	0		(Antakyal et al., 2011)
urban wastewater (unwashed product)	0	0	12	6	0	6	10	42	(STOWA, 2015)
urban wastewater (unwashed product)	0	0	5	12	0	6	2	16	(STOWA, 2015)
urban wastewater (unwashed product)	0	<0.03	2	3	0	<0.6	1	12	(STOWA, 2015)
urban wastewater (unwashed product)	<0.05	<0.6	<1.1	3	<0.01	2	<0.5	2	(STOWA, 2015)
urban wastewater	<1	<0.3	48	8	0	5	11	90	STRUBIAS - confidential data provider
urban wastewater	<0.6	<0.3	30	<0.3 (VI)	<0.06	2	6	67	STRUBIAS - confidential data provider
urban wastewater manure		<0.5	2	9	0	1	<0.5	5	(Weidelenner et al., 2005)
manure (Stichting Mestverwerking Gelderland)			16					81	(Liu et al., 2011)
urban wastewater	<2	<1	5	2	0	<2	<0.1	59	(Ehlert et al., 2016a)
dairy industry		<0.2	7	4		11	<0.2	19	(Plaza et al., 2007)
urine		<dl	<dl	<dl	<dl	<dl	<dl	<dl	(Uysal and Kuru, 2015)
waste water	<11	<1.6	89	<1.6		2	<21	224	(Gell et al., 2011)
potato industry	<6	<1.1	36	<1	<0.1	<0.5	<16	<15	(Gell et al., 2011)
potato industry	<6	1	42	17		26	7	336	(Abma et al., 2009)
potato industry			2					9	(Sigurnjak et al., 2016)

potato industry - Nuresys	<0.5	<0.12	1	0.5	<0.25	1.0	6	(Vanhoof and Tirez, 2014)
food processing (vegetable oil) - Nuresys	1.4	<0.12	0	0.7	11.0	0.9	5	Vanhoof and Tirez, 2014
urban wastewater - Nuresys	<1.25	<0.31	11	1.3	1.2	3.9	22	(Vanhoof and Tirez, 2014)
potato industry - Crustell	0.6	0.9	34	5.9	7.3	2.6	179	(Vanhoof and Tirez, 2014)
urban wastewater - Aquafin	<0.5	<0.12	3	1.7	1.3	3.9	28	(Vanhoof and Tirez, 2014)

<dl: below detection limit

16.2 Thermal oxidation materials & derivatives

16.2.1 Macroelements

Table 30: Macroelements (% , dry basis) for different types of thermal oxidation materials & derivatives.

	n	Si (%)	Ca (%)	K (%)	P (%)	Al (%)	Mg (%)	Fe (%)	S (%)	Na (%)	Ti (%)	reference
plant biomass												
wood and woody biomass												
Wood ash	1		19.4	3.1	0.2		1.5		0.0			STRUBIAS contribution - confidential data provider
Wood ash	1		24.7	4.8	0.3		2.0		0.1			STRUBIAS contribution - confidential data provider
Wood ash	1		22.8	2.7	0.1		1.3		0.2			STRUBIAS contribution - confidential data provider
Wood ash	1		8.7	2.1	0.1		0.7		0.0			STRUBIAS contribution - confidential data provider
Wood ash	1		8.3	1.7	0.1		0.7		0.0			STRUBIAS contribution - confidential data provider
Wood ash	1		13.1	1.4	0.1		0.8		0.0			STRUBIAS contribution - confidential data provider
Wood ash	1		5.8	1.2	0.1		0.5		0.0			STRUBIAS contribution - confidential data provider
Wood ash	1		9.3	2.0	0.1		0.7		0.1			STRUBIAS contribution - confidential data provider
Wood ash	1		18.5	3.4	0.2		1.4		0.1			STRUBIAS contribution - confidential data provider
Wood ash	1		21.3	2.1	0.1		1.6		0.0			STRUBIAS contribution - confidential data provider
Wood ash	23		18.1	6.1	1.9							STRUBIAS contribution - DK
Alder-fir sawdust #	1	17.5	18.8	5.1	0.9	6.5	2.4	5.7	0.3	1.3	0.6	(Miles et al., 1996)
Balsam bark #	1	12.2	32.5	8.9	2.1	1.0	1.4	1.9	1.1	2.0	0.1	(Bryers, 1996)
Beech bark #	1	5.8	48.4	2.2	1.0	0.1	6.9	0.8	0.3	0.7	0.1	(Bryers, 1996)
Birch bark #	2	2.0	49.0	7.5	1.8	0.3	3.6	1.6	1.1	1.4	0.1	(Bryers, 1996)
Christmas trees #	1	18.6	6.9	6.7	1.1	8.0	1.6	6.7	4.7	0.4	0.2	(Miles et al., 1996)
Elm bark #	1	2.1	59.3	4.5	0.7	0.1	1.5	0.3	0.4	0.6	0.1	(Bryers, 1996)
Eucalyptus bark #	1	4.7	41.0	7.7	1.0	1.6	6.5	0.8	1.4	1.4	0.1	(Theis et al., 2006)
Fir mill residue #	2	9.0	10.7	7.4	1.6	2.7	3.5	5.8	1.5	22.1	0.2	(Bryers, 1996; Thy et al., 2006)
Forest residue #	3	9.6	33.8	8.5	2.2	1.6	4.3	1.0	1.2	1.2	0.2	(Miles et al., 1995; Miles et al., 1996; Zevenhoven-Onderwater et al., 2000)
Hemlock bark #	1	5.2	42.3	4.2	1.0	1.2	8.7	1.0	0.8	0.9	0.1	(Bryers, 1996)
Land clearing wood #	2	30.7	4.1	1.8	0.3	7.9	1.1	3.7	0.1	2.0	0.3	(Miles et al., 1995)
Maple bark #	1	4.2	47.8	5.8	0.3	2.1	4.0	1.0	0.8	1.3	0.1	(Bryers, 1996)

	n	Si (%)	Ca (%)	K (%)	P (%)	Al (%)	Mg (%)	Fe (%)	S (%)	Na (%)	Ti (%)	reference
Oak sawdust #	2	14.0	11.0	26.6	0.8	2.3	3.6	2.9	1.5	1.5	0.2	(Miles et al., 1995)
Oak wood #	1	22.8	12.4	7.9	0.8	5.0	0.7	5.9	1.0	0.4	0.1	(Misra et al., 1993; Demirbas, 2004)
Olive wood #	2	4.8	29.4	20.9	4.7	1.1	1.8	0.6	1.1	2.7	0.1	(Vamvuka and Zografos, 2004)
Pine bark #	1	4.3	40.3	6.5	2.2	3.8	3.7	2.0	1.1	1.5	0.1	(Misra et al., 1993; Bryers, 1996)
Pine chips #	1	31.8	5.6	3.7	0.7	3.7	1.5	3.8	0.5	0.9	0.3	(Masia et al., 2007)
Pine pruning #	2	3.6	31.3	18.5	2.5	1.5	6.8	0.9	1.7	0.3	0.1	(Lapuerta et al., 2008)
Pine sawdust #	3	4.5	34.7	11.9	2.7	1.2	8.3	1.5	0.9	0.3	0.1	(Etiegni and Campbell, 1991)
Poplar #	1	1.8	40.7	15.5	0.4	0.4	7.9	0.8	1.5	0.2	0.2	(Misra et al., 1993; Miles et al., 1995)
Poplar bark #	2	0.9	54.9	7.4	1.1	0.3	1.4	0.5	0.3	3.6	0.1	(Bryers, 1996)
Sawdust #	3	12.2	31.3	9.0	1.0	2.4	3.2	1.3	0.8	1.8	0.2	(Tillman, 2000; Wigley et al., 2007)
Spruce bark #	1	2.9	51.4	6.0	1.2	0.4	3.0	1.3	0.8	1.5	0.1	(Bryers, 1996; Demirbas, 2005)
Spruce wood #	1	23.0	12.2	8.0	0.8	5.0	0.7	5.8	1.0	0.4	0.1	(Demirbas, 2005)
Tamarack bark #	11	3.6	38.0	4.7	2.2	4.7	5.4	2.7	1.1	2.5	0.1	(Bryers, 1996)
Willow #	1	2.8	32.7	19.4	5.7	1.0	2.4	0.5	1.2	1.2	0.0	(Miles et al., 1995; Zevenhoven-Onderwater et al., 2000)
Wood	1	10.8	26.5	9.6	1.3	3.0	4.4	2.3	2.0	1.9	0.7	(Wei et al., 2005)
Wood residue	2	24.8	8.3	4.0	0.6	6.7	1.8	4.4	0.8	3.3	0.3	(Miles et al., 1995)
Wood fly ash	1		24.7	5.0	1.3	1.0	2.4	1.6		0.4		(ECN, 2017); biodat_sample_#326
Wood ash	1	27.0	14.2	3.5	0.7	1.6	1.5	1.1		0.4		(ECN, 2017); biodat_sample_#327
Wood bottom ash	1		34.9	8.6	2.2		2.7			0.7		(ECN, 2017); biodat_sample_#328
Wood ash	1		29.0	10.7	2.0		2.5			0.9		(ECN, 2017); biodat_sample_#329
Wood fly ash	1		25.4	8.9	1.9		2.1			0.8		(ECN, 2017); biodat_sample_#330
Wood ash	1	12.0	21.0	7.4	2.4	1.2	2.8	2.0		0.9	0.1	(ECN, 2017); biodat_sample_#331
Wood fly ash	1		16.0	1.1	0.6	1.1	2.1	1.2		0.3		(ECN, 2017); biodat_sample_#332
Wood fly ash	1	19.0	14.0	3.5	0.8	4.0	1.7	2.7		1.5		(ECN, 2017); biodat_sample_#333
Wood fly ash	1	19.0	14.0	4.0	1.0	4.1	1.7	2.5		1.5	0.2	(ECN, 2017); biodat_sample_#334
Wood fly ash	1	3.6	22.0	9.0	1.4	0.9	3.7	1.4		1.0	0.1	(ECN, 2017); biodat_sample_#335
Wood bottom ash	1	5.8	5.7	1.8	0.3	1.0	0.9	0.7		0.4	0.1	(ECN, 2017); biodat_sample_#336
Wood fly ash	1	16.5	18.9	3.8	1.1	4.3	2.2	3.6	1.5	1.2	0.5	(ECN, 2017); biodat_sample_#352
Wood fly ash	1	19.8	14.9	4.5	0.9	5.0	1.5	2.9	1.1	1.5	0.4	(ECN, 2017); biodat_sample_#353
Wood fly ash	1	14.2	19.1	3.6	1.1	4.5	1.6	4.9	1.9	1.3	0.2	(ECN, 2017); biodat_sample_#354
Wood fly ash	1	15.7	17.2	3.0	0.9	4.6	1.4	4.1	1.9	1.0	0.3	(ECN, 2017); biodat_sample_#355
Wood fly ash	1	17.9	16.9	2.9	0.6	4.7	1.6	3.4	2.0	1.2	0.4	(ECN, 2017); biodat_sample_#356
Wood fly ash	1	23.4	12.3	3.8	0.8	4.6	1.5	3.8	0.8	1.1	0.5	(ECN, 2017); biodat_sample_#357
Wood fly ash	1	20.6	13.2	3.4	0.6	5.3	1.6	4.2	1.3	1.2	0.6	(ECN, 2017); biodat_sample_#358
Wood fly ash	1	21.3	12.8	3.7	0.6	5.2	1.5	3.8	1.1	1.2	0.5	(ECN, 2017); biodat_sample_#359
Wood fly ash	1	16.5	17.9	3.9	1.0	4.3	2.1	3.7	1.5	1.2	0.8	(ECN, 2017); biodat_sample_#360

	n	Si (%)	Ca (%)	K (%)	P (%)	Al (%)	Mg (%)	Fe (%)	S (%)	Na (%)	Ti (%)	reference
Wood fly ash	1	19.2	16.7	3.8	0.9	4.5	1.9	3.3	1.2	1.3	0.6	(ECN, 2017); biodat_sample_#361
Wood ash	1		21.0	3.8	1.8	1.0	2.9	0.5	0.4	0.3		(ECN, 2017); biodat_sample_#362
Wood fly ash	1	17.1	18.4	3.7	1.1	4.4	2.1	3.4	1.3	1.2	0.5	(ECN, 2017); biodat_sample_#363
Wood fly ash	1	19.9	15.8	4.0	1.0	4.6	1.9	3.3	1.0	1.3	0.4	(ECN, 2017); biodat_sample_#364
Wood fly ash	1	21.6	13.9	4.3	0.8	4.9	1.8	3.1	1.0	1.3	0.4	(ECN, 2017); biodat_sample_#365
Wood fly ash	1	20.3	14.9	4.2	1.0	4.9	1.9	3.4	1.5	1.3	0.4	(ECN, 2017); biodat_sample_#366
Wood fly ash	1	17.1	18.7	3.5	1.0	4.6	2.0	3.4	2.2	1.1	0.4	(ECN, 2017); biodat_sample_#367
Wood fly ash	1	17.1	19.4	3.5	0.9	4.5	1.9	3.4	2.0	1.0	0.4	(ECN, 2017); biodat_sample_#368
Wood ash	1		8.8	5.4	1.3	0.6	1.2	0.4	1.2	0.5		(ECN, 2017); biodat_sample_#369
Wood ash	1		8.1	2.0	0.5	1.7	1.0	2.2	0.2	0.7		(ECN, 2017); biodat_sample_#370
Wood ash	1		9.9	3.6	1.1	0.7	1.2	0.5	0.4	0.4		(ECN, 2017); biodat_sample_#371
Wood ash	1		16.0	7.6	2.3	0.9	2.9	0.6	0.4	0.6		(ECN, 2017); biodat_sample_#372
Wood ash	1		12.0	5.4	1.5	1.0	1.7	0.3	0.7	0.5		(ECN, 2017); biodat_sample_#373
Wood ash	1		13.0	6.2	1.1	2.1	1.6	1.5	1.1	1.0		(ECN, 2017); biodat_sample_#374
Wood ash	1		16.0	5.0	2.0	0.8	2.7	0.5	0.5	0.3		(ECN, 2017); biodat_sample_#375
Wood ash	1		11.0	7.8	1.7	0.8	1.6	0.6	1.6	0.7		(ECN, 2017); biodat_sample_#376
Wood fly ash	1	9.4	22.0	6.1	1.8	0.6	0.9	1.6		0.4		(ECN, 2017); biodat_sample_#377
Wood fly ash	1	11.5	20.3	7.8	2.1	1.8	2.6	0.9	2.7	1.1	0.1	(ECN, 2017); biodat_sample_#378
Wood bottom ash	1	36.1	3.4	2.5	0.3	2.2	0.5	0.5	0.0	0.7	0.0	(ECN, 2017); biodat_sample_#379
Wood fly ash	1	13.0	19.9	6.6	1.9	2.1	2.5	1.1	2.4	1.1	0.3	(ECN, 2017); biodat_sample_#380
Wood bottom ash	1	36.7	3.4	2.3	0.3	2.1	0.5	0.5	0.0	0.6	0.1	(ECN, 2017); biodat_sample_#381
Wood fly ash	1	13.0	18.9	6.6	1.6	2.6	2.3	1.5	2.4	1.2	0.5	(ECN, 2017); biodat_sample_#382
Wood bottom ash	1	36.1	3.3	2.4	0.3	2.3	0.5	0.5	0.0	0.7	0.1	(ECN, 2017); biodat_sample_#383
Wood fly ash	1	14.4	17.8	6.0	1.4	3.0	2.2	1.7	2.1	1.4	0.5	(ECN, 2017); biodat_sample_#384
Wood bottom ash	1	36.5	3.0	2.5	0.2	2.6	0.5	0.6	0.0	0.9	0.1	(ECN, 2017); biodat_sample_#385
Wood fly ash	1	14.4	18.0	5.7	1.3	3.0	2.1	1.8	1.8	1.3	0.6	(ECN, 2017); biodat_sample_#386
Wood bottom ash	1	36.9	3.3	2.6	0.3	2.6	0.5	0.6	0.0	0.9	0.1	(ECN, 2017); biodat_sample_#387
Wood fly ash	1	13.4	17.1	6.8	1.4	2.9	2.3	1.6	2.2	1.5	1.0	(ECN, 2017); biodat_sample_#388
Wood bottom ash	1	35.6	3.6	2.8	0.3	2.8	0.5	0.7	0.0	1.0	0.1	(ECN, 2017); biodat_sample_#389
Wood fly ash	1	15.0	16.4	6.5	1.4	3.1	2.1	1.5	2.1	1.4	0.8	(ECN, 2017); biodat_sample_#390
Wood bottom ash	1	36.3	3.6	3.0	0.3	2.8	0.5	0.6	0.0	0.9	0.1	(ECN, 2017); biodat_sample_#391
Wood fly ash	1	6.7	26.4	7.8	1.9	1.4	2.4	0.8	2.2	0.5	0.1	(ECN, 2017); biodat_sample_#392
Wood fly ash	1	3.7	27.0	8.9	1.9	0.5	1.9	0.3		0.3		(ECN, 2017); biodat_sample_#393
Wood fly ash	1	14.0	15.0	5.0	1.2	1.5	1.3	0.5	1.9	0.6	0.1	(ECN, 2017); biodat_sample_#394
Wood fly ash	1	0.9	25.3	7.6	1.4	1.2	2.2	0.5		1.3	0.0	(ECN, 2017); biodat_sample_#395
Wood fly ash	1	1.3	20.7	8.4	1.2	1.3	1.9	0.4		1.6	0.0	(ECN, 2017); biodat_sample_#396

	n	Si (%)	Ca (%)	K (%)	P (%)	Al (%)	Mg (%)	Fe (%)	S (%)	Na (%)	Ti (%)	reference
Wood bottom ash	1	30.0	7.4	7.3	0.3	4.6	1.1	1.4		1.4	0.1	(ECN, 2017); biodat_sample_#397
Wood fly ash	1	21.7	12.4	4.1	0.8	2.1	1.2	0.6	1.6	0.7	0.1	(ECN, 2017); biodat_sample_#398
Wood fly ash	1	8.8	14.0	6.3	1.6	1.4	1.7	0.6	3.4	0.6	0.0	(ECN, 2017); biodat_sample_#399
Wood fly ash	1	14.0	22.0	5.4	1.5	0.7	1.7	0.5	2.7	0.6	0.0	(ECN, 2017); biodat_sample_#400
Wood fly ash	1	11.7	15.9	1.1		7.2	1.3	0.2	2.4	0.3		(ECN, 2017); biodat_sample_#401
Wood fly ash	1	3.8	27.5	5.0	1.3	0.9	1.9	0.6	1.4	0.4		(ECN, 2017); biodat_sample_#402
Wood fly ash	1	17.9	14.6	3.8	0.8	6.1	2.0	4.6		1.4	0.3	(ECN, 2017); biodat_sample_#403
Wood bottom ash	1	30.1	4.6	4.9	0.1	6.6	0.7	2.6		2.1	0.1	(ECN, 2017); biodat_sample_#404
Wood fly ash	1	20.0	8.5	4.1	0.4	6.6	1.2	4.1		1.4	0.3	(ECN, 2017); biodat_sample_#405
Wood bottom ash	1	27.0	7.6	6.0	0.3	6.0	1.0	2.6		1.6	0.2	(ECN, 2017); biodat_sample_#406
Wood fly ash	1	9.1	20.0	4.2	1.2	3.2	2.1	3.9		0.9	0.2	(ECN, 2017); biodat_sample_#407
Wood bottom ash	1	26.0	7.2	5.7	0.3	5.8	0.9	1.7		1.7	0.1	(ECN, 2017); biodat_sample_#408
Wood fly ash	1	13.0	20.0	4.1	1.1	4.0	1.8	5.2		1.2	0.2	(ECN, 2017); biodat_sample_#409
Wood bottom ash	1	30.0	3.3	3.3	0.1	6.7	1.5	3.1		2.2	0.3	(ECN, 2017); biodat_sample_#410
Wood fly ash	1	12.6	20.2	3.8	1.0	4.2	1.9	3.6	2.6	1.2	0.6	(ECN, 2017); biodat_sample_#411
Wood bottom ash	1	31.0	6.3	6.3	0.4	4.0	0.8	1.2		1.4	0.1	(ECN, 2017); biodat_sample_#412
Wood bottom ash	1	34.0	3.5	4.3	0.2	4.5	0.5	1.1		1.6	0.1	(ECN, 2017); biodat_sample_#413
Wood bottom ash	1	32.0	5.5	5.2	0.4	3.9	0.8	1.2		1.2	0.1	(ECN, 2017); biodat_sample_#414
Wood bottom ash	1	31.0	7.4	5.7	0.4	3.7	1.6	1.4		1.1	0.1	(ECN, 2017); biodat_sample_#415
Wood bottom ash	1	29.0	7.1	6.7	0.4	4.8	0.9	1.6		1.5	0.1	(ECN, 2017); biodat_sample_#416
Wood bottom ash	1	28.0	8.5	7.6	0.4	4.3	1.0	1.4		1.5	0.1	(ECN, 2017); biodat_sample_#417
Wood bottom ash	1	30.0	6.9	7.2	0.3	4.4	0.8	1.2		1.4	0.1	(ECN, 2017); biodat_sample_#418
Wood bottom ash	1		8.1	4.5	1.3	0.6	1.0	0.5	0.9	0.6		(ECN, 2017); biodat_sample_#419
Wood bottom ash	1	31.0	6.2	4.9	0.3	4.6	0.8	1.2		1.7	0.1	(ECN, 2017); biodat_sample_#420
Wood fly ash	1	1.0	15.0	24.0	0.9	0.3	2.1	0.5		1.3	0.0	(ECN, 2017); biodat_sample_#421
Wood fly ash	1	0.9	15.0	24.0	0.9	0.3	2.2	0.8		1.2	0.0	(ECN, 2017); biodat_sample_#422
Wood bottom ash	1	8.3	9.0	1.9	0.5	1.0	1.5	1.4		0.3	0.1	(ECN, 2017); biodat_sample_#423
Wood fly ash	1	26.0	7.2	3.0	0.4	4.4	1.0	1.6		1.5	0.4	(ECN, 2017); biodat_sample_#424
Wood fly ash	1	29.0	5.1	7.1	0.3	6.1	0.7	1.4		2.1	0.2	(ECN, 2017); biodat_sample_#425
Wood ash	1	6.2	31.0	4.5	2.5		2.3	0.6		0.3	0.1	(ECN, 2017); biodat_sample_#426
Wood bottom ash	1	25.0	10.0	3.5	0.4	4.5	1.4	1.7		1.3	0.2	(ECN, 2017); biodat_sample_#427

	n	Si (%)	Ca (%)	K (%)	P (%)	Al (%)	Mg (%)	Fe (%)	S (%)	Na (%)	Ti (%)	reference
Wood bottom ash	1	27.0	6.7	3.2	0.3	2.2	1.3	1.5		1.2	0.1	(ECN, 2017); biodat_sample_#428
Wood bottom ash	1	31.0	6.4	3.2	0.4	3.5	1.4	1.5		1.1	0.1	(ECN, 2017); biodat_sample_#429
Wood fly ash	1	9.0	24.0	10.0	1.4	2.3	2.6	1.8		0.6	0.1	(ECN, 2017); biodat_sample_#444
Wood fly ash	1	11.0	27.0	5.8	1.0	2.3	2.0	1.4		0.5	0.1	(ECN, 2017); biodat_sample_#445
Wood fly ash	1	12.0	21.0	5.6	1.1	0.9	2.4	1.6		0.6	0.1	(ECN, 2017); biodat_sample_#446
Wood fly ash	1	14.1	18.1	5.9	1.1	2.0	2.7	1.7		0.6	0.1	(ECN, 2017); biodat_sample_#447
Wood fly ash	1		22.1	6.9	1.3		2.4					(ECN, 2017); biodat_sample_#449
Wood fly ash	1		30.2	1.9	1.7		2.6					(ECN, 2017); biodat_sample_#450
Wood fly ash	1		27.1	9.4	2.1		3.4					(ECN, 2017); biodat_sample_#451
Wood fly ash	1		31.2	6.5	1.3		2.1					(ECN, 2017); biodat_sample_#452
Wood fly ash	1		24.1	6.8	1.6		2.7					(ECN, 2017); biodat_sample_#453
Wood fly ash	1	9.3	17.5	4.7	1.0	4.5	1.8	1.2		0.7	0.4	(ECN, 2017); biodat_sample_#454
Wood bottom ash	1	23.0	15.0	4.2	0.7	3.9	1.9	1.8		1.3	0.2	(ECN, 2017); biodat_sample_#455
Wood fly ash	1	5.6	18.0	15.0	1.0	1.7	1.9	1.0		1.6	0.1	(ECN, 2017); biodat_sample_#456
Wood fly ash	1	12.0	18.0	5.0	1.0	2.7	1.8	1.1	1.3	0.7	0.2	(ECN, 2017); biodat_sample_#457
Wood bottom ash	1	25.0	13.0	4.0	0.6	4.6	1.5	1.8	0.1	1.2	0.2	(ECN, 2017); biodat_sample_#458
Wood bottom ash	1	12.0	13.0	3.8	0.7	5.7	1.4	1.3		0.7	0.7	(ECN, 2017); biodat_sample_#459
Wood bottom ash	1	21.5	11.4	3.9	0.6	5.8	1.5	2.1		1.4	0.3	(ECN, 2017); biodat_sample_#460
Wood fly ash	1	21.0	14.0	3.3	0.7	8.4	1.6	2.5		1.1	1.0	(ECN, 2017); biodat_sample_#461
Wood ash	1		24.0	5.9	1.4	2.1		4.3	0.6	0.8		(ECN, 2017); biodat_sample_#462
Wood ash	1		26.1	4.0	2.2	1.1		1.8	0.4	0.5		(ECN, 2017); biodat_sample_#463
Wood ash	1		9.5	3.0	0.7	1.5		2.0	0.3	0.5		(ECN, 2017); biodat_sample_#464
Wood ash	1		8.9	2.4	0.4	1.6		2.1	0.3	0.7		(ECN, 2017); biodat_sample_#465
Wood ash	1		13.0	6.6	1.4	1.6	1.9	1.1	0.5	0.8		(ECN, 2017); biodat_sample_#466
Wood ash	1		5.3	5.4	0.4	1.2	0.8	1.2	1.6	0.8		(ECN, 2017); biodat_sample_#467
Wood bottom ash	1		29.0	4.6	2.7	1.0	2.9	0.6	0.2	0.2		(ECN, 2017); biodat_sample_#468
Wood bottom ash	1		13.0	5.1	1.2	1.3	1.6	1.0	0.4	0.6		(ECN, 2017); biodat_sample_#469
Hemp ash	1	16.0	15.0	6.9	2.2	2.4	1.2	4.5		0.9	0.2	(ECN, 2017); biodat_sample_#470
Hemp ash	1	12.0	20.0	8.9	3.0	1.3	1.2	1.6		0.6	0.1	(ECN, 2017); biodat_sample_#471
Hemp ash	1	12.0	17.0	11.0	2.5	1.2	1.2	1.3		0.6	0.1	(ECN, 2017); biodat_sample_#472
Hemp ash	1	11.0	21.0	10.0	2.4	1.0	1.5	1.2		0.8	0.1	(ECN, 2017); biodat_sample_#473

	n	Si (%)	Ca (%)	K (%)	P (%)	Al (%)	Mg (%)	Fe (%)	S (%)	Na (%)	Ti (%)	reference
Hemp ash	1	11.0	22.0	8.4	2.0	1.1	1.3	1.3		0.6	0.1	(ECN, 2017); biodat_sample_#474
<i>mean</i>		16.6	18.2	6.2	1.2	2.9	2.1	1.9	1.2	1.2	0.2	<i>n</i> =204
<i>median</i>		14.4	16.0	5.1	1.0	2.4	1.8	1.5	1.1	1.1	0.1	
<i>minimum</i>		0.9	3.0	1.1	0.1	0.1	0.5	0.2	0.0	0.2	0.0	
<i>10th percentile</i>		3.6	5.7	2.9	0.3	0.7	0.8	0.5	0.2	0.4	0.1	
<i>90th percentile</i>		31.0	32.6	9.1	2.2	5.7	3.5	3.9	2.2	1.6	0.5	
<i>maximum</i>		36.9	59.3	26.6	5.7	8.4	8.7	6.7	4.7	22.1	1.0	
<i>coefficient of variation</i>		0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.7	1.5	1.0	
grass												
Arundo grass #	1	22	2	27	3	0	2	1	2	0	0	(Miles et al., 1995)
Bamboo whole #	1	5	3	44	9	0	4	0	1	0	0	(Scurlock et al., 2000)
Bana grass #	1	18	3	41	1	0	1	1	0	0	0	(Miles et al., 1995)
Buffalo gourd grass #	1	4	10	34	5	1	3	1	4	5	0	(Miles et al., 1995)
Kenaf grass #	1	4	31	16	2	1	5	1	3	1	0	(Miles et al., 1995; Moilanen, 2006)
Miscanthus grass #	4	26	8	16	2	0	2	1	1	0	0	(Miles et al., 1995; Wigley et al., 2007)
Reed canary grass #	1	40	2	2	2	1	1	1	0	0	0	(Moilanen, 2006)
Sorghastrum grass #	1	34	5	7	2	1	1	1	0	0	0	(Miles et al., 1995)
Sweet sorghum grass #	1	31	7	8	2	0	2	0	1	1	0	(Moilanen, 2006)
Switchgrass #	3	31	7	8	2	1	3	1	0	0	0	(Miles et al., 1995)
<i>mean</i>		21.5	8.0	20.4	2.9	0.7	2.4	0.7	1.5	0.9	0.0	<i>n</i> = 15
<i>median</i>		24.2	6.1	16.1	1.8	0.6	1.9	0.7	1.2	0.4	0.0	
<i>minimum</i>		4.1	2.1	2.4	1.4	0.4	0.9	0.4	0.3	0.1	0.0	
<i>10th percentile</i>		4.4	2.3	6.9	1.5	0.4	1.1	0.5	0.4	0.2	0.0	
<i>90th percentile</i>		34.7	12.6	41.1	5.2	1.2	4.1	1.0	3.3	1.7	0.1	
<i>maximum</i>		39.6	31.5	44.3	8.9	1.4	5.2	1.2	4.0	4.6	0.2	
<i>coefficient of variation</i>		0.6	1.1	0.7	0.8	0.5	0.6	0.3	0.9	1.5	1.0	
straw												
Wheat	1	32.1	5	30.3	2.8	3.6	2.2	0.4	1.4	18.2		(Demirbas, 2004)
Alfalfa #	1	3.7	17.7	31.7	4.6	0.1	8.5	0.3	1.0	1.1	0.0	(Miles et al., 1996)

	n	Si (%)	Ca (%)	K (%)	P (%)	Al (%)	Mg (%)	Fe (%)	S (%)	Na (%)	Ti (%)	reference
Barley #	2	23.7	7.0	23.4	1.3	0.4	1.7	0.7	0.9	1.0	0.0	(Risnes et al., 2003)
Corn #	1	23.3	10.5	15.4	1.1	2.7	2.7	1.8	0.7	0.1	0.2	(Masia et al., 2007)
Mint #	1	11.0	12.5	26.6	2.5	2.9	4.1	2.0	1.4	1.5	0.2	(Miles et al., 1996)
Oat #	1	17.6	8.5	22.3	2.7	2.5	2.7	1.5	2.0	0.5	0.1	(Theis et al., 2006)
Rape #	3	19.0	21.8	11.2	1.0	2.9	1.2	1.4	1.1	0.3	0.2	(Masia et al., 2007)
Rice #	2	36.0	1.7	10.4	0.4	0.3	1.6	0.3	0.5	1.3	0.0	(Miles et al., 1996; Thy et al., 2000; Thy et al., 2006)
Unknown	14	26.7	4.8	21.4	1.2	0.4	1.0	0.4	1.6	0.5	0.0	(Wieck-Hansen et al., 2000; Wei et al., 2005)
Wheat	9	23.5	5.8	20.7	1.6	0.8	1.6	0.6	1.7	2.6	0.1	(Miles et al., 1995; Bryers, 1996; Miles et al., 1996; Risnes et al., 2003; Demirbas, 2004; Thy et al., 2006; Nutalapati et al., 2007)
<i>mean</i>		21.7	9.5	21.3	1.9	1.7	2.7	0.9	1.2	2.7	0.1	<i>n</i> = 35
<i>median</i>		23.4	7.8	21.9	1.4	1.6	2.0	0.6	1.2	1.1	0.1	
<i>minimum</i>		3.7	1.7	10.4	0.4	0.1	1.0	0.3	0.5	0.1	0.0	
<i>10th percentile</i>		10.2	4.5	11.1	0.9	0.3	1.2	0.3	0.7	0.3	0.0	
<i>90th percentile</i>		32.5	18.1	30.4	3.0	3.0	4.6	1.8	1.7	4.2	0.2	
<i>maximum</i>		36.0	21.8	31.7	4.6	3.6	8.5	2.0	2.0	18.2	0.2	
<i>coefficient of variation</i>		0.4	0.7	0.3	0.6	0.8	0.8	0.7	0.4	2.0	0.8	
other residues												
Almond hulls #	1	5.2	6.9	53.0	2.7	1.3	2.4	0.6	0.2	0.8	0.0	(Miles et al., 1996)
Almond shells #	1	7.9	8.2	44.4	2.2	1.6	2.7	1.9	0.4	1.3	0.1	(Miles et al., 1996; Demirbas, 2004)
Coconut shells #	1	31.2	1.7	7.0	0.7	4.5	0.9	4.3	0.0	3.4	0.0	(Miles et al., 1996)
Coffee husks #	1	6.8	9.3	43.5	2.2	3.7	2.6	1.4	0.2	0.5	0.2	(Miles et al., 1996)
Cotton husks #	1	5.1	14.9	41.7	1.8	0.7	4.6	1.3	0.7	1.0	0.0	(Miles et al., 1996)
Grape #	1	4.4	20.2	30.6	3.9	1.4	2.9	1.2	2.5	0.5	0.1	(Lapuerta et al., 2008)
Groundnut shells #	1	12.9	17.6	7.1	1.6	4.4	3.2	7.2	4.2	0.6	0.1	(Miles et al., 1996)
Hazelnut shells #	1	15.7	10.9	25.2	1.4	1.6	4.7	2.7	0.4	1.0	0.1	(Demirbas, 2004)
Mustard husks #	1	8.1	31.3	6.3	0.9	0.8	5.7	0.6	5.9	1.5	0.1	(Werther et al., 2000)
Olive husks #	1	15.3	10.3	3.6	1.1	4.4	2.5	4.4	0.2	19.4	0.2	(Demirbas, 2004)
Olive pits #	2	10.0	14.2	13.6	4.3	3.2	2.3	3.0	0.9	11.7	0.2	(Miles et al., 1996) (Demirbas, 2004)
Olive residue #	1	10.4	9.2	35.5	2.7	2.2	3.5	1.4	1.5	0.1	0.1	(Masia et al., 2007)
Palm fibres-husks #	1	29.5	6.4	7.5	1.2	2.4	2.3	2.7	1.1	0.6	0.1	(Werther et al., 2000)
Palm kernels #	1	8.5	6.6	13.7	13.7	3.3	4.0	6.5	1.0	0.1	0.1	(Masia et al., 2007)

	n	Si (%)	Ca (%)	K (%)	P (%)	Al (%)	Mg (%)	Fe (%)	S (%)	Na (%)	Ti (%)	reference
Pepper plant #	1	5.9	22.9	20.4	2.3	2.6	4.4	1.4	3.9	0.7	0.3	(Masia et al., 2007)
Pepper residue #	1	7.2	7.1	29.3	4.9	4.4	2.7	2.4	4.2	0.8	0.1	(Werther et al., 2000)
Pistachio shells #	1	3.9	7.3	15.5	5.3	1.2	2.0	25.4	1.6	3.4	0.1	(Miles et al., 1996)
Plum pits #	5	1.7	10.6	37.8	9.0	0.1	7.1	0.5	1.0	0.3	0.0	(Miles et al., 1996)
Rice husks #	1	44.1	0.7	1.9	0.2	0.1	0.1	0.2	0.4	0.1	0.0	(Bryers, 1996; Miles et al., 1996; Vassilev et al., 2000; Feng et al., 2004; Umantahaswaran and Batra, 2008)
Soya husks #	2	0.9	17.9	29.9	2.5	4.6	5.0	2.1	1.7	4.6	0.1	(Werther et al., 2000)
Sugar cane #	2	21.8	3.5	5.8	1.7	7.7	2.7	7.8	1.4	1.2	1.2	(Miles et al., 1996)
Sunflower husks #	1	11.0	10.9	23.7	3.1	4.6	4.4	3.0	1.6	0.6	0.1	(Werther et al., 2000; Demirbas, 2004)
Walnut blows #	1	3.0	19.6	28.8	4.5	1.2	8.6	0.7	0.9	0.7	0.1	(Miles et al., 1996)
Walnut hulls #	1	3.9	14.2	32.9	3.3	1.5	9.7	1.0	1.1	0.9	0.1	(Miles et al., 1996)
Walnut shells #	1	10.9	11.9	27.4	2.7	1.3	8.1	1.0	0.9	0.7	0.1	(Demirbas, 2004)
<i>mean</i>		11.4	11.8	23.4	3.2	2.6	4.0	3.4	1.5	2.3	0.1	<i>n = 31</i>
<i>median</i>		8.1	10.6	25.2	2.5	2.2	3.2	1.9	1.0	0.8	0.1	
<i>Minimum</i>		0.9	0.7	1.9	0.2	0.1	0.1	0.2	0.0	0.1	0.0	
<i>10th percentile</i>		3.3	4.6	6.0	1.0	0.7	2.1	0.6	0.2	0.2	0.0	
<i>90th percentile</i>		26.4	20.0	42.8	5.2	4.6	7.7	6.9	4.0	4.1	0.2	
<i>Maximum</i>		44.1	31.3	53.0	13.7	7.7	9.7	25.4	5.9	19.4	1.2	
<i>coefficient of variation</i>		0.9	0.6	0.6	0.9	0.7	0.6	1.5	1.0	1.9	1.7	
unknown plant origin												
unknown plant origin	24			37.8	3.4		4.5		1.8	0.3		STRUBIAS - ECOFI contribution
animal biomass												
poultry manure												
poultry manure	1			21.3	8.2							STRUBIAS contribution - IE
poultry manure	1	0.9	12.7	5.6	10.4	0.9	7.9	1.5	2.4	1.2	0.0	STRUBIAS contribution - confidential data provider
poultry manure	1		32.2	4.6	4.4			4.4	2.7	1.0		STRUBIAS contribution - confidential data provider
poultry manure	1	2.7	26.5	5.7	7.2	0.5	1.9	0.2	1.7	0.3	0.0	(Masia et al., 2007)
poultry manure	1	1.5	17.4	8.0	10.6	0.4	3.1	0.5	3.1	1.7		STRUBIAS contribution - confidential data provider
poultry manure	?		1.9	10.3			1.0		2.1	5.5		STRUBIAS contribution - ESSP (Kalfos)
poultry manure	415		21.0	14.0	6.7					2.2		STRUBIAS contribution - ESSP (BMC Moerdijk, Billen et al.)
pig manure												

	n	Si (%)	Ca (%)	K (%)	P (%)	Al (%)	Mg (%)	Fe (%)	S (%)	Na (%)	Ti (%)	reference
pig manure	1	5.1	11.9	6.4	9.7	0.5	6.6	8.3	4.7	1.3	0.0	STRUBIAS contribution - confidential data provider
pig manure	1	0.9	20.5	23.6	3.6	0.1	1.8	0.9	2.3	1.9	0.0	STRUBIAS contribution - confidential data provider
slaughterhouse waste												
meat and bone meal	1	0.0	29.3	2.6	18.0	1.3	0.8	0.2	1.7	4.7	0.0	(Masia et al., 2007)
meat and bone meal	1	0.0	30.7	2.5	18.4	0.2	0.8	0.5	1.6	2.7	0.0	(Deydier et al., 2005b)
meat and bone meal	1	0.2	30.0	1.0	15.0	0.5	0.8		0.3	2.5		STRUBIAS contribution - ESPP
<i>mean</i>		1.4	21.3	8.8	10.2	0.5	2.7	2.0	2.3	2.3	0.0	<i>n</i> = 425
<i>median</i>		0.9	21.0	6.0	9.7	0.5	1.8	0.7	2.2	1.9	0.0	
<i>Minimum</i>		0.9	12.7	4.6	4.4	0.4	1.9	0.2	1.7	0.3	0.0	
<i>10th percentile</i>		0.0	11.9	2.5	4.4	0.1	0.8	0.2	1.4	1.0	0.0	
<i>90th percentile</i>		3.4	30.7	20.6	18.0	1.0	6.9	5.6	3.3	4.7	0.0	
<i>Maximum</i>		5.1	32.2	23.6	18.4	1.3	7.9	8.3	4.7	5.5	0.0	
<i>coefficient of variation</i>		1.2	0.5	0.8	0.5	0.7	1.0	1.4	0.5	0.7	1.3	

Contaminated biomass

Sewage sludge (raw)	1	15.5	9.3	1.3	7.0	6.8	1.5	11.0	0.8	1.7	0.5	(Werther et al., 2000)
Sewage sludge (raw)	1	17.9	6.5	1.8	6.8	7.8	1.7	8.7	0.4	1.6	0.5	(Wei et al., 2005)
Sewage sludge (raw)	1	13.2	12.1	0.8	7.2	5.8	1.3	13.2	1.2	1.7	0.5	STRUBIAS contribution - confidential data provider
Sewage sludge (raw)	1	11.3	0.9	0.2	10.6	0.2	0.2	10.7	0.4	0.0		STRUBIAS contribution - confidential data provider
Sewage sludge (raw - DE)	252	12.1	13.8	0.9	7.3	5.2	1.4	9.9	1.5	0.7	0.4	(Krüger and Adam, 2015)
Sewage sludge (post-processed)	1		9.3	1.1	7.7		1.3		2.5			STRUBIAS contribution - ESPP (AshDec process)
slaughterhouse waste and sewage sludge mix	1		28.3	0.3	2.6							STRUBIAS contribution - FEhS
Currency shredded #	1	1.6	10.0	1.8	0.4	7.2	0.9	15.5	4.2	3.0	16.5	(Miles et al., 1995)
Demolition wood #	3	16.9	15.2	5.8	2.2	5.1	2.9	5.1	1.6	2.1	1.0	(Miles et al., 1995; Thy et al., 2000; Masia et al., 2007)
Furniture waste #	1	26.7	9.8	3.1	0.2	6.4	2.0	3.9	0.4	1.7	0.3	(Miles et al., 1995)
Mixed waste paper #	1	13.4	5.4	0.1	0.1	28.3	1.4	0.6	0.7	0.4	2.6	(Miles et al., 1995)
Greenhouse-plastic waste #	1	13.3	18.3	8.1	1.7	2.1	3.4	12.9	1.1	0.6	0.5	(Masia et al., 2007)
Refuse-derived fuel #	1	18.0	19.0	0.2	0.3	7.7	3.9	4.4	1.2	1.0	1.1	(Miles et al., 1995)
Wood yard waste #	1	28.0	17.0	2.5	0.9	1.6	1.3	1.4	1.0	0.7	0.2	(Miles et al., 1995)

	n	Si (%)	Ca (%)	K (%)	P (%)	Al (%)	Mg (%)	Fe (%)	S (%)	Na (%)	Ti (%)	reference
municipal solid waste	1	14.2	13.6	5.0	0.1	6.9	1.9	1.7	0.9	5.2		(Demirbas, 2004)
municipal solid waste (UK)	8	0.3	26.0	2.8	0.5	1.5	0.6	0.9	0.5	2.2		(Bogush et al., 2015)
paper industry waste	?		14.8	2.7	0.7							STRUBIAS contribution - CEPI
paper industry waste	391		12.4	2.5	0.2							STRUBIAS contribution - CEPI
<i>mean</i>		14.5	13.4	2.3	3.1	6.6	1.7	7.1	1.2	1.6	2.2	
<i>median</i>		13.8	13.0	1.8	1.3	6.1	1.4	6.9	1.0	1.6	0.5	<i>n</i> = 667
<i>Minimum</i>		0.3	0.9	0.1	0.1	0.2	0.2	0.6	0.4	0.0	0.2	
<i>10th percentile</i>		4.5	6.1	0.2	0.2	1.5	0.7	1.0	0.4	0.5	0.3	
<i>90th percentile</i>		24.1	21.1	5.2	7.4	7.8	3.2	13.1	2.2	2.8	2.6	
<i>Maximum</i>		28.0	28.3	8.1	10.6	28.3	3.9	15.5	4.2	5.2	16.5	
<i>coefficient of variation</i>		0.5	0.5	0.9	1.1	1.0	0.6	0.7	0.8	0.8	2.2	

Solid fossil fuels

Peat #	1	17.5	7.1	0.9	1.2	10.7	1.3	9.7	4.8	0.1	0.2	(Theis et al., 2006)
Coal #	37	25.2	4.7	1.3	0.2	12.3	1.1	4.8	1.4	0.6	0.6	(Vassilev and Vassileva, 2007; Vassilev and Vassileva, 2009)
Lignite #	5	20.9	9.3	1.2	0.1	9.1	1.5	7.6	3.5	0.4	0.5	(Vassilev and Vassileva, 2007; Vassilev and Vassileva, 2009)
Sub-bituminous #	10	25.5	5.0	1.4	0.0	12.1	1.3	3.7	1.6	0.8	0.6	(Vassilev and Vassileva, 2007; Vassilev and Vassileva, 2009)
Bituminous #	22	26.2	3.5	1.3	0.1	13.1	0.9	4.7	0.9	0.6	0.7	(Vassilev and Vassileva, 2007; Vassilev and Vassileva, 2009)

values of the oxides are Si, Ca, K, P, Al, Mg, Fe, S, Na and Ti normalised to 100%

Proposal for the Revised Fertiliser Regulation

straight inorganic macronutrient fertiliser: the CE product shall contain one of the nutrients in the minimum quantity stated

8.5 5.0 5.3 3.0 4.0 0.7

compound inorganic macronutrient fertiliser: the CE product shall contain more than one of the nutrients in the minimum quantity stated

1.1 2.5 1.3 0.9 0.6 0.7

16.2.2 Metals and metalloids

Table 31: Metal and metalloid contents (mg kg⁻¹, dry basis) for different types of thermal oxidation materials & derivates.

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn	refe	
plant biomass																						
wood and woody biomass																						
Wood bottom ash																						reference
Wood bottom ash	1	2.3	40	0.01	12	16		99	1410		5.1	136	5900						14	446	(ECN, 2017) biodat_sample_#336	
Wood bottom ash	1	0.73	102	0.82	59	116	26				14	116	5700						43	430	(ECN, 2017) biodat_sample_#337	
Wood bottom ash	1	0.142	32.7		4	8.1			757		2.72	33.9	3990					229	8.66	697	(ECN, 2017) biodat_sample_#379	
Wood bottom ash	1		40.1		4.57	9.07	6.13		781		3.43	48.2	4360					228	11.6	799	(ECN, 2017) biodat_sample_#381	
Wood bottom ash	1		64.2		3.71	10.6	18.3		833		3.63	63.2	4040					227	8.77	985	(ECN, 2017) biodat_sample_#383	
Wood bottom ash	1		47.4		3.2	12.7	14.7		832	0.542	3.11	50.7	3690					222	10.4	971	(ECN, 2017) biodat_sample_#385	
Wood bottom ash	1		61.8		4.95	13.5	20.8		881		3.74	77.2	3920					235	9.28	1160	(ECN, 2017) biodat_sample_#387	
Wood bottom ash	1		62		5.22	19.5	17.7		971		4.62	58	3940					255	10.4	1210	(ECN, 2017) biodat_sample_#389	
Wood bottom ash	1	0.143	71.9		6.89	17	72.1		929	0.608	5.14	96.6	3530					254	10.2	1340	(ECN, 2017) biodat_sample_#391	
Wood bottom ash	1		59		11	72	3.4	7.2	1510		7.8	56	3600						20	1240	(ECN, 2017) biodat_sample_#397	
Wood bottom ash	1		50		19	14		26	1130		7	47	1900						33	856	(ECN, 2017) biodat_sample_#404	
Wood bottom ash	1		54	0.01	28	13	7.5	76	1990		9.4	77	3000						40	1630	(ECN, 2017) biodat_sample_#406	
Wood bottom ash	1		42		18	12		74	1770		6.5	62	3500						27	1330	(ECN, 2017) biodat_sample_#408	
Wood bottom ash	1		118		65	19	11	13	763		14	28	900						74	606	(ECN, 2017) biodat_sample_#410	
Wood bottom ash	1	0.15	30		11	12		72	1490		5.1	51	3600						15	1850	(ECN, 2017) biodat_sample_#412	
Wood bottom ash	1	0.12	15		12	15		34	1040		4.2	28	1700						12	427	(ECN, 2017) biodat_sample_#413	
Wood bottom ash	1		40		17	8.7		72	1270		26	47	2600						20	893	(ECN, 2017) biodat_sample_#414	
Wood bottom ash	1	0.29	91		62	11	62	81	1420		20	45	2900						18	1070	(ECN, 2017) biodat_sample_#415	
Wood bottom ash	1	0.14	22		9.6	9.8	5	55	1290		6.4	71	2800						20	1300	(ECN, 2017) biodat_sample_#416	
Wood bottom ash	1	0.13	37					64	1600		13	64	3200						22	1430	(ECN, 2017) biodat_sample_#417	
Wood bottom ash	1	0.56	16		10	13		58	1300		5.8	67	3100						18	1180	(ECN, 2017) biodat_sample_#418	
Wood bottom ash	1	15	50	0.35	12	97	7.1	200			5.1	110	9000						6.9	2900	(ECN, 2017) biodat_sample_#419	
Wood bottom ash	1	0.46	43		9.2	8.5		87	1470		5.3	36	3800						20	1170	(ECN, 2017) biodat_sample_#420	
Wood bottom ash	1	0.48	71		17	8.2		98	1150		6.8	62	7100						18	106	(ECN, 2017) biodat_sample_#423	
Wood bottom ash	1	0.52	37		15	20	3	51	1200		7.6	39	4100						30	190	(ECN, 2017) biodat_sample_#427	
Wood bottom ash	1		120		31	21		40	1200		6.3	36	4400	4.6					17	240	(ECN, 2017) biodat_sample_#428	
Wood bottom ash	1		360		53	12		43	1100		6	36	4000	7					19	270	(ECN, 2017) biodat_sample_#429	
Wood bottom ash	1	0.83	130		34	19	8.8				7.9	230	5400						26	380	(ECN, 2017) biodat_sample_#430	

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn		
Wood bottom ash	1		62		22	27	4				9.1	60	7600						18	400	(ECN, 2017) biodat_sample_#431	
Wood bottom ash	1	1.1	78	0.046	32	50					7.3	530	4100						20	370	(ECN, 2017) biodat_sample_#432	
Wood bottom ash	1	1	53	0.045	30	14					11	70							18	380	(ECN, 2017) biodat_sample_#433	
Wood bottom ash	1	4.9	49		18	45					10	59	7300						28	730	(ECN, 2017) biodat_sample_#434	
Wood bottom ash	1		91		33	7.6	12				7.3	38	2800						52	110	(ECN, 2017) biodat_sample_#435	
Wood bottom ash	1		63		19	16	3.9				8.7	36	5700						34	140	(ECN, 2017) biodat_sample_#436	
Wood bottom ash	1	0.76	78		39	19					8	62	4900						23	240	(ECN, 2017) biodat_sample_#437	
Wood bottom ash	1		49		20	10					5.1	52	6800						15	210	(ECN, 2017) biodat_sample_#438	
Wood bottom ash	1	0.56	39		22	10					5.8	40	4600						20	170	(ECN, 2017) biodat_sample_#439	
Wood bottom ash	1	0.67	30		34	6.2					7.6	73	3900						9.3	230	(ECN, 2017) biodat_sample_#440	
Wood bottom ash	1	1	36		21	9.1	4.1				6.9	48	5200						16	190	(ECN, 2017) biodat_sample_#441	
Wood bottom ash	1	0.92	39		20	10					7.1	50	6300						20	210	(ECN, 2017) biodat_sample_#442	
Wood bottom ash	1	0.88	30		18	7.1					6.4	42	5100						14	140	(ECN, 2017) biodat_sample_#443	
Wood bottom ash	1	0.73	80	0.02	39	37		135	1670		9.3	62	5000						26	719	(ECN, 2017) biodat_sample_#445	
Wood bottom ash	1	0.46	72		39	60	3.4	107			13	50	5000						29	257	(ECN, 2017) biodat_sample_#448	
Wood bottom ash	1	9.9	109	0.04	55	43		192	1060		7.5	76	4900						33	2230	(ECN, 2017) biodat_sample_#449	
Wood bottom ash	1	0.14	67		35	56		91	1360		9.1	62	5300						33	155	(ECN, 2017) biodat_sample_#460	
Wood bottom ash	1	1.4	24	0.02	25	19		330			4.9	150	7600						10	840	(ECN, 2017) biodat_sample_#468	
Wood bottom ash	1	6.5	47	0.69	13	70	6	160			7.2	110	13000						15	1900	(ECN, 2017) biodat_sample_#469	
mean		1.8	64	0.2	23	24	15	91	1221	0.6	7.8	75	4669	5.8					236	21.6	781	<i>n</i> =62
median		0.7	50	0.0	19	14	8	74	1200	0.6	7.0	59	4100	5.8					229	19.0	697	
minimum		0.1	15	0.0	3	6	3	7	757	0.5	2.7	28	900	4.6					222	6.9	106	
10th percentile		0.1	30	0.0	5	8	3	29	817	0.5	4.0	36	2800	4.8					225	9.7	164	
90th percentile		5.1	105	0.7	46	58	26	179	1621	0.6	13.0	112	7200	6.8					254	33.4	1510	
maximum		15.0	360	0.8	65	116	72	330	1990	0.6	26.0	530	13000	7.0					255	74.0	2900	
coefficient of variation		1.9	0.8	1.5	0.7	1.0	1.2	0.8	0.3	0.1	0.5	1.0	0.4	0.3					0.1	0.6	0.8	
Wood fly ash																						
Wood fly ash	1	34	35	0.26	30	34	11	404	109		16	133	15200	4.6					17	3660	(ECN, 2017) biodat_sample_#326	
Wood fly ash	1	6.7	13	0.33	13	42	4.7	151			6.3	48	8400	1.1					35	530	(ECN, 2017) biodat_sample_#332	
Wood fly ash	1	8.3	49	0.37	23	91	29	171	2060		11	76	7700						45	1120	(ECN, 2017) biodat_sample_#333	
Wood fly ash	1	10	56	0.36	31	91	17	222	2090		13	81	7800						43	1370	(ECN, 2017) biodat_sample_#334	
Wood fly ash	1	26	73	0.22	35	209	22	480	3970		13	226	23000						16	3420	(ECN, 2017) biodat_sample_#335	
Wood fly ash	1	5.95	136	0.815	58.7	171	34.6	141	1900	1.18	19.9	137	10000	7.51				613	76.3	1900	(ECN, 2017) biodat_sample_#352	
Wood fly ash	1	4.6	104	0.309	33.2	108	53.2	140	1620	1.81	13	121	7100	14.2				589	48.1	1330	(ECN, 2017) biodat_sample_#353	
Wood fly ash	1	5.93	56	0.742	52	124	45.6	191	1860	1.79	17.3	82.8	8300	12.6				555	38.3	1600	(ECN, 2017) biodat_sample_#354	

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn	
Wood fly ash	1	4.75	78.1	0.57	51.2	225	44.3	144	1430	2.17	13.5	106	4700	11.5				538	55.5	1670	(ECN, 2017) biodat_sample_#355
Wood fly ash	1	4.97	119	0.47	44.9	221	215	151	1460	1.51	10.1	135	4500	6.01				471	61	1570	(ECN, 2017) biodat_sample_#356
Wood fly ash	1	4.43	178	0.563	47.6	218	83.2	153	1910	1.3	15.2	193	5900	7.62				483	71.6	2530	(ECN, 2017) biodat_sample_#357
Wood fly ash	1	5.93	232	0.512	68.9	355	90.4		1620	1.59	26.7	205	4900	11				451	75.7	2590	(ECN, 2017) biodat_sample_#358
Wood fly ash	1	5.13	172	0.453	63.2	257	60.7	154	1500	1.6	22.8	160	5100	8.17				449	66.6	1940	(ECN, 2017) biodat_sample_#359
Wood fly ash	1	7.5	149	0.818	56.6	245	48.5	144	2060	1.16	19.8	168	9700	8.95				615	70.5	2400	(ECN, 2017) biodat_sample_#360
Wood fly ash	1	5.76	129	0.821	53.3	184	33.6	97.2	1720	1.23	18.9	134	8200	6.28				549	71.1	1790	(ECN, 2017) biodat_sample_#361
Wood fly ash	1	5.82	112	0.737	59.1	170	32.2	135	1830	1.11	21.2	122	10100	6.48				598	72.8	1710	(ECN, 2017) biodat_sample_#363
Wood fly ash	1	5.46	99.2	0.441	50.1	131	20.3	96.3	1700	1.22	17.9	98.7	9300	6				542	70.9	1500	(ECN, 2017) biodat_sample_#364
Wood fly ash	1	4.33	88.3	0.484	48	101	17.2	70.6	1540	1.38	17	81.4	8200	6				498	72.3	1300	(ECN, 2017) biodat_sample_#365
Wood fly ash	1	4.73	99.7	1.38	60.7	124	19.4	117	1630	1.36	19.3	125	9900	6.96				520	72.8	1590	(ECN, 2017) biodat_sample_#366
Wood fly ash	1	6.17	106	0.822	62.7	191	27.9	183	1690	1.34	20.5	155	10100	8.18				588	77.5	1960	(ECN, 2017) biodat_sample_#367
Wood fly ash	1	5.32	95.4	0.8	61.6	143	27.2	161	1720	1.29	38.1	125	9000	7.52				583	74.8	1320	(ECN, 2017) biodat_sample_#368
Wood fly ash	1	13	28	0.95	63	71	4.4	800	2300		7.8	360	24400						20	4300	(ECN, 2017) biodat_sample_#377
Wood fly ash	1	17.9	57.4	1.07	45.2	258	12		2600		13.1	137	29000					974	39.2	3100	(ECN, 2017) biodat_sample_#378
Wood fly ash	1	22.1	144	1.21	60.3	386	88.2		2680		16.4	207	29400	6.41				930	36.6	4120	(ECN, 2017) biodat_sample_#380
Wood fly ash	1	22	291	0.769	55.6	573	176		3490		19.1	315	26600	9.69				895	37.8	5810	(ECN, 2017) biodat_sample_#382
Wood fly ash	1	21	225	0.906	60.5	510	115		3110		18.8	264	26700	6.69				866	40.4	4410	(ECN, 2017) biodat_sample_#384
Wood fly ash	1	17.1	266	0.939	54.3	616	160		3160		19.3	301	23400	7.19				795	39.3	5870	(ECN, 2017) biodat_sample_#386
Wood fly ash	1	19.3	252	0.856	58.6	709	139		3960		24.8	315	20100	8.8				845	39.2	5900	(ECN, 2017) biodat_sample_#388
Wood fly ash	1	16.4	272	0.992	68.2	688	156		3360		21.7	302	17500	7.64				809	35.2	5120	(ECN, 2017) biodat_sample_#390
Wood fly ash	1	18	45.8	0.848	33.5	105	39.2		3700		10.4	111	28500					956	27.2	4720	(ECN, 2017) biodat_sample_#392
Wood fly ash	1	14	12	0.63	25	88	5.2		2800		10	130	17000			2.1			15	2900	(ECN, 2017) biodat_sample_#393
Wood fly ash	1	10	28	0.35	11	58	8.4	190	1700		5	56	9300	2.9					12	2000	(ECN, 2017) biodat_sample_#394
Wood fly ash	1	7.53	45.5	0.602	75.1	32.9	8.21		2460		8.09	93.1	13000					836	31.2	3330	(ECN, 2017) biodat_sample_#395
Wood fly ash	1	6.61	47.4	0.663	122	33	6		2360		10.6	78	11800					757	72.7	2960	(ECN, 2017) biodat_sample_#396
Wood fly ash	1	6.8	37	0.34	13	52	4.2	130	1400		4.1	52	7100	3					11	1100	(ECN, 2017) biodat_sample_#398
Wood fly ash	1	12	56	0.21	24	74	5.1	200	1900		8.6	120	13000	4.9					14	2700	(ECN, 2017) biodat_sample_#399
Wood fly ash	1	9.4	23	0.46	22	82		650	2100		5.3	76	15000	3					11	2400	(ECN, 2017) biodat_sample_#400
Wood fly ash	1	11	22	0.45	24	110	4.3	480	1700		6.4	91	9900	4.7					14	1900	(ECN, 2017) biodat_sample_#401
Wood fly ash	1	9.5	32	0.28	25	64		260	2400		6.3	96	17100						12	2800	(ECN, 2017) biodat_sample_#402
Wood fly ash	1	6	113	0.62	97	61	21	174	1560		21	130	6700	12.5					90	1060	(ECN, 2017) biodat_sample_#403
Wood fly ash	1	1.6	88	0.2	74	38	15	72	1240		14	150	2700	7.3					89	1050	(ECN, 2017) biodat_sample_#405
Wood fly ash	1	9.2	109	1.1	77	105	29	313	2320		17	180	8700	11					50	2290	(ECN, 2017) biodat_sample_#407
Wood fly ash	1	7.9	71	1.1	84	85	48	205	1930		19	90	7500	11					48	1610	(ECN, 2017) biodat_sample_#409
Wood fly ash	1	10	464	2.51	69.8	514	148	249	2000	0.883	20.5	352	10500	13.1				636	74.3	3280	(ECN, 2017) biodat_sample_#411

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn	
Wood fly ash	1	69	251	0.42	23	234	9.4	428	1830		8.2	894	14000						5.8	13300	(ECN, 2017) biodat_sample_#421
Wood fly ash	1	75	144	0.24	27	226	23	372	1930		10	794	15000	11					8.5	13800	(ECN, 2017) biodat_sample_#422
Wood fly ash	1	6.9	147	0.31	33	462	86	115	1750		9.2	375	3200						28	2540	(ECN, 2017) biodat_sample_#424
Wood fly ash	1		155	0.01	15	76	54	45	1730		5.2	367	2200						21	3310	(ECN, 2017) biodat_sample_#425
Wood fly ash	1	24	61	0.61	41	130	14	370	2100		14	140	9700	8.1	2.5				37	5900	(ECN, 2017) biodat_sample_#444
Wood fly ash	1	16	54	0.55	27	94	9.4	320	1700		11	95	7900	4.5					28	2800	(ECN, 2017) biodat_sample_#445
Wood fly ash	1	19	140	0.27	48	82	13	260	2100		12	110	9100	17					29	2700	(ECN, 2017) biodat_sample_#446
Wood fly ash	1	24	160	0.24	67	91	10	310	2100		11	120	9600	27					27	3400	(ECN, 2017) biodat_sample_#447
Wood fly ash	1	6.8	57		36	33	8.7				8.3	72	6500						25	980	(ECN, 2017) biodat_sample_#448
Wood fly ash	1	27	150	0.39	49	90	17	330				120							32	4100	(ECN, 2017) biodat_sample_#449
Wood fly ash	1	29	44	0.21	20	75	7.5	370				130							13	5300	(ECN, 2017) biodat_sample_#450
Wood fly ash	1	32	69	0.18	31	69	5.9	400				120							23	3000	(ECN, 2017) biodat_sample_#451
Wood fly ash	1	32	26	0.13	31	68		450				150							15	7000	(ECN, 2017) biodat_sample_#452
Wood fly ash	1	26	44	0.28	23	37	13	440				140							16	7800	(ECN, 2017) biodat_sample_#453
Wood fly ash	1	14	109	0.17	78	67		264	1500		10	109	7700						36	3360	(ECN, 2017) biodat_sample_#454
Wood fly ash	1	24	96	0.06	94	152	7.8	439	1820		10	158	6600	17					39	16500	(ECN, 2017) biodat_sample_#456
Wood fly ash	1	12	92		67	52	3.9	320			10	84	7100						25	3310	(ECN, 2017) biodat_sample_#457
Wood fly ash	1		155		60	10		127	1320		10	67	5200	8.3					49	388	(ECN, 2017) biodat_sample_#461
mean		14.9	110.7	0.6	49	174	42	257	2065	1.4	14	174	11681	8.6	2.5	2.1		664	41	3436	<i>n=104</i>
median		10.0	95.7	0.5	50	105	21	200	1900	1.3	13	130	9300	7.6	2.5	2.1		598	37	2700	
minimum		1.6	12.0	0.0	11	10	4	45	109	0.9	4	48	2200	1.1	2.5	2.1		449	6	388	
10th percentile		4.9	28.4	0.2	23	38	5	111	1472	1.1	6	76	5020	4.5	2.5	2.1		478	13	1138	
90th percentile		27.2	231.3	1.0	75	454	125	442	3145	1.8	21	315	23800	13.1	2.5	2.1		909	74	5897	
maximum		75.0	464.0	2.5	122	709	215	800	3970	2.2	38	894	29400	27.0	2.5	2.1		974	90	16500	
coefficient of variation		0.9	0.8	0.7	0.5	1.0	1.2	0.6	0.3	0.2	0.5	0.9	0.6	0.5				0.3	0.6	0.9	
Wood (unknown)																					
Wood ash	1	3.5	91	0.006	39	6.5	3.2	102	779		9.7	58	9050	5.7					16	497	(ECN, 2017) biodat_sample_#327
Wood ash	1	14	160	0.29	79	120	4.7	360	2300		11	170	18000	9.6					30	2100	(ECN, 2017) biodat_sample_#331
Wood ash	1	3.3	39	0.012	17	26	1.8	220			7.1	100	9400						14	870	(ECN, 2017) biodat_sample_#362
Wood ash	1	12	29	1.1	14	80	8	220			4.1	100	11000						12	2300	(ECN, 2017) biodat_sample_#369
Wood ash	1	11	26	0.47	17	36		110			11	59	5000						34	1500	(ECN, 2017) biodat_sample_#370
Wood ash	1	2.2	31	0.08	13	17	3.2	200			5.1	68	7800						13	770	(ECN, 2017) biodat_sample_#371
Wood ash	1	5.8	41	0.36	25	59	2.5	340			8.2	160	22000						20	1900	(ECN, 2017) biodat_sample_#372
Wood ash	1	5.3	24	0.37	15	49	2.8	240			5.9	110	13000						11	1300	(ECN, 2017) biodat_sample_#373
Wood ash	1	15	49	0.43	21	120	4.2	210			13	120	9800						28	3400	(ECN, 2017) biodat_sample_#374

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn	
Wood ash	1	4.3	41	0.27	16	44		200			5.1	180	17000						13	1500	(ECN, 2017) biodat_sample_#375
Wood ash	1	21	44	0.97	20	200	5.8	190			6.4	230	15000						13	5600	(ECN, 2017) biodat_sample_#376
Wood ash	1	2.3	10		20	17	6	260	2300		7.2	110	8100	3.2					7.9	210	(ECN, 2017) biodat_sample_#426
Wood ash	1	11	39	0.08	47	47					18	140	21000								(ECN, 2017) biodat_sample_#462
Wood ash	1	12	29	0.163	28	45					11	134	14200								(ECN, 2017) biodat_sample_#463
Wood ash	1	4.9	21	0.25	12	39					6.9	58	7400								(ECN, 2017) biodat_sample_#464
Wood ash	1	6.5	23	0.28	13	60					7.5	72	5600								(ECN, 2017) biodat_sample_#465
Wood ash	1	6.5	40	0.43	14	59					5.9	130	11000								(ECN, 2017) biodat_sample_#466
Wood ash	1	11	22	0.38	12	60					6.8	53	4140								(ECN, 2017) biodat_sample_#467
Wood (unknown)	1	6.2			100.6	5.7	18.3		2324	1.1	13	193	23562		0.78	0.9	1.6	2178	37.1	1086	(Thy et al., 2008)
Wood (unknown)	1	4.5			99	2.9	10.7		2476	1.2	14	215	26451		0.79	0.4	1.6	2692	36.1	1112	(Thy et al., 2008)
Wood (unknown)	1	2.1			103.5	0.3	17.8		2604	1.1	14	201	26039		0.82	0.9	1.6	2450	40.9	1172	(Thy et al., 2008)
Wood (unknown)	1	7.1			85.1	1.8	17.5		2390	1.0	10	183	22215		0.92	1	1.4	2263	35.2	997	(Thy et al., 2008)
Wood (unknown)	1	7.5			71.2	4.9	13.6		1811	1.0	9	166	19745		0.78	1.2	1.2	2116	30.2	870	(Thy et al., 2008)
Wood (unknown)	1	7.5			92	9.5	16.5		2201	1.0	9	162	17799		0.66	1.1	1.1	2128	30.5	806	(Thy et al., 2008)
Wood (unknown)	1	8.9			72.8	12.2	19.4		2380	1.1	10	197	22063		0.71	1.3	1.3	2382	35.8	992	(Thy et al., 2008)
Wood (unknown)	1	8.4			61.5	10.3	17.8		2098	1.1	9	176	19581		0.67	1	1.1	2110	32.3	968	(Thy et al., 2008)
Wood (unknown)	1	7.8			64.3	11.3	18.6		2219	1.0	9	171	17937		0.6	1.2	1.2	2086	32.5	875	(Thy et al., 2008)
Wood (unknown)	1	7.5			59.6	10.7	17.6		2210	1.0	8	160	17731		0.57	0.7	1.1	2095	30.8	812	(Thy et al., 2008)
Wood (unknown)	1	5.9			43.1	8.6	9.6		1731	1.0	6	117	13298		1.27		0.9	1844	21.1	603	(Thy et al., 2008)
Balsam bark	1												20160								(Bryers, 1996)
beech wood	1	16.6	76.2	1.1	34.6	325	16.9				9.6	358	90.5	15.7	63.5	85.8	78.9		23.6		(Demirbas, 2005)
Beech bark	1												3100								(Bryers, 1996)
Birch bark	2												22870								(Bryers, 1996)
Elm bark	1												775								(Bryers, 1996)
Eucalyptus bark	1												10850								(Theis et al., 2006)
Fir mill residue	2												13640								(Miles et al., 1995) (Thy et al., 2008)
Forest residue	3												13180								(Miles et al., 1995; Miles et al., 1996; Zevenhoven-Or)
Hemlock bark	1												9300								(Bryers, 1996)
Maple bark	2												5430								(Bryers, 1996)
Oak wood	2												14900								(Misra et al., 1993; Demirbas, 2004)
Pine bark	2												12400								(Bryers, 1996; Moilanen, 2006)
Pine chips	1								558.0				2090							1495.0	(Masia et al., 2007)
Pine sawdust	2												10550								(Etegni and Campbell, 1991; Moilanen, 2006)
Poplar	3												4500								(Misra et al., 1993; Miles et al., 1995)
Poplar bark	1												2330								(Bryers, 1996)

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn	
Sawdust	2												27910								(Tillman, 2000; Wigley et al., 2007)
Spruce bark	1												13950								(Demirbas, 2005)
Tamarack bark	1												26360								(Bryers, 1996)
Wood (unknown)	1												35740								(Wei et al., 2005)
Wood (unknown)	1																				(Zevenhoven et al., 2012)
Wood (unknown)	1												98								(Zevenhoven et al., 2012)
Wood (unknown)	1												100								(Zevenhoven et al., 2012)
Wood (unknown)	1												0								(Zevenhoven et al., 2012)
Wood (unknown)	1												87								(Zevenhoven et al., 2012)
Wood (unknown)	1												167								(Zevenhoven et al., 2012)
Wood (unknown)	1												92								(Zevenhoven et al., 2012)
Wood (unknown)	1												166								(Zevenhoven et al., 2012)
Wood (unknown)	1												112								(Zevenhoven et al., 2012)
Wood (unknown)	1												26								(Zevenhoven et al., 2012)
Forest residue (unknown)	1												270								(Zevenhoven et al., 2012)
Forest residue (unknown)	1												164								(Zevenhoven et al., 2012)
Forest residue (unknown)	1												408								(Zevenhoven et al., 2012)
Forest residue (unknown)	1												545								(Zevenhoven et al., 2012)
Forest residue (unknown)	1												440								(Zevenhoven et al., 2012)
Forest residue (unknown)	1												440								(Zevenhoven et al., 2012)
Forest residue (unknown)	1												370								(Zevenhoven et al., 2012)
Forest residue (unknown)	1												290								(Zevenhoven et al., 2012)
Forest residue (unknown)	1												300								(Zevenhoven et al., 2012)
Forest residue (unknown)	1												330								(Zevenhoven et al., 2012)
Forest residue (fly ash)	1	25.0	290.0	1.7	47.0	76.0	4.0		4260.0		13.0	200	20000						39.0	3630.0	(Pöykiö et al., 2014)
Forest residue (bottom ash)	1	5.7	318.0		36.0	29.0	14.0		2210.0		11.0	196.0	15600						41.0	950.0	(Pöykiö et al., 2009)
Forest residue fly-ash (sawdust and bark)	1	19	92	0.8	31.0	352	19	263	484		39	11	8400	24.0	10.0			284	36		(Lanzerstorfer, 2015)
Forest residue fly-ash (chips; 80% softwood)	1	105	76	0.1	23.0	602	36	221	91		39	140	4100	43.0	12.0			242	38		(Lanzerstorfer, 2015)
Forest residue fly-ash (chips; 80% softwood)	1	41	87	1.7	27.0	250	27	671	191		25	145	14600	5.0	10.0			641	10		(Lanzerstorfer, 2015)
Forest residue fly ash (chips; 90% softwood)	1	77	70	4.2	4.0	892	62	292	136		25	156	6800	5.0	10.0			283	10		(Lanzerstorfer, 2015)
Forest residue fly-ash (rubber tree; 95% chips, 5% bark)	1	9	15	0.1	31.0	53	15	227	357		34	5	2900	27.0	10.0			461	30		(Lanzerstorfer, 2015)
Forest residue fly-ash (90% chips, 10% horse dung)	1	32	41	0.1	6.0	228	19	114	144		34	5	1000	32.0	11.0			141	10		(Lanzerstorfer, 2015)
Wood bark (unknown)	1												274								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												300								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												0								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												4210								(Zevenhoven et al., 2012)

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn	
Wood bark (unknown)	1												1630								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												99								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												500								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												550								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												270								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												530								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												470								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												290								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												202								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												428								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												532								(Zevenhoven et al., 2012)
Wood bark (unknown)	1												465								(Zevenhoven et al., 2012)
bark, sawdust and offcuts	1		38.8	0.5	74.0	160	7.4	438.0	2600		17	144	11040		4			741	24	9100	(Kröppl et al., 2011)
bark, trimmings and offcuts, left over wood, sawdust	1		33.2	2.9	81.5	213	32.8	194.0	1400		9	100	10900		1			516	28	4100	(Kröppl et al., 2011)
raw wood	1		5.0	0.9	15.8	13.7	5.0	20.0	275.0		5.0	5.0	2000.0		1.0			105.0	2.0	330.0	(Kröppl et al., 2011)
mean		14.6	96.9	1.3	34	261	22	271	1059		23	101	5174		22.7	7.6		379	24	3268	<i>n = 107</i>
median		7.7	70.0	0.9	31	213	19	227	421		25	140	532		25.5	10.0		284	28	2563	
minimum		2.1	5.0	0.1	4	14	4	20	91		5	5	0		5.0	1.0		105	2	330	
10th percentile		3.4	15.0	0.1	6	29	5	95	137		9	5	99		5.0	1.0		134	10	640	
90th percentile		27.1	290.0	3.0	74	602	36	485	2561		39	196	14600		37.5	11.2		661	39	6600	
maximum		105.0	318.0	4.2	82	892	62	671	4260		39	200	35740		43.0	12.0		741	41	9100	
coefficient of variation		1.4	1.1	1.1	0.7	1.0	0.8	0.7	1.2		0.5	0.8	1.5		0.7			0.6	0.6	1.0	
grass																					
Miscanthus	4												3100								(Miles et al., 1995; Moilanen, 2006; Wigley et al., 2006)
straw																					
wheat	1	3	22	0.3	5	20	7	17	271		25	5	700	5	10			55	10	238	(Lanzerstorfer, 2015)
wheat	1	8	7	0.4	5	20	10	103	33		33	5	40	46	10			25	13	325	(Lanzerstorfer, 2015)
Corn	1								338				620							374	(Masia et al., 2007)
Oat	1												775								(Theis et al., 2006)
Rape	1								338				310							249	(Masia et al., 2007)
Rice	3												2790								(Miles et al., 1995; Thy et al., 2000; Thy et al., 2006)
Straw	2												155								(Wieck-Hansen et al., 2000; Wei et al., 2005)
straw ash	1	0.1	4.7	0.0	3.7	1.0														81.0	(Schiemenz et al., 2011)
Wheat	14												540								(Risnes et al., 2003; Moilanen, 2006; Thy et al., 2006)

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn	
Wheat (unknown)	1	1.4			14.3		3.8		684	0.9	2	38	752			3	0.4		12.8	65	(Miles et al., 1995; Bryers, 1996; Miles et al., 1996; D
Wheat (unknown)	1	1.9			31.5		4.4		786	0.9	6	68	896			0.8	2		16.8	94	(Thy et al., 2008)
Wheat (unknown)	1	1.8			23.5		4.6		826	1.0	7	56	915			0.9	0.9		18.6	98	(Thy et al., 2008)
Wheat (unknown)	1	1.6			22.3		4.5		741	0.9	5	50	842			1.1	1.2		15.3	80	(Thy et al., 2008)
Wheat (unknown)	1	1.7			20.5		4.5		800	0.9	9	48	851			1.5	0.9		16.6	77	(Thy et al., 2008)
Wheat (unknown)	1	2			19.1		5		783	0.9	6	52	892			1.7	20.6		17	85	(Thy et al., 2008)
Wheat (unknown)	1	1.4			19.6		4.3		750	0.9	3	52	822			2.7	20.7		16.5	77	(Thy et al., 2008)
Wheat (unknown)	1	1.8			17.1		5.6		711	0.9	17	76	811			2.7	0.6		14.6	94	(Thy et al., 2008)
Wheat (unknown)	1	1.4			17.6		4.1		699	0.9	2	42	779			2.7	0.7		15.4	70	(Thy et al., 2008)
Wheat (unknown)	1	1.2			19		11.8		647	0.9	2	32	732			2.5	0.4		17.7	61	(Thy et al., 2008)
Straw (unknown)	1												200								(Zevenhoven et al., 2012)
Straw (unknown)	1												0								(Zevenhoven et al., 2012)
Straw (unknown)	1												55								(Zevenhoven et al., 2012)
Straw (unknown)	1												66								(Zevenhoven et al., 2012)
Straw (unknown)	1												11								(Zevenhoven et al., 2012)
Straw (unknown)	1												9								(Zevenhoven et al., 2012)
Rice (unknown)	1	0.2			9.9		3.1		131	1.1	7	20	4348				0.4		4	162	(Thy et al., 2008)
Rice (unknown)	1	0.1			10.4		2.8		118	1.1	7	29	3899			0.1	0.8		3.3	184	(Thy et al., 2008)
Rice (unknown)	1	0.3			11.8		4		129	1.1	7	26	4127			0.1	0.5		4.1	192	(Thy et al., 2008)
Rice (unknown)	1	0.3			16.7		6		118	1.1	6	24	3726				0.4		3.6	185	(Thy et al., 2008)
Rice (unknown)	1	0.3			13		6.6		113	0.8	7	41	4054			0.1	0.4		3.4	201	(Thy et al., 2008)
Rice (unknown)	1	0.3			7		6.9		118	0.9	6	55	4201				0.4		3.4	218	(Thy et al., 2008)
Rice (unknown)	1	0.5			7.9		5.6		98	0.8	5	37	3559				0.3		2.8	175	(Thy et al., 2008)
Rice (unknown)	1	1			7		6.7		114	0.9	6	32	4175				0.5		3.4	201	(Thy et al., 2008)
Rice (unknown)	1	0.3			12.6		6		107	0.8	4	32	3798				0.3		3.1	187	(Thy et al., 2008)
Rice (unknown)	1	0.4			8.6		6.5		109	0.8	2	60	3921				0.4		3.3	213	(Thy et al., 2008)
Rice (unknown)	1	0.3			8.6		6.4		114	0.9	1	32	4001				0.3		3.2	197	(Thy et al., 2008)
Rice (unknown)	1	0.2			11.1		6.2		104	0.8	1	54	3879				0.4		3.2	211	(Thy et al., 2008)
Rice (unknown)	1	0.3			7.1		5.8		102	0.9	1	33	3557				0.3		2.8	172	(Thy et al., 2008)
Rice (unknown)	1	0.2			5.5		6.1		96	0.9	1	15	3675				0.3		3.3	161	(Thy et al., 2008)
mean		1.2	11.2	0.2	13.2	14	5.7	60	356	0.9	6.8	39.0	1829	25.5	10.0	1.5	2.3	40	8.9	163	<i>n=104</i>
median		0.5	7.0	0.3	11.8	20	5.7	60	130	0.9	6.0	37.5	847	25.5	10.0	1.5	0.4	40	4.1	175	
minimum		0.1	4.7	0.0	3.7	1	2.8	17	33	0.8	1.0	5.0	0	5.0	10.0	0.1	0.3	25	2.8	61	
10th percentile		0.2	5.2	0.1	5.3	5	3.9	26	101	0.8	1.0	17.5	51	9.1	10.0	0.1	0.3	28	3.2	76	
90th percentile		1.9	19.0	0.4	21.2	20	7.0	94	784	1.1	13.0	58.0	4076	41.9	10.0	2.7	1.8	52	16.9	240	

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn	
maximum		8.0	22.0	0.4	31.5	20	11.8	103	826	1.1	33.0	76.0	4348	46.0	10.0	3.0	20.7	55	18.6	374	
coefficient of variation		1.3	0.8	0.8	0.5	0.8	0.3	1.0	0.8	0.1	1.1	0.5	0.9	1.1	0.0	0.7	2.5	0.5	0.7	0.5	
other residues																					
hazelnut shell	1	11	58	0.5	32.6	181	6.9				7.5	416	86.3	11.4	51.5	42	62		14.6	1180	(Demirbas, 2005)
wheat straw	1	9.2	62.5	0.4	30.4	184	7.2				4.2	284	64.1	15.5	56.3	58.5	82		11.2	2680	(Demirbas, 2005)
olive husk	1	12.8	35.2	0.3	26.8	226	8.7				2.8	197	73.5	8.1	50.2	76.6	44.6		16.4	3870	(Demirbas, 2005)
waslnut shell	1	8.4	70.4	0.1	32.7	214	6.4				5	326	48.5	13.7	45.1	67.1	79		12.8	1850	(Demirbas, 2005)
almond shell	1	6.5	18.6	0.2	21.5	132	7.5				3.6	174	29.7	6.8	65.4	49.9	53.6		9.4	1250	(Demirbas, 2005)
sunflower shell	1	7.1	47.3	0.4	29.5	168	5.1				7.1	261	34.6	10.9	37.2	56.4	64.5		15	668	(Demirbas, 2005)
mustard stalks	1	7	61	0.1	35	26	0.1		376			113	77	10		0.1		885	59	161	(Singh et al., 2011b)
Olive residue	1								112.0				310.0							249.0	(Masia et al., 2007)
Palm kernels	1								<112				4570.0							748.0	(Masia et al., 2007)
Pepper plant	1												1320.0								(Masia et al., 2007)
Rice husks	5												155.0								(Umantahaswaran and Batra, 2008; Madhiyanon et al., 2004)
																					(Bryers, 1996; Feng et al., 2004)
Rice waste	1												660.0								(Zevenhoven et al., 2012)
Rice waste	1												176.0								(Zevenhoven et al., 2012)
Rice waste	1												182.0								(Zevenhoven et al., 2012)
oil residue	1												12.0								(Zevenhoven et al., 2012)
oil residue	1												25.0								(Zevenhoven et al., 2012)
oil residue	1												60.0								(Zevenhoven et al., 2012)
shell seeds and hulls	1												0.0								(Zevenhoven et al., 2012)
shell seeds and hulls	1												12.0								(Zevenhoven et al., 2012)
shell seeds and hulls	1												4.0								(Zevenhoven et al., 2012)
bagasse	1												48.0								(Zevenhoven et al., 2012)
bagasse	1												43.0								(Zevenhoven et al., 2012)
rape meal ash	1	0.5	228.0	0.0	274.0	11.9														249.0	(Schiemenz et al., 2011)
cereal ash	1	1.3	13.7	0.0	13.1	2.6														750.0	(Schiemenz et al., 2011)
unknown plant origin																					
unknown plant origin	24																				STRUBIAS - ECOFI contribution
animal biomass																					
poultry manure																					
poultry manure	1	1.8	25.3	0.0	21.6	11.9	3.3					585.0								2379.0	STRUBIAS contribution - IE

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn		
poultry manure	1								<112											998.0	(Masia et al., 2007; Tortosa Masia et al., 2007)	
poultry manure	1	0.2	4.5	0.0	5.0	0.9	0.3					69.7	4395.0						2.6	389.7	STRUBIAS contribution - confidential data provider	
poultry manure	1	1.9	23.0	0.0	31.2	11.3	2.7					526.0	24.0						23.9	2494.0	STRUBIAS contribution - confidential data provider	
poultry manure	1							110.0			5.6	333.0	1950.0	12.1							1621.0	STRUBIAS contribution - confidential data provider
poultry manure	1	3.4	16.2	0.0	18.4	43.6	4.5					216.0							9.2	1652.0	STRUBIAS contribution - confidential data provider	
poultry manure	?							130.0			2.0	300.0	1200.0	5.0		2.0						STRUBIAS contribution - ESSP (Fibrphos)
poultry manure	415																					STRUBIAS contribution - ESSP (BMC Moerdijk, Biller
poultry manure	1		24.0						72.0			176.0	1196								991.0	(Staroń et al., 2016)
poultry manure	1											165.0	209			2.4					136.0	(Blake and Hess, 2014)
poultry manure	1	2.0	14.3		42.0	3.7	1.0				7.0	553.0	4143	96.0					12.0	3795.0	(Lynch et al., 2014)	
poultry manure	1		112.0		10.0							71.0	596								209.0	(Abelha et al., 2003)
poultry manure	1	0.4			14.8	6.0	15.0					43.1	1600								600.0	(Codling et al., 2002)
poultry manure	1							249.0				1222.0	3120								2670.0	(Reiter and Middleton, 2016)
poultry manure	1							139.0				1089.0	2160								1510.0	(Reiter and Middleton, 2016)
poultry manure	1							221.0				3429.0	4600								2888.0	(Reiter and Middleton, 2016)
poultry manure	1							234.0				1861.0	2940								2515.0	(Reiter and Middleton, 2016)
poultry manure	1							98.0				809.0	860								2879.0	(Reiter and Middleton, 2016)
poultry manure	1							242.0				3252.0	2450								1793.0	(Reiter and Middleton, 2016)
mean		1.6	31	0.0	20	13	4.5	178	72		4.9	865	2096	38		2.2			12	1736	<i>n</i> =440	
median		1.9	23	0.0	18	9	3.0	180	72		5.6	526	1950	12		2.2			11	1652		
minimum		0.2	4	0.0	5	1	0.3	98	72		2.0	43	24	5		2.0			3	136		
10th percentile		0.3	10	0.0	8	2	0.6	106	72		2.7	70	364	6		2.0			5	317		
90th percentile		2.7	60	0.0	36	28	9.7	244	72		6.7	2417	4294	79		2.4			20	2883		
maximum		3.4	112	0.0	42	44	15.0	249	72		7.0	3429	4600	96		2.4			24	3795		
coefficient of variation		0.7	1.2	0.4	0.6	1.2	1.2	0.4			0.5	1.2	1	1		0.1			0.7	0.6		
slaughterhouse waste																						
meat and bone meal	1								<112											623.0	(Masia et al., 2007)	
meat and bone meal	1																			0.0	(Deydier et al., 2005b)	
meat and bone meal (bottom ash)	1	0.4	50.0		25.0	2.0		5.0				50.0							2.0	100.0	STRUBIAS contribution - ESPP	
slaughterhouse waste (bottom ash)	1	0.3	136.2		93.0	15			208.4		9.5	189.5			8.7		10	273.8	206.1	262.0	(Coutand et al., 2008)	
slaughterhouse waste (fly ash)	1	1.7	115.3		97.0	15			158.0		73.5	133.2			12.1		23	104.1	177.6	1349.0	(Coutand et al., 2008)	
slaughterhouse waste (fly ash washed)	1	0.4	155.3		119.9	15			184.6		24.3	213.7			36.9		48	237.0	197.3	3372.0	(Coutand et al., 2008)	
chicken feathers	1		51.0						112.0			582.0	1770.0								8444.0	(Staroń et al., 2016)
meat and bone meal	1		36.0						154.0			42.5	76.0								521.0	(Staroń et al., 2016)
meat and bone meal	1	1.0	13.0	5.0	9.0	15	5.0					270.0									940.0	(Skodras et al., 2006)

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn		
meat and bone meal	1		5.0	0.0	5.0	5	25.0					5.0	5.0								87.1	(Gulyurtlu et al., 2007)
meat and bone meal (bottom ash)	1	0.3	32.4		17.7	1.3	0.4		43.0	0.9	1.2	70.0		2.7	4.1		1	145.0	3.1	39.2		(Cyr and Ludmann, 2006)
mean		1.1	60	0.9	41	13	8.1	121	120		15.7	575	1587	37		1.7			71	1516		<i>n=15</i>
median		0.6	50	0.0	25	15	5.0	106	112		6.9	133	364	6		2.2			20	521		
minimum		0.2	1	0.0	1	1	0.3	0	43		0.5	1	1	1		0.1			1	0		
10th percentile		0.3	6	0.0	5	1	0.5	2	66		1.0	13	3	2		0.7			2	16		
90th percentile		2.7	130	2.2	97	26	18.0	247	187		34.1	1867	4386	88		2.4			198	3584		
maximum		3.4	155	5.0	120	44	25.0	249	208		73.5	3429	4600	96		2.4			206	8444		
coefficient of variation		1.0	0.9	2.1	1.0	1.0	1.1	0.9			1.5	1.8	1	1		0.5			1.3	1.5		

Contaminated biomass

Waste water treatment sludge (raw)

waste water treatment sludge (raw)	1																				0.5	(Werther et al., 2000)
waste water treatment sludge (raw)	1																				0.5	(Wei et al., 2005)
waste water treatment sludge (raw)	1																				0.5	STRUBIAS contribution - confidential data provider
waste water treatment sludge (raw)	1	4.1	142.0	0.1	92.0	440.0				0.5	26.0	1300.0	1900.0	36.0	14.0	1.0				50.0	3600.0	STRUBIAS contribution - confidential data provider
wastewater treatment sludge (raw - DE)	252	3.3	267.0	0.8	105.8	151.0	17.5		2173.0		28.1	916.0	1914.0	25.3	23.0	2.5	194.0	578.0	136.0	2535.0		(Krüger and Adam, 2015)
waste water treatment sludge (raw, mono-inc)	191	1.8	66.6	0.1	37.9	50.4	11.1					703.0								1650.0		STRUBIAS contribution - confidential data provider
waste water treatment sludge (raw, mono-inc)	196	1.7	89.0	0.5	742.0	77.0	9.3					48.0								2160.0		STRUBIAS contribution - confidential data provider
waste water treatment fly ash	1	7.0	1047.0	0.0	119.5	138.0	16.2				27.2	665.5		25.5	6.9		364.0			4472.0		(Kasina et al., 2016)
wastewater treatment sludge (raw - FI)	1																					(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												171.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												98.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												50.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												15.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												20.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												20.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												160.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												94.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												57.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												70.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												211.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												60.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - FI)	1												58.0									(Zevenhoven et al., 2012)
wastewater treatment sludge (raw - UK)	1	8.7	621.5	1.4	212.8	575.0	17.9					563.0		44.8	31.2	1.3				2179.0		(Donatello et al., 2010)
wastewater treatment sludge (raw - UK)	1	3.0	169.0	0.1	70.0	361.5	18.8					305.0		16.7	36.1	3.2				1355.0		(Donatello et al., 2010)

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn	
wastewater treatment sludge (raw - UK)	1	2.3	248.5	0.1	70.9	285.0	50.7					317.0		15.7	52.1	2.1				1410.5	(Donatello et al., 2010)
wastewater treatment sludge (raw - UK)	1	1.6	264.5	0.1	81.6	229.5	9.6					354.5		12.6	20.0	2.4				1136.0	(Donatello et al., 2010)
wastewater treatment sludge (raw - UK)	1	17.4	383.5	0.5	143.0	554.5	161.0					556.0		31.4	160.0	2.5				2337.5	(Donatello et al., 2010)
wastewater treatment sludge (raw - UK)	1	1.8	59.6	2.9	61.8	238.5	10.1					398.0		17.4	14.1	5.3				1105.0	(Donatello et al., 2010)
waste water treatment sludge (raw)	1	270.0	490.0	0.5	100.0	4600.0	460.0	300.0	400.0	2.0	12.0	2000.0	810.0	36.0	####	5.0	1200.0		49.0	37.0	(Kalmykova and Karlfeldt Fedje, 2013)
mean		26.9	320.7	0.6	153	642	71					642		25		3.1				1366	<i>n</i> =665
median		3.2	256.5	0.3	96	262	18					398		17		2.5				1355	
minimum		1.6	59.6	0.0	38	50	9					305		13		1.3				37	
10th percentile		1.7	68.8	0.1	63	83	10					312		14		1.7				678	
90th percentile		16.5	608.4	1.3	206	573	161					1138		40		5.1				2242	
maximum		270.0	1047.0	2.9	742	4600	460					2000		45		5.3				2338	
coefficient of variation		2.9	0.9	1.4	1.2	2.0	1.9					0.9		0		0.5				0.6	
Waste water treatment sludge (post-processed)																					
wastewater treatment sludge (post-processed)	1	0.3	0.1 (IV)	0.3	56.0	60	3.6					601.0								1710.0	STRUBIAS contribution - ESPP (AshDec process)
wastewater treatment sludge (post-processed)	1	0.7	<1 (IV)	0.1	29.0	14	9.9	74.0			4.0	330.0	2400.0	10.0					32.0	290.0	STRUBIAS contribution - confidential data provider
wastewater treatment sludge (post-processed)	1	0.0	<1 (IV)	0.0	<15	<20	0.6					74.0								85.0	STRUBIAS contribution - confidential data provider
wastewater treatment sludge (post-processed)	4	0.3	109.5	0.7	17.0	4.2	4.7					115.0								85.0	P-REX (Mephrec process)
wastewater treatment sludge (post-processed)	4	3.9	34.2	0.2	13.9	25.3	10.0					853.0								1394.0	P-REX (LeachPhos process)
wastewater treatment sludge (post-processed)	1	0.4	1.4	0.4	0.4	0.43						1.0								1.0	P-Rex (Ecophos process)
mean		0.9	48.4	0.3	23.3	20.8	5.8					329.0								594.2	<i>n</i> =12
median		0.4	34.2	0.3	17.0	14.0	4.7					222.5								187.5	
minimum		0.0	0.9	0.0	0.4	0.4	0.6					0.9								0.6	
10th percentile		0.2	8.0	0.0	5.8	1.9	1.8					37.5								43.0	
90th percentile		2.3	94.4	0.6	45.2	46.1	10.0					727.0								1552.0	
maximum		3.9	109.5	0.7	56.0	60.0	10.0					853.0								1710.0	
coefficient of variation		1.6	1.1	0.9	0.9	1.2	0.7					1.0								1.3	
mix of wood, treated wood and sewage sludge	1		41.5	0.5	66.5	110	19.2	20.0	780		6	82	2700		1			415	34	11400	(Kröppl et al., 2011)
treated and untreated wood	1		108.0	2.5	65.0	1500	32.9	91.5	3550		14	291	6050		24			410	30	6700	(Kröppl et al., 2011)
treated wood, saw mills, swarf, trimmings	1		215.0	0.5	92.1	3030	59.5	288.0	6000		17	1100	2040		146			360	69	10600	(Kröppl et al., 2011)
slaughterhouse waste and sewage sludge mix	1														1.0			2			STRUBIAS contribution - FEhS
Currency shredded	1																			16.5	
Demolition wood	3																			1.0	
Waste wood	1												77								(Zevenhoven et al., 2012)

Input material	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Be	Co	Cu	Mn	Mo	Sb	Se	Sn	Sr	V	Zn		
Waste wood	1												83									(Zevenhoven et al., 2012)
Waste wood	1												84									(Zevenhoven et al., 2012)
Waste wood	1												76									(Zevenhoven et al., 2012)
Waste wood	1												54									(Zevenhoven et al., 2012)
Waste wood	1												107									(Zevenhoven et al., 2012)
Waste wood	1												77									(Zevenhoven et al., 2012)
Waste wood	1												355									(Zevenhoven et al., 2012)
Waste wood	1												545									(Zevenhoven et al., 2012)
Waste wood	1												159									(Zevenhoven et al., 2012)
Furniture waste	1																				0.3	
Mixed waste paper	1																				2.6	
Greenhouse-plastic waste	1																				0.5	
Refuse-derived fuel	1																				1.1	
Wood yard waste	1																				0.2	
municipal solid waste	1	160	204	8.9	42	1530	18.8				14.2	680	420	16.2	90.2	40.8	130		23.4	3840		(Demirbas, 2005)
municipal solid waste (UK)	8																					(Bogush et al., 2015)
paper industry waste	?	1.7		0.3	32.1	35.9						38.2									110.0	STRUBIAS contribution - CEPI
paper industry waste	391	5.7		0.3	40.0	72.8	17.6					200.9									1545.0	STRUBIAS contribution - CEPI

16.3 Pyrolysis & gasification materials

16.3.1 Macroelements

Table 32: Macroelements (% , dry matter) for C-rich and nutrient-rich pyrolysis materials (references: Kleber et al. (2015), Someus (2015), Zwetsloot et al. (2016))

	C	N	P	K	S	Ca	Mg	Fe
	(% , dry matter)							
C-rich pyrolysis materials								
Corn	58.8	1.06	0.2	1.9	0.0	0.9	0.7	0.7
Wheat/barley	60.8	1.41		0.1		1.3	1.0	0.2
Rice straw/husk	43.6	1.4	0.1	0.1	0.4			
Sorghum	56.4	0.74	0.2	0.4				
Soybean stover	75.4	1.59			0.0			
Peanut shell	75.3	1.83	0.2	1.1	0.1	0.3	0.1	
Pecan shell	75.9	0.26		11.6	0.0	0.6	0.1	0.0
Hazelnut shell	77.5	0.52	0.0	0.5		0.3	0.1	
Switchgrass	73.9	0.98	0.2	0.8		0.3		0.0
Bagasse	78.6	0.87	0.1	0.2		0.7	0.2	0.0
Coconut coir	73.8	0.88						
Other	64.9	1.16	0.2	1.4	0.1	0.6	0.3	0.1
Hardwoods	74.4	0.72	0.1	0.9	1.6	1.0	1.0	0.2
Softwoods	74.6	0.79	0.1	1.7	0.0	2.1	1.8	1.0
Food waste	44.4	3.28	0.7	0.9		5.2	0.5	
nutrient-rich pyrolysis materials								
Papermill waste	19.9	0.09	0.1	0.3		28.1	0.3	
Poultry manure/litter	35.3	2.15	3.3	6.0	0.9	10.3	1.2	0.3
Turkey manure/litter	31.8	2.02	3.1	4.8	0.5	4.8	1.0	0.3

Swine manure	44.9	2.79	6.1	2.3	0.8	4.8	2.9	0.6
Dairy manure	58.1	2.37	0.9	1.7	0.3	2.7	1.2	0.6
Cattle manure	48.5	1.9	0.9	4.1	0.4	2.9	1.0	0.3
Animal bone	8.0		12.4	2.0		24.3	5.7	
Animal bone	8.2	1.5	15.3	0.3	0.1	33.7	0.6	0.0
Sewage sludge	23.8	1.12	4.2					

1 16.3.2 Metals and metalloids

2 **Table 33: Metal and metalloid contents (mg kg⁻¹, dry basis) and persistent organic pollutants for different types of pyrolysis & gasification materials**

	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Co	Cu	Mn	Mo	Sb	Se	V	Zn	PAH	PCB¥	reference
(mg kg ⁻¹ dry matter)																				
C-rich pyrolysis materials																				
soybean stover	1										34									(Ippolito et al., 2015)
pecan shell	1										8.28									(Ippolito et al., 2015)
coconut coir	1										66.2									(Ippolito et al., 2015)
rice (300°C)	1																	2		(Freddo et al., 2012)
rice (600°C)	1																	1		(Freddo et al., 2012)
bamboo (300°C)	1	0.03	4.3		1.4	1.9	0.3				10						124	2		(Freddo et al., 2012)
bamboo (600°C)	1	0.03	3.4		1.2	3.9	0.3				6.3						207	1		(Freddo et al., 2012)
redwood (300°C)	1	0.94	4.5		0.4	0.6	0.1				2						38	4		(Freddo et al., 2012)
redwood (600°C)	1	0.02	3.4		0.6	0.9	0.2				2						38	0		(Freddo et al., 2012)
maize (300°C)	1	0.03	5.1		0.4	0.1	0.2				10.6						92	4		(Freddo et al., 2012)
maize (600°C)	1	0.03	6.5		0.6	1.1	0.2				13.2						54	5		(Freddo et al., 2012)
softwood (500°C)	1	0.02	0.1		0.1	0.1	0				0.04						0.9	9		(Freddo et al., 2012)
pine	1	0.1	2.8			1					14						16			(Knowles et al., 2011)
sawdust	1				7						48	185					31			(Mankasingh et al., 2011)
palm leaves	1				7						87	193					46			(Mankasingh et al., 2011)
rice paddy husk	1				10						27	704					77			(Mankasingh et al., 2011)
rice paddy husk	1				2						8	321					36			(Mankasingh et al., 2011)
Prosopis	1				26						20	940					48			(Mankasingh et al., 2011)
cassia stems	1				12						29	191					46			(Mankasingh et al., 2011)
citrous wood	1							60			39	145					505			(Graber et al., 2010b)
peanut hulls (400°C)	1	1	4		2			32			16	116	5				35			(Gaskin et al., 2008)

	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Co	Cu	Mn	Mo	Sb	Se	V	Zn	PAH	PCB¥	reference
peanut hulls (500°C)	1		4		2			34			19	131					37			(Gaskin et al., 2008)
pine chips (400°C)	1				2			6			25	274					15			(Gaskin et al., 2008)
pine chips (500°C)	1		3		3			4			9	258					18			(Gaskin et al., 2008)
wood	5	1	10	0.1	11	9	3	19	20	3	12	215	3.5	5		3	102	10.5		(ECN, 2017)
herbaceous plants	9	0.1	12.1	0	17	45	4	55	97	6	19	380	2.3	6	2	8	48	15.5		(ECN, 2017)
plant (unknown)					3	1	<1			<1	3				<0.3		19	1	-	(Someus, 2015)
plant (unknown)	1	<0.3	9	0.04	13	8	<1			1	9				<0.3		150	5	-	(Someus, 2015)
plant (unknown)	1	0.4	15	<1	14	14	1			3	49				0.5		294	0	-	(Someus, 2015)
other	1										4.76									(Ippolito et al., 2015)
shrub cutting (untreated)	1	0.56	81.5	0.01	75.4	23	1.9													STRUBIAS - EUROFEMA
slug pellet (98% wheat flour, 2% ferric phosphate)	1	0.49	69.5	0.01	60.4	19	1.6													STRUBIAS - EUROFEMA
tobacco flour	1	0.42	46.1	0.01	31.1	4	0.55													STRUBIAS - EUROFEMA
carbonaceous product	1	0	4	0	5	16	3				25						45			STRUBIAS - EUROFEMA
mineral-rich pyrolysis materials																				
fermentation residues	1	0.58	181	0.01	237	29	2.33													
poultry manure/litter	1										472								0.4	(Ippolito et al., 2015)
poultry litter (400°C)	1	3	28		14			91			805	596	17				628			(Gaskin et al., 2008)
poultry litter (500°C)	1		59		20			100			1034	725	14				752			(Gaskin et al., 2008)
poultry litter (350°C)	1	0.25			8	1					213									(Uchimiya et al., 2012)
poultry litter (700°C)	1	0.11			11	1					310									(Uchimiya et al., 2012)
turkey manure/litter	1										107								0.4	(Ippolito et al., 2015)
turkey litter (350°C)	1	0.7			29	2					535									(Uchimiya et al., 2012)
turkey litter (700°C)	1	0.7			40	-					762									(Uchimiya et al., 2012)

	n	Cd	Cr (total)	Hg	Ni	Pb	As	B	Ba	Co	Cu	Mn	Mo	Sb	Se	V	Zn	PAH	PCB¥	reference
swine manure	1	<1	11	<0.01	18	<10	1.2				377						1098	<0.1		STRUBIAS - confidential
swine manure	1										114								0.4	(Ippolito et al., 2015)
swine solids (350°C)	1	0.57			16	3					1538									(Uchimiya et al., 2012)
swine solids (700°C)	1	0.23			26	-					2446									(Uchimiya et al., 2012)
dairy manure	1										222								0.4	(Ippolito et al., 2015)
dairy manure (350°C)	1	0.2			16	1					99									(Uchimiya et al., 2012)
dairy manure (700°C)	1	-			25	0					163									(Uchimiya et al., 2012)
paved feedlock manure (350°C)	1	0.2			4	1					92									(Uchimiya et al., 2012)
paved feedlock manure (700°C)	1	0.02			7	0					136									(Uchimiya et al., 2012)
animal bone material	1	<0.3	<1	<0.03	<1	<1	<1			<1	8				<0.3		203			(Someus, 2015)
papermill waste	1										513									(Ippolito et al., 2015)
undetermined	1	<0.5	11	<0.05	7.9	<5	<4	98.2		5.52	158	1070	10.9		<2		1500			STRUBIAS - confidential

¥: WHO eq, ng kg-1 dry matter

3

4

5 **17 Methods**

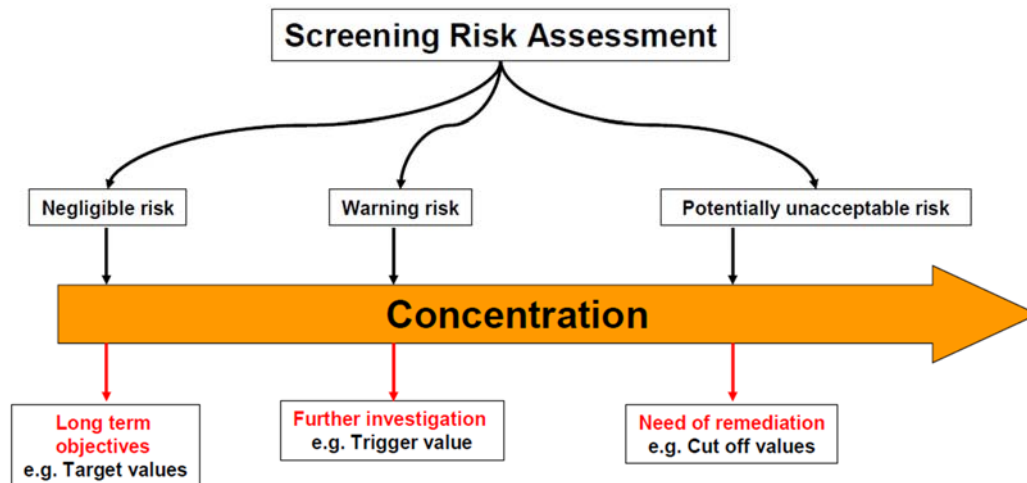
6 **17.1 Soil screening values and acceptable soil screening limit concentrations**

7 **Soil Screening Values** are concentration limits (mg kg^{-1} soil dry weight) of contaminants in
8 the soil above which certain actions are recommended, enforced or adopted in many Member
9 States in Europe in order to protect the environment and human health (Carlton, 2007). Hence,
10 **this assessment cannot be interpreted as a risk assessment as the relationship between**
11 **the soil screening limit values and the actual risk for human health or the environment**
12 **has been established by the individual Member States.** Rather, the calculations should aid
13 Member States and stakeholders to make a valid approximation of the limit concentrations
14 for fertilising materials in order to ensure that the long-term use of such materials does not
15 lead to exceeding the soil screening values that have been established at Member State level
16 based on scientific and other concerns.

17
18 Clear **advantages** of the use of soil screening values are the speed and ease of the
19 assessment, and the comparability, transparency and the straightforward understanding by a
20 wide variety of non-specialist stakeholders (Carlton, 2007). One of the major **limitations** is
21 that crucial site-specific considerations cannot be included for which reason rather
22 conservative limit values are typically set.

23
24 The **type of soil screening values** can be related to **different levels of risk**, e.g. negligible
25 risk or potentially unacceptable risk levels (Carlton, 2007). On the one hand, the derivation of
26 *negligible risk* levels aims at excluding any type of adverse effect on even the most sensitive
27 land. It is characterized by a very high conservatism, the comprehensive protection of the
28 natural environment and the definition of long term sustainability objectives. On the other
29 hand, the derivation of *potentially unacceptable risk levels* aims at preventing significant
30 adverse effects. It is characterised by a low conservatism and a functional perspective of soil
31 protection directed to the support of human living and main ecological functions. In some
32 cases, the need for further investigations is related to some intermediate risk levels. A useful
33 intermediate risk is then associated with a scenario based on generic (protective)
34 assumptions, the validity of which could be checked in a site-specific risk assessment.
35 Therefore, in some cases three sets of soil screening values can be derived on the basis of
36 negligible, *intermediate (warning)* and potentially unacceptable risk levels, and these soil
37 screening values may be applied as long term quality objectives, trigger values and cut-off
38 (remediation needed) values, respectively, as it is exemplified in Figure 33.

39



40
41 **Figure 33: Derivation of soil screening values based on various risk levels and**
42 **application of the different screening values (adopted from Carlon, 2007)**
43

44 In summary, screening values can be classified into different risk categories, broadly termed
45 negligible risk, *warning risk* and potentially unacceptable risk. The appreciation triggered by
46 each risk category as well as the exact interpretation thereof, however, depends on the
47 national regulation. Moreover, they can be distinguished into screening risk and site-specific
48 risk concentration values (Carlon, 2007).
49

50 The applied **category of risk** in the derivation of a specific screening value is usually related
51 to the intended application within the legal framework. In this regard, there are no fixed rules,
52 but common practices. Long term objectives for soil quality, for example, are usually based
53 on the negligible risk level; in this case soil screening values might relate to multifunctional
54 uses of the site or could be a representation of sustainable soil quality. By definition and for
55 practical reasons, natural average background values are often regarded to be associated to
56 negligible risk level (soil quality objectives lower than the average background level would
57 not be feasible). On the other hand, the possible need for actions is often related to levels
58 indicating a potential unacceptable risk. In an extended definition, actions can include
59 remediation, restrictions in land use, urgency for remediation, further investigations and/or
60 the application of site-specific risk assessment.
61

62 Soil screening values adopted in **European countries vary widely** in multiple aspects
63 (Carlon, 2007). The use of soil screening values varies from setting long term quality
64 objectives, via triggering further investigations, to enforcing remedial actions. Derivation
65 methods of soil screening values have scientific and political bases. In relation to the
66 common market and common environmental policies in Europe, this variability has raised
67 concern among both regulators and risk assessors (Carlon, 2007).
68

69 The **predicted accumulation** estimates how much of a trace metal accumulates in soil
70 following annual applications (over years of farming) and takes into account an estimated
71 loss of trace metals in soil from transport of the trace metal into surrounding media – a mass-

72 balance approach (The Weinberg Group Inc., 2000). The accumulation and behaviour of
 73 trace metals in soil from agricultural application depends essentially on (1) **farming duration**
 74 **(years)**, (2) **the application rate of the fertilising products**, (3) **the concentration of the**
 75 **trace metal in the fertiliser and (4) the fate and transport of the trace metal in soil.**
 76

77 Because soil accumulation depends on so many different factors, which all vary given any
 78 situation, not all situations can be represented when deriving the predicted accumulation. The
 79 soil accumulation calculation is based on the most important parameters and loss pathways,
 80 and is estimated based on representative high-end (general, not site-specific) assumptions
 81 resulting in **more protective limit metal and metalloid concentrations.**
 82

83 Therefore, the assessment deployed in this work is based on following principles and
 84 assumptions:

- 85 ○ The *warning risk* will be considered as the level of risk for the derivation of
 86 the soil screening values. Some Member States (e.g. Italy, Lithuania, the
 87 Netherlands, Poland, UK) apply only two levels of risk (negligible risk and
 88 potentially unacceptable risk), in which case their screening value for
 89 potentially unacceptable risk will be considered. Soil screening values differ
 90 largely between Member States across Europe (Table 34). **The value of the**
 91 **25th percentile of the distribution of soil screening values across EU Member**
 92 **States has been selected as the maximum accumulation** (i.e. 75% of the soil
 93 screening values across EU Member States are higher than the selected value).
 94 For Ba, however, the 25th percentile values is close to its average background
 95 concentration in European soils for which reason the 50th percentile value was
 96 selected as predicted no-effect concentration (Table 34).
 97
 98

99 **Table 34: Soil screening values for different EU Member States (regular format: warning risk;**
 100 **italic format: potentially unacceptable risk for metals and metalloids (mg kg⁻¹ dry weight)**
 101 **(Source: Carlon, 2007). The values given in bold indicate the predicted no-effect concentrations**
 102 **(PNEC) applied for the assessment of this study based on the interpolated 25th percentile of the**
 103 **distribution of soil screening values across EU Member States, with the exception of Ba where**
 104 **the median value (50th percentile) was used.**

	AT	BE-FI	BE-Wa	CZ	FI	DE	SK	DK	SE	IT	LT	NL	PL	UK	median value	25th percentile
As	20	58	40	65	5	50	30	10	15	20	10	55	22.5	20	21.25	16
Ba			1000								600	625	285		612.5	521
Be			15			20				2	10	30			15	10
Co			180	20		50		200	20	30	240	45			47.5	28
Cr	50		125	450	100	400	250	50	250	150	100	380	170	130	150	100
Mo			50			40	2			5	200	25			32.5	10
Sb	2		25	2						3	5	100		35	5	3
Se						5				3	5	100		35	5	5
V			340	100		200		200	200	90	150	250			200	125

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- With the exception of Tl, the screening of the list of metals and metalloids revealed that the list of elements is complete and encompasses all different potentially toxic metals/metalloids that can be found in thermal oxidation materials & derivatives and pyrolysis & gasification materials derived from the eligible input materials. **Thallium is considered as toxic for human and animal organisms, microorganisms and plants (Nriagu, 1998; Peter and Viraraghavan, 2005).** The toxicity of this element is higher compared to Hg, Cd and Pb (Repetto et al., 1998; Peter and Viraraghavan, 2005). **Major sources, which could lead to increased concentrations of Tl in the environment, include materials derived from fossil fuels and mineral ores, both present on the eligible input material list for this CMC (Antonia López Antón et al., 2013; Karbowska, 2016).** Environmentally safe limits for Tl in soils vary from 1 to 2 mg kg⁻¹ (Canadian Council of Ministers of the Environment (CCME), 2003; Xiao et al., 2004; van Vlaardingen et al., 2005). In this assessment, **the upper value of 2 mg kg⁻¹ will be used for deriving soil screening acceptable limit concentrations of selected metals and metalloids.**

- The **application scenario** of the STRUBIAS materials is a challenging aspect to consider given their wide-ranging nutrient concentration. Compared to traditional fertilisers, much bigger single doses of wood ash should be applied to get plant growth responses or liming effects from ash additions (up to 3 tonnes of wood ash per hectare per year (Haglund and Expertsgrup, 2008)). The application rates of 3 tonnes ha⁻¹ yr⁻¹ is retained in this assessment. On croplands, the fertilising products are often ploughed into the soil, but this is not the case for applications at forests and permanent grasslands. A farming duration of *100 years* and a soil-fertiliser mixing layer of 20 cm is assumed for this evaluation. The assumed application rates vary as a function of STRUBIAS material, with assumed rates of *3, 5 and 20 tonnes ha⁻¹ yr⁻¹* for thermal oxidation materials & derivatives, nutrient-rich pyrolysis & gasification materials and carbon-rich pyrolysis & gasification materials, respectively. This high-end scenario enables to consider more readily available, average values for background trace metal concentrations in soils, atmospheric trace metal deposition and solid-liquid partition coefficients. Moreover, the soil bulk density is assumed to be 1.4 g cm⁻³ (Table 35).

Table 35: Assumptions made for the application scenario for STRUBIAS materials

Parameter	Description	value applied	unit
AR	application rate	3/5/20	tonne ha ⁻¹ yr ⁻¹
T	deposition period	100	yr
Z	soil mixing depth	20	cm
BD	soil bulk density	1.4	g cm ⁻³

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- European *averages* of metals and metalloids for soil background concentrations are used as these are well-documented for most metals and metalloids (FOREGS, 2005) (Table 36). As no value was available for Se in the FOREGS database, the values documented by De Temmerman et al. (2014) were used (Table 36).
 - *Average* data on atmospheric deposition at agricultural and forested European ecosystems is preferentially used (Heinrichs and Mayer, 1977; Tyler, 1978; Zöttle et al., 1979; Bergkvist, 1987; Injuk et al., 1998; Chester et al., 1999; Ruschetta et al., 2003; Morselli et al., 2004; Kyllonen et al., 2009; Morabito et al., 2014; Pan and Wang, 2015) (Table 36). Data available for the different metals and metalloids is, however, rather limited. Moreover, the data do not show good geographic coverage for Europe. If no values for particular elements are available for terrestrial ecosystems, best estimates from atmospheric deposition at sea or other geographic regions are used. A sensitivity analysis was performed to assess the importance of any variations on atmospheric deposition rates of metals and metalloids, but indicated that the outcomes are only insignificantly affected by variations in atmospheric deposition.
 - Leaching and plant uptake are considered as outputs of metals and metalloids from the soil. Fate and transport of trace metals depends on the soil condition, climatic conditions and trace metal behaviour and adsorption kinetics. The deployed approach is based on the assumption of *elemental solid-liquid partitioning* for the elements, and it is considered that any metals available in the liquid fraction are removed from the soil through leaching and plant uptake. Liquid-solid partition coefficients applied in this assessment are average values as collected from different studies and soil types (van Vlaardingen et al., 2005; Sheppard et al., 2009; Janik et al., 2015b). Based on the results from the GEMAS project (Janik et al., 2015b), it is recognised that the use of K_d coefficients to model sorption of metals and metalloids is associated to a high degree of uncertainty since K_d values are extremely variable as a result of the impact of, for instance, pH, organic matter and to some extent clay and oxides on the retention of metals in soils. Therefore, sensitivity analyses with different K_d values were executed to evaluate the robustness of the analysis performed.
 - A default percolation (precipitation minus evapotranspiration) estimate of 200 mm year⁻¹ and a gravimetric soil water content of 0.3 (v/v) are assumed (conservative estimates from an EU perspective). Sensitivity analyses indicated that the liquid-solid partition coefficient was the most important parameter determining trace metal losses, and that the outcome was relatively insensitive to variations in precipitation and soil moisture content.

189 **Table 36: Applied values of soil background concentration, solid/liquid partition coefficients**
 190 **and atmospheric depositions as applied for deriving soil screening acceptable limit**
 191 **concentrations of selected metals and metalloids in CE fertilising products derived from**
 192 **STRUBIAS materials.**

	soil background concentration (mg kg ⁻¹) (adopted from FOREGS, 2005)	atmospheric deposition (mg m ⁻² yr ⁻¹) (various sources (1-11))		Solid/liquid partition coefficients (K _d , L kg ⁻¹) (mean values from (12), (13) and (14))
As	11.6	0.17	(1) and (2)	140
Ba	400	1.99	(3)	1269
Be	2.0	0.03	(4)	179
Co	10.4	0.29	(4,8)	1302
Cr	60.0	4.1	(5-9)	350
Mo	0.94	2.6	(10)	297
Sb	1.04	0.3	(9)	224
Se	0.33*	0	(3)	17
Tl	0.66	0.35	(11)	12579
V	60.4	3.8	(1, 2, 5, 7, 8)	582

(1) Kyllönen et al., 2009; (2) Injuk et al., 1998; (3) Ruschetta et al., 2006; (4) Zöttle et al., 1979; (5) Tyler, 1978; (6) Bergkvist, 1987; (7) Morselli et al., 2004; (8) Chester et al., 1999; (9) Heinrichs and Mayer, 1977; (10) Morabito et al., 2014; (11) Pan and Wang, 2015; (12) van Vlaardingen et al., 2005; (13) Sheppard et al., 2009; (14) Janik et al., 2015.

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- Trace metals are added to soil over years of farming. Because of losses from the root zone, the rate of accumulation of the trace metals in the soil will slow down over the years. Following application year after year, on the same soil, the concentrations of the trace metals are expected to reach a steady state. The rate at which a metal/metalloid is lost from the soil through leaching and plant uptake is defined as the soil loss constant. Following equation is then used to calculate the soil loss constant (The Weinberg Group Inc., 2000):

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$$K_s = \frac{P}{\theta * Z * (1 + BD * \frac{K_d}{\theta})} \quad \text{(Equation 1)}$$

203

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where:

206

K_s = soil loss constant (yr⁻¹)

207

P = average annual precipitation (cm yr⁻¹)

208

Z = soil mixing depth (cm)

209

BD = soil bulk density (g cm⁻³)

210

K_d = soil-water partitioning coefficient (mL g⁻¹)

211

Θ = soil volumetric water content (mL cm⁻³)

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The predicted accumulation is then modelled using following equation (The Weinberg Group Inc., 2000):

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$$PA = \frac{(AR + AD) * [1 - \exp(-K_s * T)] * 1e4}{Z * BD * K_s} \quad \text{(Equation 2)}$$

219

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where:

221

PA: predicted accumulation (mg kg⁻¹)

222 AR: application rate (tonne ha⁻¹ yr⁻¹)
223 AD: atmospheric deposition (tonne ha⁻¹ yr⁻¹)

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225 In a final step, the metal/metalloid concentration in the STRUBIAS material is then optimised
226 so that the predicted accumulation is lower than the soil screening acceptable limit
227 concentration.

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230 **17.2 Meta-analyses**

231 17.2.1 Data sources

232 Data sources that provided pertinent evidence from trustworthy sources in a manner that is
233 comprehensive, scientifically robust, objective and transparent were collected. In order to
234 safeguard transparency, confidential and non-publically available works were not considered
235 in this meta-analysis.

236
237 Studies that quantitatively reported DMY and/or PUE for recovered P and mineral P-fertiliser
238 treatments with a minimum of three experimental replicates were selected. Only assessments
239 that were performed on soils and plant species from boreal, temperate and Mediterranean
240 climate regions - within or outside Europe - were retained in order to provide an assessment
241 that is relevant for the EU-27 (i.e. geographic coordinated > 35°N/S). F_{prim} treatments
242 included different P fertilising substances, such as triple superphosphate, monoammonium
243 phosphate, diammonium phosphate, calcium super phosphate, single superphosphate, and
244 potassium phosphate. Dry matter yield and plant P uptake was mostly measured for
245 aboveground plant biomass yield, but some studies assessed whole plant biomass or specific
246 plant organs. If not directly reported, PUE was derived from the DMY and plant P
247 concentration, and concomitant standard deviations were calculated assuming error
248 propagation rules for normal distributions. When data were only provided in graphical
249 format, the corresponding authors of the studies were contacted to obtain the raw numerical
250 data. If not successful, relevant data points were extracted graphically from available figures.
251 When studies did not report measures of variance, the corresponding author was contacted
252 with a request to provide the raw data for the calculation of the standard deviation. For
253 studies in which it was not possible to acquire measures of variance, the uncertainty of the
254 missing effect sizes was drawn from a multiple imputation algorithm based on the
255 assumption of a common underlying variance, after which Rubin's rules were applied to get
256 the point estimates and standard errors of the meta-analysis results (Schwarzer et al., 2015).

257
258 Following studies were included in the assessment:

259 Precipitated phosphate salts & derivatives: (Johnston and Richards, 2003; Hammond and
260 White, 2005; Gonzalez Ponce and Garcia Lopez De Sa, 2007; Plaza et al., 2007; Massey et
261 al., 2009; Weinfurtnner et al., 2009; Ruiz Diaz et al., 2010; Cabeza et al., 2011; Gell et al.,
262 2011; Liu et al., 2011; Antonini et al., 2012; Ackerman et al., 2013; Thompson, 2013; Achat
263 et al., 2014b; Uysal et al., 2014; Bonvin et al., 2015; Cerrillo et al., 2015; Vogel et al., 2015;

264 Wragge, 2015; Hilt et al., 2016; Katanda et al., 2016; Liu et al., 2016; Sigurnjak et al., 2016;
265 STOWA, 2016b; Talboys et al., 2016; Vaneeckhaute et al., 2016; Degryse et al., 2017).
266 Thermal oxidation materials & derivatives: (Codling et al., 2002; Franz, 2008; Bird and Drizo,
267 2009; Kuligowski et al., 2010; Schiemenz and Eichler-Löbermann, 2010; Cabeza et al., 2011;
268 Schiemenz et al., 2011; Komiyama et al., 2013; Rex et al., 2013; Weigand et al., 2013; Wells,
269 2013; Nanzer et al., 2014; Severin et al., 2014; Vogel et al., 2015; Wragge, 2015; Brod et al.,
270 2016; Delin, 2016; Reiter and Middleton, 2016).
271 Pyrolysis & gasification materials: (Codling et al., 2002; Kuligowski et al., 2010; Müller-
272 Stöver et al., 2012; Alotaibi et al., 2013; Collins et al., 2013; Ma and Matsunaka, 2013;
273 Siebers et al., 2014; Reiter and Middleton, 2016).

274

275 17.2.2 Effect size

276 Standardisation of the raw results was undertaken through calculation of the effect size. This
277 allows quantitative statistical information to be pooled from, and robust statistical
278 comparisons to be made between effects from a range of studies that reported results based
279 on different experimental variables. The effect size was calculated as the natural logarithm of
280 the response ratio R by using the following equation (Borenstein et al., 2009):

281

282

$$\ln R = \ln RAE$$

283

284 The response ratio was then calculated for a number of "cases" where all grouping variables
285 (such as soil and crop used, crop harvest time, P application rate, etc.; see below) are identical
286 for both fertiliser treatments. The log response ratio and its variance was used in the analysis
287 to yield summary effects and confidence limits in log units during the different meta-analysis
288 steps. Each of these values was then converted back to response ratios to report the final
289 results (Borenstein et al., 2009). All analysis were performed in the R software environment.

290

291 17.2.3 Grouping variables

292 Data were grouped prior to meta-analysis to enable a broad ranging assessment of fertilising
293 effectiveness of F_{sec} as a function of grouping variables that relate to soil type, plant group
294 and management option. For all selected studies, quantitative information on following
295 grouping variables were recorded: soil pH, soil texture, feedstock, sowed plant species,
296 application form, harvest time after fertiliser application, soil P fertility, and experimental
297 design. When specific parameters were not documented in the publication, the corresponding
298 author was requested to provide the information; in case quantitative data was not available
299 an expert opinion on parameter categorisation into groups was requested from the lead
300 author.

301

302 *Soil pH* was classified as acidic for soils with a pH value less or equal than 6.0, and as
303 neutral/basic for soils of pH greater than 6.0. *Soil texture* was classified as coarse (sand,
304 loamy sand and sandy loam), medium (loam, silt loam, and silt) or fine (sandy clay, sandy
305 clay loam, clay loam, silty sandy clay loam, silty clay and clay). *Feedstock* indicated the
306 input materials from which the STRUBIAS material was derived (e.g. sewage sludge,

307 manure). For thermal oxidation materials & derivatives, *post-processing* refers to the
308 completing of a wet-digestion or thermal post-processing step to improve the plant P-
309 availability of specific feedstocks (e.g. sewage sludge). *Plant groups* involved grasses (both
310 annual and perennial species), oilseeds, cereals, legumes and others (leaf vegetable, cormous
311 flowering plants, fruit vegetable, and pulse crops). *Application form* distinguished fertilisers
312 that were applied as a powder or as granules. *Assessment time* was categorised as short and
313 long for studies that harvested plants within and posterior to a period of 65 days of fertiliser
314 application. In case of assessments on grasses, only the cumulative biomass and P uptake at
315 the end of the experiment was considered. *Soil P status* was categorised as P-poor and P-rich,
316 with a cut-off value of extractable Olsen-P content of 12.4 mg P kg⁻¹. The cut-off value was
317 based on the average limit value for the "very low" P fertility category for a single soil within
318 a number of European countries (Jordan-Meille et al., 2012). When other extractable P
319 methods were applied, conversion methods and comparative relationships as given in Jordan-
320 Meille et al. (2012), Neyroud and Lischer (2003) and McLaughlin (2002) were applied.
321 When no extractable P data values were reported, expert opinions were requested from the
322 corresponding authors. The approach applied based on a single cut-off value to discern soil P
323 fertility for all soil-plant combinations is a simplification of a complex scientific matter
324 (Jordan-Meille et al., 2012), but we are confident that it meets the objective of generally
325 discerning settings in this meta-analysis study. *Experimental setting* separated pot from field
326 studies. *Experimental design* assessed if the experimental study design involved the addition
327 of plant nutrients, other than P, present in F_{sec} were also added in F_{prim}; "Fully balanced"
328 corresponds to cases where all nutrients present in F_{sec} were also added in the F_{prim}
329 treatments. "Deficient" refers to design where primary and secondary macronutrient present
330 in F_{sec} were not added in F_{prim} (e.g. struvite as F_{sec}, but no addition of Mg in F_{prim}; poultry
331 litter pyrolysis & gasification materials as F_{sec}, but no addition of N or K in P_{prim}).

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BIBLIOGRAPHY

335

336 3R AgroCarbon (2016) 3R AgroCarbon [ONLINE]. Available at:

337 <http://www.3ragrocarbon.com/> [Accessed 26 May 2016].

338 Abbiramy K.S. & Ross P.R. (2016) Avoidance Behavioural Test with Earthworm, *Eisenia*
339 *Fetida* Exposed to the Fertilizer, Potash on Oecd Soil. *International Journal of*
340 *Contemporary Research and Review* **7**: 20250-20255.

341 Abbiramy K.S., Ross P.R., Paramanandham J. & Thenmozhi P. (2014) Use of tropical
342 artificial soil as a new substrate for avoidance behavioral test of earthworm, *Eisenia*
343 *foetida* exposed to urea. *Journal of Environmental Biology* **35**: 205-210.

344 Abelha P., Gulyurtlu I., Boavida D., Seabra Barros J., Cabrita I., Leahy J., . . . Leahy M.
345 (2003) Combustion of poultry litter in a fluidised bed combustor☆. *Fuel* **82**: 687-
346 692.

347 Abma W.R., Driessen W., Haarhuis R. & Loosdrecht M.C.M. (2009) Upgrading of sewage
348 treatment plant by sustainable & cost-effective separate treatment of industrial
349 wastewater. Paper presented at the IWE Nutrient Management in Wastewater
350 Treatment Processes, 6-9 September 2009.

351 Achat D.L., Daumer M.-L., Sperandio M., Santellani A.-C. & Morel C. (2014a) Solubility
352 and mobility of phosphorus recycled from dairy effluents and pig manures in
353 incubated soils with different characteristics. *Nutrient Cycling in Agroecosystems*
354 **99**: 1-15.

355 Achat D.L., Sperandio M., Daumer M.-L., Santellani A.-C., Prud'Homme L., Akhtar M. &
356 Morel C. (2014b) Plant-availability of phosphorus recycled from pig manures and
357 dairy effluents as assessed by isotopic labeling techniques. *Geoderma* **232**: 24-33.

358 Ackerman J.N., Zvomuya F., Cicek N. & Flaten D. (2013) Evaluation of manure-derived
359 struvite as a phosphorus source for canola. *Canadian Journal of Plant Science* **93**:
360 419-424.

361 Adam C., Eicher N., Hermann L., Herzel H., Mallon J., Schaaf M. & Stemann J. (2015)
362 Technical comparison on the design, operation and performances of ash processes.
363 Sustainable sewage sludge management fostering phosphorus recovery and energy
364 efficiency (P-REX report). Berlin.

365 ADEME - Naskeo Rittmo Timab (2016) Démonstrateur industriel de production de struvite
366 sur la STEP de Castres. 77 pages.

367 Adriano D.C., Woodford T.A. & Ciravolo T.G. (1978) Growth and Elemental Composition
368 of Corn and Bean Seedlings as Influenced by Soil Application of Coal Ash1.
369 *Journal of Environmental Quality* **7**: 416-421.

370 AEEP (2017) Data and Statistics - Fertilizers. Available at: [http://aEEP.eu/data-and-](http://aEEP.eu/data-and-statistics/fertilizers/)
371 [statistics/fertilizers/](http://aEEP.eu/data-and-statistics/fertilizers/).

372 Agrotechnology Atlas (2016) Livestock manure [ONLINE], available at: [http://agro-](http://agro-technology-atlas.eu/)
373 [technology-atlas.eu/](http://agro-technology-atlas.eu/). Agro Business Park, Tjele, Denmark.

374 Aitken R.L. & Bell L.C. (1985) Plant uptake and phytotoxicity of boron in Australian fly
375 ashes. *Plant and Soil* **84**: 245-257.

376 Akhiar A., Battimelli A., Torrijos M. & Carrere H. (2017) Comprehensive characterization of
377 the liquid fraction of digestates from full-scale anaerobic co-digestion. *Waste*
378 *Management* **59**: 118-128.

379 Al Seadi T. & Lukehurst C. (2012) Quality management of digestate from biogas plants used
380 as fertiliser. IEA Bioenergy Report Task 37 - Energy from Biogas.

- 381 Alaya M.N., Girgis B.S. & Mourad W.E. (2000) Activated Carbon from Some Agricultural
382 Wastes Under Action of One-Step Steam Pyrolysis. *Journal of Porous Materials* **7**:
383 509-517.
- 384 Aller M.F. (2016) Biochar properties: Transport, fate, and impact. *Critical Reviews in*
385 *Environmental Science and Technology* **46**: 1183-1296.
- 386 Almeida J.R.M., Bertilsson M., Gorwa-Grauslund M.F., Gorsich S. & Lidén G. (2009)
387 Metabolic effects of furaldehydes and impacts on biotechnological processes.
388 *Applied Microbiology and Biotechnology* **82**: 625.
- 389 Almendros G., Gonzalezvila F.J. & Martin F. (1990) FIRE-INDUCED
390 TRANSFORMATION OF SOIL ORGANIC-MATTER FROM AN OAK FOREST
391 - AN EXPERIMENTAL APPROACH TO THE EFFECTS OF FIRE ON HUMIC
392 SUBSTANCES. *Soil Science* **149**: 158-168.
- 393 Almendros G., Knicker H. & González-Vila F.J. (2003) Rearrangement of carbon and
394 nitrogen forms in peat after progressive thermal oxidation as determined by solid-
395 state ¹³C- and ¹⁵N-NMR spectroscopy. *Organic Geochemistry* **34**: 1559-1568.
- 396 Alonso Camargo-Valero M., Bamelis L., De Clercq L., Delvigne F., Meers E., Michels E., . .
397 . Williams P.T. (2015) Recycling inorganic chemicals from agro- and bio-industrial
398 waste streams. Project/Contract number: 320J - Biorefine. Document number:
399 BIOREFINE – WP2 – A7 – P1, 2, 5 – D.
- 400 Alotaibi K.D., Schoenau J.J. & Fonstad T. (2013) Possible utilization of ash from meat and
401 bone meal and dried distillers grains gasification as a phosphorus fertilizer: crop
402 growth response and changes in soil chemical properties. *Journal of Soils and*
403 *Sediments* **13**: 1024-1031.
- 404 Altland J.E. & Locke J.C. (2012) Biochar Affects Macronutrient Leaching from a Soilless
405 Substrate. *HortScience* **47**: 1136-1140.
- 406 Álvarez-Ayuso E., Querol X. & Tomás A. (2006) Environmental impact of a coal
407 combustion-desulphurisation plant: Abatement capacity of desulphurisation process
408 and environmental characterisation of combustion by-products. *Chemosphere* **65**:
409 2009-2017.
- 410 Amann A., Zoboli O., Krampe J., Rechberger H., Zessner M. & Egle L. (2018)
411 Environmental impacts of phosphorus recovery from municipal wastewater.
412 *Resources, Conservation and Recycling* **130**: 127-139.
- 413 Andrade A. & Schuiling R.D. (2001) The chemistry of struvite crystallization. *Mineralogical*
414 *Journal of Ukraine* **23**: 37-46.
- 415 Angst T.E. & Sohi S.P. (2013) Establishing release dynamics for plant nutrients from
416 biochar. *GCB Bioenergy* **5**: 221-226.
- 417 Antakyal D., Kuch B., Preyl V. & Steinmetz H. (2011) Effect of Micropollutants in
418 Wastewater on Recovered Struvite. *Proceedings of the Water Environment*
419 *Federation*, pp. 575-582.
- 420 Antille D.L., Sakrabani R., Tyrrel S.F., Le M.S. & Godwin R.J. (2013) Characterisation of
421 Organomineral Fertilisers Derived from Nutrient-Enriched Biosolids Granules.
422 *Applied and Environmental Soil Science* **2013**: 11.
- 423 Antonia López Antón M., Alan Spears D., Somoano M.D. & Rosa Martínez Tarazona M.
424 (2013) Thallium in coal: Analysis and environmental implications. *Fuel* **105**: 13-18.
- 425 Antonini S., Arias M.A., Eichert T. & Clemens J. (2012) Greenhouse evaluation and
426 environmental impact assessment of different urine-derived struvite fertilizers as
427 phosphorus sources for plants. *Chemosphere* **89**: 1202-1210.
- 428 Apte A.D., Tare V. & Bose P. (2006) Extent of oxidation of Cr(III) to Cr(VI) under various
429 conditions pertaining to natural environment. *Journal of Hazardous Materials* **128**:
430 164-174.

- 431 Arai Y. & Sparks D.L. (2007) Phosphate reaction dynamics in soils and soil components: A
 432 multiscale approach. *Advances in Agronomy* **94**: 135-179.
- 433 Ayers R.S. & Westcot D.W. (1985) Water quality for agriculture. FAO irrigation drainage
 434 paper No. 22-82.
- 435 Bachmann H.J., Bucheli T.D., Dieguez-Alonso A., Fabbri D., Knicker H., Schmidt H.-P., . . .
 436 Zehetner F. (2016) Toward the Standardization of Biochar Analysis: The COST
 437 Action TD1107 Interlaboratory Comparison. *Journal of Agricultural and Food*
 438 *Chemistry* **64**: 513-527.
- 439 Baes C.F. & Mesmer R.E. (1976) *The Hydrolysis of Cations*. . John Wiley & Sons,, New
 440 York.
- 441 Bagge E., Sahlstrom L. & Albiñ A. (2005) The effect of hygienic treatment on the microbial
 442 flora of biowaste at biogas plants. *Water Research* **39**: 4879-4886.
- 443 Bagge E., Persson M. & Johansson K.E. (2010) Diversity of spore-forming bacteria in cattle
 444 manure, slaughterhouse waste and samples from biogas plants. *Journal of Applied*
 445 *Microbiology* **109**: 1549-1565.
- 446 Ballabio C., Panagos P. & Monatanarella L. (2016) Mapping topsoil physical properties at
 447 European scale using the LUCAS database. *Geoderma* **261**: 110-123.
- 448 Balmér P., Book K., Hultman B., Jönsson H., Kärrman E., Levlin E., . . . Åberg H. (2002)
 449 System för återanvändning av fosfor ur avlopp. Report as manuscript delivered to
 450 Statens Naturvårdsverk 2002-01-14.
- 451 Bamelis L., Blancke S., Camargo-Valero M.A., De Clercq L., Haumont A., De Keulenaere
 452 F., . . . Williams P.T. (2015) Recycling inorganic chemicals from agro- and bio-
 453 industrial waste streams. Project/Contract number: 320J - Biorefine. Document
 454 number: BIOREFINE – WP2 – A5 – P1, 2, 5, 8 – D.
- 455 Barber T.R., Lutes C.C., Doorn M.R.J., Fuchsman P.C., Timmenga H.J. & Crouch R.L.
 456 (2003) Aquatic ecological risks due to cyanide releases from biomass burning.
 457 *Chemosphere* **50**: 343-348.
- 458 Barber W.P.F. (2016) Thermal hydrolysis for sewage treatment: A critical review. *Water*
 459 *Research* **104**: 53-71.
- 460 Barbosa R., Lapa N., Lopes H., Gulyurtlu I. & Mendes B. (2011) Stabilization/solidification
 461 of fly ashes and concrete production from bottom and circulating ashes produced in
 462 a power plant working under mono and co-combustion conditions. *Waste*
 463 *Management* **31**: 2009-2019.
- 464 Barnhart J. (1997) Chromium chemistry and implications for environmental fate and toxicity.
 465 In: Chromium in Soil: Perspectives in Chemistry, Health, and Environmental
 466 Regulation, Proctor et al (eds.), AEHS, CRC Lewis Publishers, Boca Raton, FL.
- 467 Barrett G.E., Alexander P.D., Robinson J.S. & Bragg N.C. (2016) Achieving environmentally
 468 sustainable growing media for soilless plant cultivation systems - A review. *Scientia*
 469 *Horticulturae* **212**: 220-234.
- 470 Barrow N.J. (1984) Modelling the effects of pH on phosphate sorption by soils. *Journal of*
 471 *Soil Science* **35**: 283-297.
- 472 Bartsch S., Breuer J., drissen P., Pischke J. & Rex M. (2014) Enrichment of Phosphorus in
 473 BOF-slag for Improved Application in Agriculture. The 7th European Oxygen
 474 Steelmaking Conference. Třinec, Czech republic, September 9-11, 2014.
- 475 Basu M., Pande M., Bhadoria P.B.S. & Mahapatra S.C. (2009) Potential fly-ash utilization in
 476 agriculture: A global review. *Progress in Natural Science* **19**: 1173-1186.
- 477 Baur R.J. (2009) Waste activated sludge stripping to remove internal phosphorus.
- 478 Beck D.A., Johnson G.R. & Spolek G.A. (2011) Amending greenroof soil with biochar to
 479 affect runoff water quantity and quality. *Environmental Pollution* **159**: 2111-2118.

- 480 Becker R., Dorgerloh U., Helmig M., Mumme J., Diakité M. & Nehls I. (2013)
 481 Hydrothermally carbonized plant materials: Patterns of volatile organic compounds
 482 detected by gas chromatography. *Bioresource Technology* **130**: 621-628.
- 483 Beesley L., Moreno-Jimenez E., Fellet G., Melo L. & Sizmuur T. (2015) Biochar and heavy
 484 metals. *Biochar environmental management - science, technology and*
 485 *implementation*, Lehmann J. & Joseph S. (eds.), pages. 563-594. Routledge, Oxon.
- 486 Beesley L., Moreno-Jiménez E., Gomez-Eyles J.L., Harris E., Robinson B. & Sizmur T.
 487 (2011) A review of biochars' potential role in the remediation, revegetation and
 488 restoration of contaminated soils. *Environmental Pollution* **159**: 3269-3282.
- 489 Beighle D.E., Boyazoglu P.A., Hemken R.W. & Serumagazake P.A. (1994) Determination of
 490 calcium, phosphorus, and magnesium values in rib bones from clinically normal
 491 cattle. *American Journal of Veterinary Research* **55**: 85-89.
- 492 Berg U. & Schaum C. (2005) Recovery of Phosphorus from sewage sludge and sludge ashes
 493 - Applications in Germany and Northern Europe. First National Sludge Symposium
 494 NSS 2005, Izmir, Turkey.
- 495 Bergkvist B.O. (1987) Soil solution chemistry and metal budgets of spruce forest ecosystems
 496 in S. Sweden. *Water, Air, and Soil Pollution* **33**: 131-154.
- 497 Bhuiyan M.I.H., Mavinic D.S. & Koch F.A. (2008) Thermal decomposition of struvite and its
 498 phase transition. *Chemosphere* **70**: 1347-1356.
- 499 Bicudo J.R. (2009) Animal solid manure: storage, handling and disposal. *Agricultural*
 500 *Mechanization and Automation*, McNulty P. & Grace P.M. (eds.), pages. 265-291.
 501 Encyclopedia of Life Support Systems, Paris.
- 502 Biederman L.A. & Harpole W.S. (2013) Biochar and its effects on plant productivity and
 503 nutrient cycling: a meta-analysis. *Global Change Biology Bioenergy* **5**: 202-214.
- 504 Billen P., Costa J., Van der Aa L., Van Caneghem J. & Vandecasteele C. (2015) Electricity
 505 from poultry manure: a cleaner alternative to direct land application. *Journal of*
 506 *Cleaner Production* **96**: 467-475.
- 507 Bio Intelligence Service - Umweltbundesamt - AEA (2010) Preparatory study on food waste
 508 across EU27, Contract #: 07.0307/2009/540024/SER/G4 for the European
 509 Commission. Brussels.
- 510 BIOMACON (2016) BIOMACON [ONLINE]. Available at:
 511 <http://www.biomacon.com/index-e.html> [Accessed 26 May 2016].
- 512 Bird S.C. & Drizo A. (2009) Investigations on phosphorus recovery and reuse as soil
 513 amendment from electric arc furnace slag filters. *Journal of Environmental Science*
 514 *and Health Part a-Toxic/Hazardous Substances & Environmental Engineering* **44**:
 515 1476-1483.
- 516 Bischel H.N., Özel Duygan B.D., Strande L., McArdell C.S., Udert K.M. & Kohn T. (2015)
 517 Pathogens and pharmaceuticals in source-separated urine in eThekweni, South
 518 Africa. *Water Research* **85**: 57-65.
- 519 Black Carbon (2016) Black Carbon - a biochar technology [ONLINE]. Available at:
 520 <http://www.blackcarbon.dk/Biochar> [Accessed 26 May 2016].
- 521 Blackwell P., Riethmuller G. & Collins M. (2009) Biochar application to soil. *Biochar for*
 522 *Environmental Management: Science and Technology*, Lehmann J. & Joseph S.
 523 (eds.), pages. Earthscan, London.
- 524 Blake J.P. & Hess J.B. (2014) Poultry litter ash as a replacement for dicalcium phosphate in
 525 broiler diets. *The Journal of Applied Poultry Research* **23**: 101-107.
- 526 Blissett R.S. & Rowson N.A. (2012) A review of the multi-component utilisation of coal fly
 527 ash. *Fuel* **97**: 1-23.
- 528 BMA (2015) Mestverwerkingsloket, Bureau Mest Afzet. Landelijke inventarisatie
 529 mestverwerkingscapaciteit, BMA, The Netherlands.

- 530 Boateng A.A., Garcia-Perez M., Masek O., Brown R.A. & del Campo B. (2015) Biochar
531 production technology. *Biochar environmental management - science, technology
532 and implementation*, Lehmann J. & Joseph S. (eds.), pages. 63-88. Routledge, Oxon.
- 533 Bogush A., Stegemann J.A., Wood I. & Roy A. (2015) Element composition and
534 mineralogical characterisation of air pollution control residue from UK energy-from-
535 waste facilities. *Waste Management* **36**: 119-129.
- 536 Bolland M.D.A. & Gilkes R.J. (1990) Rock phosphates are not effective fertilizers in Western
537 Australian soils: A review of one hundred years of research. *Fertilizer research* **22**:
538 79-95.
- 539 Bonvin C., Etter B., Udert K.M., Frossard E., Nanzer S., Tamburini F. & Oberson A. (2015)
540 Plant uptake of phosphorus and nitrogen recycled from synthetic source-separated
541 urine. *Ambio* **44**: S217-S227.
- 542 Borenstein M., Hedges L.V., Higgins J.P.T. & Rothstein H.R. (2009) *Introduction to meta-
543 analysis*. John Wiley & Sons, Ltd, Chichester, UK.
- 544 Bouzas A., Doñate S., Barat R., Martí N., Borrás L., Grau S., . . . Pastor L. (2016)
545 Implementation of a P-recovery system in Calahorra wastewater treatment plant.
546 Proceedings of the 13th IWA Leading Edge Conference on Water and Wastewater
547 Technologies. 13-16 June, 2016. Jerez de la Frontera (Spain).
- 548 Bowden-Green B. & Briens L. (2016) An investigation of drum granulation of biochar
549 powder. *Powder Technology* **288**: 249-254.
- 550 Boxall A.B.A. (2012) New and Emerging Water Pollutants arising from Agriculture. OECD
551 Report.
- 552 Bradford-Hartke Z., Lane J., Lant P. & Leslie G. (2015) Environmental Benefits and Burdens
553 of Phosphorus Recovery from Municipal Wastewater. *Environmental Science &
554 Technology* **49**: 8611-8622.
- 555 Branca T.A., Pistocchi C., Colla V., Ragolini G., Amato A., Tozzini C., . . . Romaniello L.
556 (2014) Investigation of (BOF) Converter slag use for agriculture in Europe.
557 *Metallurgical Research & Technology* **111**: 155-167.
- 558 Brennan A., Jiménez E.M., Puschenreiter M., Albuquerque J.A. & Switzer C. (2014) Effects
559 of biochar amendment on root traits and contaminant availability of maize plants in
560 a copper and arsenic impacted soil. *Plant and Soil* **379**: 351-360.
- 561 Brentrup F. & Pallière C. (2010) Nitrogen Use Efficiency as an Agro-Environmental
562 Indicator. Proceedings of the OECD Workshop on OECD Agri-environmental
563 Indicators: Lessons Learned and Future Directions, 23-26 March, 2010, Leysin,
564 Switzerland. OECD.
- 565 Brink N. (1993) Composting of food waste and catching nitrogen. *Acta Agriculturae
566 Scandinavica* **43**: 114-120.
- 567 Brod E., Haraldsen T.K. & Breland T.A. (2012) Fertilization effects of organic waste
568 resources and bottom wood ash: results from a pot experiment. *Agricultural and
569 Food Science* **21**: 332-347.
- 570 Brod E., Øgaard A.F., Krogstad T., Haraldsen T.K., Frossard E. & Oberson A. (2016) Drivers
571 of Phosphorus Uptake by Barley Following Secondary Resource Application.
572 *Frontiers in Nutrition* **3**.
- 573 Brown R.A., del Camp B., Boateng A.A., Garcia-Perez M. & Masek O. (2015) Fundamentals
574 of biochar production. *Biochar environmental management - science, technology
575 and implementation*, Lehmann J. & Joseph S. (eds.), pages. 39-61. Routledge, Oxon.
- 576 Bruun E.W., Ambus P., Egsgaard H. & Hauggaard-Nielsen H. (2012) Effects of slow and fast
577 pyrolysis biochar on soil C and N turnover dynamics. *Soil Biology and Biochemistry*
578 **46**: 73-79.

- 579 Bruun S., Hansen T.L., Christensen T.H., Magid J. & Jensen L.S. (2006) Application of
580 processed organic municipal solid waste on agricultural land – a scenario analysis.
581 *Environmental Modeling & Assessment* **11**: 251-265.
- 582 Bryers R.W. (1996) Fireside slagging, fouling, and high-temperature corrosion of heat-
583 transfer surface due to impurities in steam-raising fuels. *Progress in Energy and*
584 *Combustion Science* **22**: 29-120.
- 585 Bucheli T.D., Hilber I. & Schmidt H.P. (2015) Polycyclic aromatic hydrocarbons and
586 polychlorinated aromatic compounds in biochar. *Biochar environmental*
587 *management - science, technology and implementation*, Lehmann J. & Joseph S.
588 (eds.), pages. 595-624. Routledge, Oxon.
- 589 Buck J.K., Honston R.J. & Beimborn W.A. (1990) Direct seedling of anthracite refuge using
590 coal flyash as a major soil amendment. In: Proceedings of the mining and
591 reclamation conference and exhibition. West Virginia Univ. Pub. Service No. 2; .
592 pages. 603.
- 593 Buckwell A. & Nadeu E. (2016) Nutrient recovery and reuse (NRR) in European agriculture.
594 A review of the issues, opportunities, and actions. Brussels.
- 595 Buczek S.B., Cope W.G., McLaughlin R.A. & Kwak T.J. (2017) Acute toxicity of
596 polyacrylamide flocculants to early life stages of freshwater mussels. *Environmental*
597 *Toxicology and Chemistry* **36**: 2715-2721.
- 598 Busch D., Kammann C., Grünhage L. & Müller C. (2012) Simple Biototoxicity Tests for
599 Evaluation of Carbonaceous Soil Additives: Establishment and Reproducibility of
600 Four Test Procedures. *Journal of Environmental Quality* **41**: 1023-1032.
- 601 Buss W. & Mašek O. (2014) Mobile organic compounds in biochar – A potential source
602 of contamination – Phytotoxic effects on cress seed (*Lepidium sativum*)
603 germination. *Journal of Environmental Management* **137**: 111-119.
- 604 Buss W. & Mašek O. (2016) High-VOC biochar—effectiveness of post-treatment measures
605 and potential health risks related to handling and storage. *Environmental Science*
606 *and Pollution Research* **23**: 19580-19589.
- 607 Buss W., Mašek O., Graham M. & Wüst D. (2015) Inherent organic compounds in biochar—
608 Their content, composition and potential toxic effects. *Journal of Environmental*
609 *Management* **156**: 150-157.
- 610 Buss W., Graham M.C., MacKinnon G. & Masek O. (2016) Strategies for producing biochars
611 with minimum PAH contamination. *Journal of Analytical and Applied Pyrolysis*
612 **119**: 24-30.
- 613 Butkovskiy A. (2016) Overview of organic contaminants in municipal sewage biosolids and
614 approaches and treatments to decrease these. Workshop on pharmaceuticals and
615 organic chemicals in sewage biosolids: questions for recycling, Malmö, 27 October,
616 2016.
- 617 Cabeza R., Steingrobe B., Römer W. & Claassen N. (2011) Effectiveness of recycled P
618 products as P fertilizers, as evaluated in pot experiments. *Nutrient Cycling in*
619 *Agroecosystems* **91**: 173-184.
- 620 Camargo-Valero M.A., De Clercq L., Delvigne F., Haumont A., Lebuf V., Meers E., . . .
621 Williams P.T. (2015) Recycling inorganic chemicals from agro- and bio-industrial
622 waste streams. Project/Contract number: 320J - Biorefine Document number:
623 BIOREFINE – WP2 – A6 – P1, 2, 3, 5, 8 – D.
- 624 Camps-Arbestain M., Amonette J.E., Singh B.P., Wang T. & Schmidt H.P. (2015) A biochar
625 classification system and associated test methods. *Biochar environmental*
626 *management - science, technology and implementation*, Lehmann J. & Joseph S.
627 (eds.), pages. 165-193. Routledge, Oxon.

- 628 Camps-Arbestain M., Shen Q., Wang T., van Zwieten L. & Novak J.M. (2017) Available
629 nutrients in biochar. *Biochar - a guide to analytical methods*, Singh B.P., Camps-
630 Arbestain M. & Lehmann J. (eds.), pages. 109-126. CRC Press, Boca Raton, FL.
631 Canadian Council of Ministers of the Environment (2003) Soil Quality Guidelines for the
632 Protection of Environmental and Human Health. Available at
633 https://www.ccme.ca/en/resources/canadian_environmental_quality_guidelines/
634 .
635 Canadian Council of Ministers of the Environment (CCME) (2003) Summary of existing
636 Canadian environmental quality guidelines.
637 Cantrell K.B., Hunt P.G., Uchimiya M., Novak J.M. & Ro K.S. (2012) Impact of pyrolysis
638 temperature and manure source on physicochemical characteristics of biochar.
639 *Bioresource Technology* **107**: 419-428.
640 Carliell-Marquet C. & Cooper J. (2014) Towards closed-loop phosphorus management for
641 the UK Water Industry. In Sustainable Phosphorus Summit, 1-3 September 2014.
642 Carlon C. (2007) Derivation methods of soil screening values in Europe - a review and
643 evaluation of national procedures towards harmonisation. European Commission,
644 Joint Research Centre, Ispra, EUR 22805-EN, 306 pp.
645 Carlson C.L., Adriano D.C., Sajwan K.S., Abels S.L., Thoma D.P. & Driver J.T. (1991)
646 Effects of selected trace metals on germinating seeds of six plant species. *Water, Air,*
647 *and Soil Pollution* **59**: 231-240.
648 CBS Statistics Netherlands (2015) Urban waste water treatment per province and river basin
649 district, 1981-2013 Statistics Netherlands (CBS).
650 Centre E. (2017) Ecoinvent v3.3 database. Zurich, Switzerland: Swiss Centre for Life Cycle
651 Inventories. Available at: [http://www.ecoinvent.org/database/ecoinvent-version-](http://www.ecoinvent.org/database/ecoinvent-version-3/introduction/)
652 [3/introduction/](http://www.ecoinvent.org/database/ecoinvent-version-3/introduction/).
653 Cerrillo M., Palatsi J., Comas J., Vicens J. & Bonmati A. (2015) Struvite precipitation as a
654 technology to be integrated in a manure anaerobic digestion treatment plant -
655 removal efficiency, crystal characterization and agricultural assessment. *Journal of*
656 *Chemical Technology and Biotechnology* **90**: 1135-1143.
657 Chabbi A., Lehmann J., Ciais P., Loescher H.W., Cotrufo M.F., Don A., . . . Rumpel C.
658 (2017) Aligning agriculture and climate policy. *Nature Climate Change* **7**: 307.
659 Chandrajith R. & Dissanayake C.B. (2009) Phosphate mineral fertilizers, trace metals and
660 human health. *Journal of the National Science Foundation of Sri Lanka* **37**: 153-165.
661 Chandrappa R. & Das D.B. (2012) Waste quantities and characteristics. *Solid waste*
662 *management, Environmental Science and Engineering*, Chandrappa R. & Das D.B.
663 (eds.), pages. 47-63. Springer-Verlag, Berlin Heidelberg.
664 Chang A.C., Lund L.J., Page A.L. & Warneke J.E. (1977) Physical Properties of Fly Ash-
665 Amended Soils1. *Journal of Environmental Quality* **6**: 267-270.
666 Chang L.W., Magos L. & Suzuki T. (1996) *Toxicology of Metals*. CRC Press, Boca Raton.
667 FL, USA.
668 Charles W., Cord-Ruwisch R., Ho G., Costa M. & Spencer P. (2006) Solutions to a combined
669 problem of excessive hydrogen sulfide in biogas and struvite scaling. *Water Science*
670 *and Technology* **53**: 203-211.
671 Chaurand P., Rose J., Domas J. & Bottero J.-Y. (2006) Speciation of Cr and V within BOF
672 steel slag reused in road constructions. *Journal of Geochemical Exploration* **88**: 10-
673 14.
674 Chen Q.-L., An X.-L., Zhu Y.-G., Su J.-Q., Gillings M.R., Ye Z.-L. & Cui L. (2017)
675 Application of Struvite Alters the Antibiotic Resistome in Soil, Rhizosphere, and
676 Phyllosphere. *Environmental Science & Technology* **51**: 8149-8157.

- 677 Chen Q., An X., Li H., Su J., Ma Y. & Zhu Y.-G. (2016) Long-term field application of
678 sewage sludge increases the abundance of antibiotic resistance genes in soil.
679 *Environment International* **92-93**: 1-10.
- 680 Chester R., Nimmo M. & Preston M.R. (1999) The trace metal chemistry of atmospheric dry
681 deposition samples collected at Cap Ferrat: a coastal site in the Western
682 Mediterranean. *Marine Chemistry* **68**: 15-30.
- 683 Chia C.H., Downie A. & Munroe P. (2015) Characteristics of biochar: physical and structural
684 properties. *Biochar environmental management - science, technology and
685 implementation*, Lehmann J. & Joseph S. (eds.), pages. 89-110. Routledge, Oxon.
- 686 Churka Blum S., Lehmann J., Solomon D., Caires E.F. & Alleoni L.R.F. (2013) Sulfur forms
687 in organic substrates affecting S mineralization in soil. *Geoderma* **200-201**: 156-
688 164.
- 689 Clements W.H., Stahl R.G. & Landis R.C. (2015) Ecological Effects of Biochar on the
690 Structure and Function of Stream Benthic Communities. *Environmental Science &
691 Technology* **49**: 14649-14654.
- 692 Cleveland C.C. & Liptzin D. (2007) C : N : P stoichiometry in soil: is there a "Redfield ratio"
693 for the microbial biomass? *Biogeochemistry* **85**: 235-252.
- 694 Codling E.E., Chaney R.L. & Sherwell J. (2002) Poultry litter ash as a potential phosphorus
695 source for agricultural crops. *Journal of Environmental Quality* **31**: 954-961.
- 696 Collins H. (2008) Use of biochar from the pyrolysis of waste organic material as a soil
697 amendment: laboratory and greenhouse analyses. A quarterly progress report
698 prepared for the biochar project. USDA-ARS, Prosser, WA.
- 699 Collins H.P., Streubel J., Alva A., Porter L. & Chaves B. (2013) Phosphorus Uptake by
700 Potato from Biochar Amended with Anaerobic Digested Dairy Manure Effluent.
701 *Agronomy Journal* **105**: 989-998.
- 702 Conesa J.A., Fullana A. & Font R. (2003) Thermal decomposition of meat and bone meal.
703 *Journal of Analytical and Applied Pyrolysis* **70**: 619-630.
- 704 Connolly E.L. & Gueriot M.L. (2002) Iron stress in plants. *Genome Biology* **3**:
705 reviews1024.1021-reviews1024.1024.
- 706 Conti R., Fabbri D., Vassura I. & Ferroni L. (2016) Comparison of chemical and physical
707 indices of thermal stability of biochars from different biomass by analytical
708 pyrolysis and thermogravimetry. *Journal of Analytical and Applied Pyrolysis* **122**:
709 160-168.
- 710 Cornel P. & Schaum C. (2009) Phosphorus recovery from wastewater: needs, technologies
711 and costs. *Water Science and Technology* **59**: 1069-1076.
- 712 Cornelis G., Johnson C.A., Gerven T.V. & Vandecasteele C. (2008) Leaching mechanisms of
713 oxyanionic metalloid and metal species in alkaline solid wastes: A review. *Applied
714 Geochemistry* **23**: 955-976.
- 715 Coutand M., Cyr M., Deydier E., Guilet R. & Clastres P. (2008) Characteristics of industrial
716 and laboratory meat and bone meal ashes and their potential applications. *Journal of
717 Hazardous Materials* **150**: 522-532.
- 718 Cox A.E., Camberato J.J. & Smith B.R. (1997) Phosphate availability and inorganic
719 transformation in an alum sludge-affected soil. *Journal of Environmental Quality*
720 **26**: 1393-1398.
- 721 Crittenden S., Daumer M.L., Gésan-Guiziou G. & Gaucheron F. (2008) Treatment and
722 Recycling of Phosphorus in Effluent From the Dairy and Agri-Food Industries.
723 Cemagref - BBA Report, France.
- 724 Crombie K., Mašek O., Sohi S.P., Brownsort P. & Cross A. (2013) The effect of pyrolysis
725 conditions on biochar stability as determined by three methods. *GCB Bioenergy* **5**:
726 122-131.

- 727 Crossgrove J. & Zheng W. (2004) Manganese toxicity upon overexposure. *NMR in*
728 *biomedicine* **17**: 544-553.
- 729 Cyr M. & Ludmann C. (2006) Low risk meat and bone meal (MBM) bottom ash in mortars
730 as sand replacement. *Cement and Concrete Research* **36**: 469-480.
- 731 Czaja Z. & Hermann J. (2011) Adverse environmental impact caused by thermal destruction
732 of animal byproducts. *Contemporary problems of management and environmental*
733 *protection*, Skibniewska K.A. (ed.), pages. 89-98. Zakład poligraficzny UWM w
734 Olsztynie.
- 735 Daghrir R. & Drogui P. (2013) Tetracycline antibiotics in the environment: a review.
736 *Environmental Chemistry Letters* **11**: 209-227.
- 737 Davidson D.F. & Sheldon R.P. (1986) Phosphate Deposits of the World: Volume 2,
738 Phosphate Rock Resources.
- 739 de Boer M.A., Hammerton M. & Slootweg J.C. (2018) Uptake of pharmaceuticals by
740 sorbent-amended struvite fertilisers recovered from human urine and their
741 bioaccumulation in tomato fruit. *Water Research* **133**: 19-26.
- 742 de Brogniez D., Ballabio C., Stevens A., Jones R.J.A., Montanarella L. & van Wesemael B.
743 (2015) A map of the topsoil organic carbon content of Europe generated by a
744 generalized additive model. *European Journal of Soil Science* **66**: 121-134.
- 745 De Clercq L., Michels E., Meers E., Buysse J. & Haumont A. (2015) Legal framework of
746 recovered phosphorus (struvite) as fertiliser in North-Western Europe. Document
747 number: BIOREFINE – WP5 – A19 – P1 - D. Ghent, Belgium.
- 748 De Graaff L., Odegard I. & Nusselder S. (2017) LCA of thermal conversion of poultry litter
749 at BMC Moerdijk. CE Delft, Publication code 17.2H94.01.
- 750 de las Fuentes L., Sanders B., Klemes J. & Urbaniec K. (2003) European Project
751 AWARENET: Agro-food Wastes minimisation and REduction NETwork. 22nd
752 general assembly of the International Commission for Sugar Technology, Madrid.
- 753 de Ruijter F.J., van Dijk W., van Middelkoop J.C. & van Reuler H. (2015) Phosphorus
754 recycling from the waste sector. Wagenigen UR, PRI report 641.
- 755 De Saeger S., Audenaert K. & Croubels S. (2016) Report from the 5th International
756 Symposium on Mycotoxins and Toxigenic Moulds: Challenges and Perspectives
757 (MYTOX) Held in Ghent, Belgium, May 2016. *Toxins* **8**: 146.
- 758 De Temmerman L., Waegeneers N., Thiry C., Du Laing G., Tack F. & Ruttens A. (2014)
759 Selenium content of Belgian cultivated soils and its uptake by field crops and
760 vegetables. *Science of the Total Environment* **468-469**: 77-82.
- 761 de Vries W., Leip A., Reinds G.J., Kros J., Lesschen J.P. & Bouwman A.F. (2011)
762 Comparison of land nitrogen budgets for European agriculture by various modeling
763 approaches. *Environmental Pollution* **159**: 3254-3268.
- 764 De Windt L., Chaurand P. & Rose J. (2011) Kinetics of steel slag leaching: Batch tests and
765 modeling. *Waste Management* **31**: 225-235.
- 766 Decrey L., Udert K.M., Tilley E., Pecson B.M. & Kohn T. (2011) Fate of the pathogen
767 indicators phage ΦX174 and *Ascaris suum* eggs during the production of struvite
768 fertilizer from source-separated urine. *Water Research* **45**: 4960-4972.
- 769 Degryse F., Baird R., da Silva R.C. & McLaughlin M.J. (2017) Dissolution rate and
770 agronomic effectiveness of struvite fertilizers – effect of soil pH, granulation and
771 base excess. *Plant and Soil* **410**: 139-152.
- 772 Delin S. (2016) Fertilizer value of phosphorus in different residues. *Soil Use and*
773 *Management* **32**: 17-26.
- 774 Demeyer A., Voundi Nkana J.C. & Verloo M.G. (2001) Characteristics of wood ash and
775 influence on soil properties and nutrient uptake: an overview. *Bioresource*
776 *Technology* **77**: 287-295.

- 777 Demirbas A. (2003) Trace metal concentrations in ashes from various types of biomass
778 species. *Energy Sources* **25**: 743-751.
- 779 Demirbas A. (2004) Combustion characteristics of different biomass fuels. *Progress in*
780 *Energy and Combustion Science* **30**: 219-230.
- 781 Demirbas A. (2005) Potential applications of renewable energy sources, biomass combustion
782 problems in boiler power systems and combustion related environmental issues.
783 *Progress in Energy and Combustion Science* **31**: 171-192.
- 784 Desmidt E., Ghyselbrecht K., Zhang Y., Pinoy L., Van der Bruggen B., Verstraete W., . . .
785 Meesschaert B. (2015) Global Phosphorus Scarcity and Full-Scale P-Recovery
786 Techniques: A Review. *Critical Reviews in Environmental Science and Technology*
787 **45**: 336-384.
- 788 Dewaele C. (2015) NuReSys - from P-recovery to fertilizer production.
- 789 Deydier E., Guilet R., Sarda S. & Sharrock P. (2005a) Physical and chemical characterisation
790 of crude meat and bone meal combustion residue: "waste or raw material?". *Journal*
791 *of Hazardous Materials* **121**: 141-148.
- 792 Deydier E., Guilet R., Sarda S. & Sharrock P. (2005b) Physical and chemical characterisation
793 of crude meat and bone meal combustion residue: "waste or raw material?". *Journal*
794 *of Hazardous Materials* **121**: 141-148.
- 795 Dikov G., Hermann L., Hukari S., Muskolus A., Nattorp A., Pokorna M. & Gonzales de
796 Ubieta C. (2014) Pre-Normative matrix. Review of fertilization schemes. Review of
797 current legal framework for phosphorus recovery. Sustainable sewage sludge
798 management fostering phosphorus recovery and energy efficiency (P-REX report).
- 799 Dobbelare D. (2017) Statistical overview of the animal by-products industry in the EU in
800 2016. European Fat Processors and Renderers Association (EFPPA) Congress, 2
801 June 2017, Hamburg.
- 802 Domene X., Enders A., Hanley K. & Lehmann J. (2015) Ecotoxicological characterization of
803 biochars: Role of feedstock and pyrolysis temperature. *Science of the Total*
804 *Environment* **512-513**: 552-561.
- 805 Donatello S. & Cheeseman C.R. (2013) Recycling and recovery routes for incinerated
806 sewage sludge ash (ISSA): A review. *Waste Management* **33**: 2328-2340.
- 807 Donatello S., Tyrer M. & Cheeseman C.R. (2010) EU landfill waste acceptance criteria and
808 EU Hazardous Waste Directive compliance testing of incinerated sewage sludge ash.
809 *Waste Management* **30**: 63-71.
- 810 Dong J., Wu F. & Zhang G. (2006) Influence of cadmium on antioxidant capacity and four
811 microelement concentrations in tomato seedlings (*Lycopersicon esculentum*).
812 *Chemosphere* **64**: 1659-1666.
- 813 Doring R. & Borrello A. (2014) Economic Performance of the EU Fish Processing Industry
814 Sector - Scientific, Technical and Economic Committee for Fisheries (STECF).
- 815 Dros B., Fuchs W., Al Saedi T., Madsen M. & Kinke B. (2015) Nutrient Recovery by
816 Biogas Digestate Processing. IEA Bioenergy Report.
- 817 Dros B., Fuchs W., Al Saedi T., Madsen M. & Linke B. (2015) Nutrient Recovery by Biogas
818 Digestate Processing - IEA Bioenergy report.
- 819 Dumroese R.K., Heiskanen J., Englund K. & Tervahauta A. (2011) Pelleted biochar:
820 Chemical and physical properties show potential use as a substrate in container
821 nurseries. *Biomass & Bioenergy* **35**: 2018-2027.
- 822 Dutta T., Kwon E., Bhattacharya S.S., Jeon B.H., Deep A., Uchimiya M. & Kim K.-H.
823 (2016) Polycyclic aromatic hydrocarbons and volatile organic compounds in biochar
824 and biochar-amended soil: a review. *GCB Bioenergy* n/a-n/a.
- 825 DWA (2005) Stand der Slurschlammbehandlung und Entsorgung in Deutschland, p. 66.

- 826 Dzonzi-Unidm J., Masek O. & Abass O. (2012) Determination of Spontaneous Ignition
827 Behaviour
828 of Biochar Accumulations. *International Journal of Science and Research* **3**: 656-662.
829 E-PRTR (2013) European Pollutant Release and Transfer Register (E-PRTR).
830 EBC (2012) 'European Biochar Certificate - Guidelines for a Sustainable Production of
831 Biochar.' European Biochar Foundation (EBC), Arbaz, Switzerland.
832 <http://www.europeanbiochar.org/en/download>. Version 6.2E of 04th February
833 2016, DOI: 10.13140/RG.2.1.4658.7043.
834 ECHA (2010) Guidance on waste and recovered substances. Helsinki.
835 ECHA (2016) Guidance for identification and naming of substances under REACH and CLP,
836 December 2016, Version 2.0. Available at:
837 [https://echa.europa.eu/documents/10162/23036412/substance_id_en.pdf/ee696b](https://echa.europa.eu/documents/10162/23036412/substance_id_en.pdf/ee696bad-49f6-4fec-b8b7-2c3706113c7d)
838 [ad-49f6-4fec-b8b7-2c3706113c7d](https://echa.europa.eu/documents/10162/23036412/substance_id_en.pdf/ee696bad-49f6-4fec-b8b7-2c3706113c7d).
839 ECN (2017) Phyllis database. ECN, Biomass Coal & Environmental Research, Petten.
840 EcoPhos (2016) EcoPhos - Our technology [ONLINE], Available at:
841 <http://www.ecophos.com/#/en/technology/> [Accessed 20 May 2016].
842 Ecophos (2018) The Ecophos process for producing dihydrate decalcium phosphate: What
843 makes the difference? Available at: [www.aliphos.com/wp-content/.../The-](http://www.aliphos.com/wp-content/.../The-Ecophos-process-for-producing-dihydrate.pdf)
844 [Ecophos-process-for-producing-dihydrate.pdf](http://www.aliphos.com/wp-content/.../The-Ecophos-process-for-producing-dihydrate.pdf).
845 EFPIRA (2017) The facts about rendering. Available at: [http://efpra.eu/wp-](http://efpra.eu/wp-content/uploads/2016/11/The-facts-about-rendering.pdf)
846 [content/uploads/2016/11/The-facts-about-rendering.pdf](http://efpra.eu/wp-content/uploads/2016/11/The-facts-about-rendering.pdf).
847 EFSA (2004) Opinion of the Scientific Panel on Dietetic Products, Nutrition and Allergies on
848 a request from the Commission related to the Tolerable Upper Intake Level of Boron
849 (Sodium Borate and Boric Acid) (Request N° EFSA-Q-2003-018). *The EFSA*
850 *Journal* **80**: 1-22.
851 Eghball B., Wienhold B.J., Gilley J.E. & Eigenberg R.A. (2002) Mineralization of manure
852 nutrients. *Journal of Soil and Water Conservation* **57**: 470-473.
853 Egle L., Rechberger H., Krampe J. & Zessner M. (2016) Phosphorus recovery from
854 municipal wastewater: An integrated comparative technological, environmental and
855 economic assessment of P recovery technologies. *Science of the Total Environment*
856 **571**: 522-542.
857 Ehlert P.A.I. & Nelemans J.A. (2015a) Efficacy of phosphorus of hydrated poultry litter ash;
858 Phosphorus use efficiency of rye grass. Wageningen, Alterra Wageningen UR
859 (University & Research centre), the Netherlands, Alterra report. Commissioned by
860 BMC Moerdijk (<https://www.bmcmoerdijk.nl/en/home.htm>).
861 Ehlert P.A.I. & Nelemans J.A. (2015b) Efficacy of phosphorus of hydrated poultry litter ash;
862 Phosphorus use efficiency of green bean. Wageningen, Alterra Wageningen UR
863 (University & Research centre), the Netherlands, Alterra report. Commissioned by
864 BMC Moerdijk (<https://www.bmcmoerdijk.nl/en/home.htm>).
865 Ehlert P.A.I., Van Dijk K.C. & Oenema O. (2016a) Towards a legal status for struvite in the
866 Netherlands. Wageningen, Statutory Research Tasks Nature & Environment.
867 Wageningen, Wettelijke Onderzoekstaken Natuur & Milieu, WOt-technical report
868 69.
869 Ehlert P.A.I., van Wijnen H.J., Struijs J., Dijk T.A.v., van Scholl L. & de Poorter L.R.M.
870 (2016b) Risicobeoordeling van contaminanten in afval- en reststoffen bestemd voor
871 gebruik als covergistingmateriaal. Wot-technical report 70, Wageningen, NL.
872 Elliott A.L., Davis J.G., Waskom R.M., Self J.R. & Christensen D.K. (2007) Phosphorus
873 fertilizers for organic farming systems. Publ. No. 0.569. Colorado State Univ. Coop.
874 Ext., Fort Collins, CO.

- 875 Elser J. & Bennett E. (2011) Phosphorus cycle: A broken biogeochemical cycle. *Nature* **478**:
876 29-31.
- 877 Enders A., Hanley K., Whitman T., Joseph S. & Lehmann J. (2012) Characterization of
878 biochars to evaluate recalcitrance and agronomic performance. *Bioresource*
879 *Technology* **114**: 644-653.
- 880 Enell A., Fuhrman F., Lundin L., Warfvinge P. & Thelin G. (2008) Polycyclic aromatic
881 hydrocarbons in ash: Determination of total and leachable concentrations.
882 *Environmental Pollution* **152**: 285-292.
- 883 Energy Information Administration of the United States (2001) Emissions of Greenhouse
884 Gases in the United States 2000. Washington.
- 885 EPA (2003a) Ecological Screening Level for Aluminum. U.S. Environmental Protection
886 Agency. OSWER Directive 9285.7-60.
- 887 EPA (2003b) Ecological Screening Level for Iron. U.S. Environmental Protection Agency.
888 OSWER Directive 9285.7-60.
- 889 EPA (2003c) Ecological Screening Level for Manganese. U.S. Environmental Protection
890 Agency. OSWER Directive 9285.7-60.
- 891 Eriksson J. (2001) Concentrations of 61 trace elements in sewage sludge, farmyard manure,
892 mineral fertiliser, precipitation and in oil and crops. Swedish Environmental
893 Protection Agency, Naturvårdsverkets reprocentral 2001/10.
- 894 Escher B.I., Pronk W., Suter M.J.F. & Maurer M. (2006) Monitoring the removal efficiency
895 of pharmaceuticals and hormones in different treatment processes of source-
896 separated urine with bioassays. *Environmental Science & Technology* **40**: 5095-
897 5101.
- 898 ESDAT (2017) Environmental Database Management Software.
899 [7http://www.esdat.net/Environmental%20Standards/Australia/NEPM%20Tabl](http://www.esdat.net/Environmental%20Standards/Australia/NEPM%20Tables.pdf)
900 [es.pdf](http://www.esdat.net/Environmental%20Standards/Australia/NEPM%20Tables.pdf).
- 901 ESPP (2016) Scope Newsletter n°122, November 2016. Brussels. available at:
902 <http://phosphorusplatform.eu/images/scope/ScopeNewsletter122.pdf>.
- 903 ESPP (2017) Scope Newsletter n°124, February 2017. Brussels. available at:
904 <http://phosphorusplatform.eu/images/scope/ScopeNewsletter124.pdf>.
- 905 ETC/SIA (2013) Review of the EU bioenergy potential from a resource efficiency
906 perspective. Background report, Alterra, Wageningen.
- 907 Etiegni L. & Campbell A.G. (1991) PHYSICAL AND CHEMICAL CHARACTERISTICS
908 OF WOOD ASH. *Bioresource Technology* **37**: 173-178.
- 909 EUBIA (2015) Bio-based Char Market Potentials - An emerging large scale commodity in
910 Europe. EUBIA Report. Brussels, Belgium.
- 911 EURAR (2008) European Union Risk Assessment Report - diantimony trioxide.
912 European Chemicals Bureau (2005) Chromium trioxide, sodium chromate, sodium
913 dichromate, ammonium dichromate, potassium dichromate. European Union Risk
914 Assessment Report. Available at
915 [https://echa.europa.eu/documents/10162/3be377f2-cb05-455f-b620-](https://echa.europa.eu/documents/10162/3be377f2-cb05-455f-b620-af3cbe2d570b)
916 [af3cbe2d570b](https://echa.europa.eu/documents/10162/3be377f2-cb05-455f-b620-af3cbe2d570b).
- 917 European Climate Foundation (2013) Biomass for heat and power: Opportunities and
918 economics [ONLINE]. Available at:
919 http://www.europeanclimate.org/documents/Biomass_report_-_Final.pdf.
- 920 European Commission (2005) Reference Document on Best Available Techniques in the
921 Slaughterhouses and Animal By-products Industries. Available at:
922 eippcb.jrc.ec.europa.eu/reference/BREF/sa_bref_0505.pdf.

923 European commission (2006a) Reference Document on Best Available Techniques in the
924 Food, Drink and Milk Industries. Integrated Pollution Prevention and Control
925 Bureau, Seville.

926 European Commission (2006b) Reference Document on Best Available Techniques in the
927 Food, Drink and Milk Industries. Integrated Pollution Prevention and Control
928 Bureau. Seville, Spain.

929 European Commission (2006c) Integrated Pollution Prevention and Control Reference
930 Document on the Best Available Techniques for Waste Incineration.

931 European Commission (2010a) Communication from the Commission to the Council and the
932 European Parliament on future steps in bio-waste management in the European
933 Union

934 European Commission (2010b) Communication from the Commission to the council and the
935 European parliament on future steps in bio-waste managemetn in the European
936 Union (COM(2010)235 Final. Luxembourg.

937 European Commission (2011) Commission Staff Working paper - 6th Commission
938 Summary on the Implementation of the Urban Waste Water Treatment Directive.

939 European Commission (2012) Guidance on the interpretation of key provisions of Directive
940 2008/98/EC on waste. Brussels.

941 European Commission (2013a) Communication from the Commission to the European
942 parliament, the council, the European Economic and Social Committee and the
943 Committee of the Regions - Consultative Communication on the Sustainable Use of
944 Phosphorus. Brussel.

945 European Commission (2013b) Report from the Commission to the council and the European
946 Parliament on the implementation of Council Directive 91/676/EEC concerning the
947 protection of waters against pollution caused by nitrates from agricultural sources
948 based on Member State reports for the period 2008–2011.

949 European commission (2014) Best Available Techniques (BAT) Reference Document for
950 Common Waste water and Waste Gas Treatment/Management Systems in the
951 Chemical Sector - final draft. European IPPC Bureau.

952 European Commission (2015a) Best Available Techniques (BAT) Reference Document for
953 the Production of Pulp, Paper and Board. European IPPC Bureau.

954 European Commission (2015b) The Water Framework Directive and the Floods Directive:
955 Actions towards the 'good status' of EU water and to reduce flood risks - 4th
956 implementation report on the Programmes of Measures (March 2015).

957 European Commission (2016a) EU agricultural outlook - Prospect for the EU agricultural
958 markets and income 2016-2026.

959 European Commission (2016b) Limiting the presence of total chromium in fertilising
960 products. Working Document of the Fertilisers Working Group.

961 European Commission (2017a) Facts and Figures about Urban Waste Water Treatment.
962 Available at: [http://ec.europa.eu/environment/water/water-
963 urbanwaste/implementation/factsfigures_en.htm](http://ec.europa.eu/environment/water/water-urbanwaste/implementation/factsfigures_en.htm).

964 European Commission (2017b) Best Available Techniques (BAT) Reference Document in
965 the Food, Drink and Milk Industries - First Draft (January 2017). European IPPC
966 Bureau.

967 European Commission (2017c) Reference Document on Best Available Techniques on Waste
968 Incineration - First Draft May 2017. Available at:
969 eippcb.jrc.ec.europa.eu/reference/BREF/.

970 European Commission (2017d) Impact of long-term application of blast furnace and steel
971 slags as liming materials on soil fertility, crop yields and plant health

- 972 (SLAGFERTILISER). Final report - Study. Directorate-General for Research and
 973 Innovation, Brussels.
- 974 European Environment Agency (2006) How much bioenergy can Europe produce without
 975 harming the environment?, EEA Report No 7/2006, European Environment Agency.
- 976 European Environment Agency (2012) Soil organic carbon. Indicator Assessment - Data and
 977 maps. Available at: [https://www.eea.europa.eu/data-and-maps/indicators/soil-](https://www.eea.europa.eu/data-and-maps/indicators/soil-organic-carbon-1/assessment)
 978 **organic-carbon-1/assessment**.
- 979 European Environment Agency (2013a) EU bioenergy potential from a resource-efficiency
 980 perspective. EEA Report No 6/2013.
- 981 European Environment Agency (2013b) Urban waste water treatment. Copenhagen.
- 982 European Environment Agency (2016) Renewable energy in Europe 2016 - Recent growth
 983 and knock-on effects. EEA Report No 4/2016.
- 984 European Phosphate Fertilizer Alliance (2017) Phosphate fertilizers - Production. Available
 985 at: <http://aeep.eu/phosphate-fertilizers/production/> (consulted on 02/10/2017).
- 986 Eurostat (2016) Eurostat - your key to European statistics [ONLINE]. available at:
 987 <http://ec.europa.eu/eurostat/data/database>. Accessed 17 December 2016.
- 988 Ewert W., Hermanussen O., Kabbe C., Mele C., Niewersch C., Stossel E., . . . Stemann J.
 989 (2014) Comparison of sludge related processes. Sustainable sewage sludge
 990 management fostering phosphorus recovery and energy efficiency (P-REX report).
- 991 FAOSTAT-Commodity Balances Livestock (2012) FAOSTAT — Food Balance —
 992 Commodity
- 993 Balances — Livestock and Fish Primary Equivalent Data., Food and Agriculture
 994 Organization of the United Nations (FAO), Rome.
- 995 Feng Q.G., Lin Q.Y., Gong F.Z., Sugita S. & Shoya M. (2004) Adsorption of lead and
 996 mercury by rice husk ash. *Journal of Colloid and Interface Science* **278**: 1-8.
- 997 Ferrari S., Belevi H. & Baccini P. (2002) Chemical speciation of carbon in municipal solid
 998 waste incinerator residues. *Waste Management* **22**: 303-314.
- 999 Filella M., Belzile N. & Chen Y.-W. (2002a) Antimony in the environment: a review focused
 1000 on natural waters: I. Occurrence. *Earth-Science Reviews* **57**: 125-176.
- 1001 Filella M., Belzile N. & Chen Y.-W. (2002b) Antimony in the environment: a review focused
 1002 on natural waters: II. Relevant solution chemistry. *Earth-Science Reviews* **59**: 265-
 1003 285.
- 1004 Flach B., Lieberz S., Rondon M., Williams B. & Teiken C. (2015) EU Biofuels Annual 2015.
 1005 USDA Foreign Agricultural Service.
- 1006 Flotats X., Bonmati A., Palatsi J. & Foget H.L. (2013) Trends on manure processing in
 1007 Europe. Wastes: solutions, treatments and opportunities. 2nd International
 1008 Conference, 11-13 September 2013, Braga, Portugal.
- 1009 Flynn H.C., Meharg A.A., Bowyer P.K. & Paton G.I. (2003) Antimony bioavailability in
 1010 mine soils. *Environmental Pollution* **124**: 93-100.
- 1011 Foget H.L., Flotats X., Bonmati Blasi A., Palatsi J., Magri A. & Schelde K.M. (2011)
 1012 Inventory of manure processing activities in Europe. Technical Report No. I
 1013 concerning “Manure Processing Activities in Europe” to the European Commission,
 1014 Directorate-General Environment. Brussels.
- 1015 FOREGS (2005) Forum of the European Geological Survey Directors. Geochemical Atlas of
 1016 Europe, Geological Survey of Finland, Espoo.
- 1017 Formisani C. (2003) Trends in bulk blending world wide. Baltimore.
- 1018 Fowler B. & Goering P. (1991) Antimony. *Metals and Their Compounds in the Environment:*
 1019 *Occurrence, Analysis, and Biological Relevance*, Merian E. (ed.), pages. 743-750.
 1020 VCH, Weinheim.

- 1021 Franke-Whittle I.H. & Insam H. (2013) Treatment alternatives of slaughterhouse wastes, and
 1022 their effect on the inactivation of different pathogens: A review. *Critical Reviews in*
 1023 *Microbiology* **39**: 139-151.
- 1024 Franz M. (2008) Phosphate fertilizer from sewage sludge ash (SSA). *Waste Management* **28**:
 1025 1809-1818.
- 1026 Frattini P. (2005) Thallium properties and behaviour - a literature study. Etelä-Suomen
 1027 yksikkö S41/0000/2005/2, GTK, Finland.
- 1028 Freddo A., Cai C. & Reid B.J. (2012) Environmental contextualisation of potential toxic
 1029 elements and polycyclic aromatic hydrocarbons in biochar. *Environmental Pollution*
 1030 **171**: 18-24.
- 1031 Freire M., Lopes H. & Tarelho L.A.C. (2015) Critical aspects of biomass ashes utilization in
 1032 soils: Composition, leachability, PAH and PCDD/F. *Waste Management* **46**: 304-
 1033 315.
- 1034 Frieri M., Kumar K. & Boutin A. (2017) Antibiotic resistance. *Journal of Infection and*
 1035 *Public Health* **10**: 369-378.
- 1036 Fröschle B., Messelhäusser U., Höller C. & Lebuhn M. (2015) Fate of Clostridium botulinum
 1037 and incidence of pathogenic clostridia in biogas processes. *Journal of Applied*
 1038 *Microbiology* **119**: 936-947.
- 1039 Galinato S.P., Yoder J.K. & Granatstein D. (2011) The economic value of biochar in crop
 1040 production and carbon sequestration. *Energy Policy* **39**: 6344-6350.
- 1041 García C., T. R., Lynne B., Gali A., Rougé P. & Fabregras C. (2012) Struvite recovery: pilot-
 1042 scale results and economic assesment of different scenarios. IWA World Water
 1043 Congress and Exhibition, Busan, Korea.
- 1044 Garg A.X., Hackam D. & Tonelli M. (2008) Systematic review and meta-analysis: when one
 1045 study is just not enough. *Clinical Journal of the American Society of Nephrology* **3**:
 1046 253-260.
- 1047 Gascó G., Paz-Ferreiro J. & Méndez A. (2012) Thermal analysis of soil amended with
 1048 sewage sludge and biochar from sewage sludge pyrolysis. *Journal of Thermal*
 1049 *Analysis and Calorimetry* **108**: 769-775.
- 1050 Gaskin J.W., Steiner C., Harris K., Das K.C. & Bibens B. (2008) Effect of Low-Temperature
 1051 Pyrolysis Conditions on Biochar for Agricultural Use. *Transactions of the Asabe* **51**:
 1052 2061-2069.
- 1053 Ge H., Zhang L., Batstone Damien J., Keller J. & Yuan Z. (2013) Impact of Iron Salt Dosage
 1054 to Sewers on Downstream Anaerobic Sludge Digesters: Sulfide Control and
 1055 Methane Production. *Journal of Environmental Engineering* **139**: 594-601.
- 1056 Geertjes K., Baas K., Verschuren S., Kaashoek R. & Graveland C. (2016) Fosfor in
 1057 afvalwater en slib. Centraal Bureau voor de Statistiek (NL), Projectnummer 14159.
- 1058 Gell K., Ruijter F.J.d., Kuntke P., Graaff M.d. & Smit A.L. (2011) Safety and effectiveness
 1059 of struvite from black water and urine as a phosphorus fertilizer. *Journal of*
 1060 *Agricultural Science* **3**.
- 1061 Gendebien A., Ferguson R., Brink J., Horth H., Sullivan M. & Davis M. (2001) Survey of
 1062 wastes spread on land - final report.
- 1063 Gerba C.P. (2015) Chapter 29 - Disinfection. *Environmental Microbiology (Third edition)*,
 1064 pages. 645-662. Academic Press, San Diego.
- 1065 Ghidotti M., Fabbri D. & Hornung A. (2017a) Profiles of Volatile Organic Compounds in
 1066 Biochar: Insights into Process Conditions and Quality Assessment. *ACS Sustainable*
 1067 *Chemistry & Engineering* **5**: 510-517.
- 1068 Ghidotti M., Fabbri D., Mašek O., Mackay C.L., Montalti M. & Hornung A. (2017b) Source
 1069 and Biological Response of Biochar Organic Compounds Released into Water;

- 1070 Relationships with Bio-Oil Composition and Carbonization Degree. *Environmental*
1071 *Science & Technology* **51**: 6580-6589.
- 1072 Ghosh G.K., Mohan K.S. & Sarkar A.K. (1996) Characterization of soil-fertilizer P reaction
1073 products and their evaluation as sources of P for gram (*Cicer arietinum* L). *Nutrient*
1074 *Cycling in Agroecosystems* **46**: 71-79.
- 1075 Godbold D.L., Fritz E. & Hüttermann A. (1988) Aluminum toxicity and forest decline.
1076 *Proceedings of the National Academy of Sciences* **85**: 3888-3892.
- 1077 González-Ponce R., López-de-Sá E.G. & Plaza C. (2009) Lettuce Response to Phosphorus
1078 Fertilization with Struvite Recovered from Municipal Wastewater. *HortScience* **44**:
1079 426-430.
- 1080 Gonzalez Ponce R. & Garcia Lopez De Sa M.E. (2007) Evaluation of struvite as a fertilizer:
1081 A comparison with traditional P sources. *Agrochimica* **51**: 301-308.
- 1082 Good A.G. & Beatty P.H. (2011) Fertilizing Nature: A Tragedy of Excess in the Commons.
1083 *Plos Biology* **9**.
- 1084 Graber E.R., Meller Harel Y., Kolton M., Cytryn E., Silber A., Rav David D., . . . Elad Y.
1085 (2010a) Biochar impact on development and productivity of pepper and tomato
1086 grown in fertigated soilless media. *Plant and Soil* **337**: 481-496.
- 1087 Graber E.R., Harel Y.M., Kolton M., Cytryn E., Silber A., David D.R., . . . Elad Y. (2010b)
1088 Biochar impact on development and productivity of pepper and tomato grown in
1089 fertigated soilless media. *Plant and Soil* **337**: 481-496.
- 1090 Gratuito M.K.B., Panyathanmaporn T., Chumnanklang R.A., Sirinuntawittaya N. & Dutta A.
1091 (2008) Production of activated carbon from coconut shell: Optimization using
1092 response surface methodology. *Bioresource Technology* **99**: 4887-4895.
- 1093 Griffiths B.S., Spilles A. & Bonkowski M. (2012) C:N:P stoichiometry and nutrient
1094 limitation of the soil microbial biomass in a grazed grassland site under experimental
1095 P limitation or excess. *Ecological Processes* **1**: 6.
- 1096 Grösslová Z., Vaněk A., Mihaljevič M., Ettler V., Hojdová M., Zádorová T., . . . Ash C.
1097 (2015) Bioaccumulation of thallium in a neutral soil as affected by solid-phase
1098 association. *Journal of Geochemical Exploration* **159**: 208-212.
- 1099 Gruda N. (2012) Current and Future Perspective of Growing Media in Europe. *V Balkan*
1100 *Symposium on Vegetables and Potatoes*, Vol. 960, Balliu A. & Gruda N. (eds.),
1101 pages. 37-43.
- 1102 Gulyurtlu I., Crujeira A.T., Abelha P. & Cabrita I. (2007) Measurements of dioxin emissions
1103 during co-firing in a fluidised bed. *Fuel* **86**: 2090-2100.
- 1104 Gunes A., Inal A., Sahin O., Taskin M.B., Atakol O. & Yilmaz N. (2015) Variations in
1105 mineral element concentrations of poultry manure biochar obtained at different
1106 pyrolysis temperatures, and their effects on crop growth and mineral nutrition. *Soil*
1107 *Use and Management* **31**: 429-437.
- 1108 Günther L., Dockhorn T., Dichtl N., Müller J., Phan L.-C., Urban I., . . . Bayerle N. (2007)
1109 Technical and scientific monitoring of the large-scale seaborne technology at the
1110 WWTP Gifhorn. IWA Specialised Conference on Facing Sludge Diversities:
1111 Challenges, Risks and Opportunities, Antalya, Turkey.
- 1112 Hach company (2017) The Cost Of Spilled Milk: Analyzing Product Loss In The Dairy
1113 Industry.
- 1114 Haglund N. & Expertsgrup (2008) Guideline for classification of ash from solid biofuels and
1115 peat utilised for recycling and fertilizing in forestry and agriculture. 0283-7234, NT
1116 TECHN REPORT 613, Approved 2008-06, Norway.
- 1117 Hamilton H.A., Brod E., Hanserud O.S., Gracey E.O., Vestrum M.I., Bøen A., . . . Brattebø
1118 H. (2016) Investigating Cross-Sectoral Synergies through Integrated Aquaculture,

- 1119 Fisheries, and Agriculture Phosphorus Assessments: A Case Study of Norway.
1120 *Journal of Industrial Ecology* **20**: 867-881.
- 1121 Hammond J. & White P. (2005) Is struvite a valuable phosphate source for agriculture?
1122 Entrust project report 675382.006.
- 1123 Hao X.-D., Wang C.-C., Lan L. & van Loosdrecht M.C.M. (2008) Struvite formation,
1124 analytical methods and effects of pH and Ca²⁺. *Water Science and*
1125 *Technology* **58**: 1687-1692.
- 1126 Hao X., Wang C., van Loosdrecht M.C.M. & Hu Y. (2013) Looking Beyond Struvite for P-
1127 Recovery. *Environmental Science & Technology* **47**: 4965-4966.
- 1128 Hapke H.-J. (1996) Heavy metal transfer in the food chain to humans. *Fertilizers and*
1129 *Environment: Proceedings of the International Symposium "Fertilizers and*
1130 *Environment", held in Salamanca, Spain, 26-29, September, 1994*, Rodriguez-
1131 Barrueco C. (ed.), pages. 431-436. Springer Netherlands, Dordrecht.
- 1132 Haraldsen T.K., Pedersen P.A. & Krogstad T. (2011) Mixtures of bottom wood ash and meat
1133 and bone meal as NPK fertilizer. *Recycling of Biomass Ashes*, Insam H. & Knapp B.
1134 (eds.), pages. 33-44. Springer-Verlag, Berlin.
- 1135 Hass A., Gonzalez J.M., Lima I.M., Godwin H.W., Halvorson J.J. & Boyer D.G. (2012)
1136 Chicken Manure Biochar as Liming and Nutrient Source for Acid Appalachian Soil.
1137 *Journal of Environmental Quality* **41**: 1096-1106.
- 1138 He Y.D., Zhai Y.B., Li C.T., Yang F., Chen L., Fan X.P., . . . Fu Z.M. (2010) The fate of Cu,
1139 Zn, Pb and Cd during the pyrolysis of sewage sludge at different temperatures.
1140 *Environmental Technology* **31**: 567-574.
- 1141 Heijerick D. & Van Sprang P.A. (2004) Probabilistic Distribution of Boron in European
1142 Surface Waters. EURAS, Gent, Belgium. Report prepared for IAIOA (International
1143 Antimony Oxide Industry Association).
- 1144 Heinrichs H. & Mayer R. (1977) Distribution and Cycling of Major and Trace Elements in
1145 Two Central European Forest Ecosystems¹. *Journal of Environmental Quality* **6**:
1146 402-407.
- 1147 Helsen L., Van den Bulck E., Van den Broeck K. & Vandecasteele C. (1997) Low-
1148 temperature pyrolysis of CCA-treated wood waste: Chemical determination and
1149 statistical analysis of metal input and output; mass balances. *Waste Management* **17**:
1150 79-86.
- 1151 Hemme A., Spark M., Wolf P., Paschertz H. & Kamphues J. (2005) Effects of different
1152 phosphorus sources in the diet on bone composition and stability (breaking strength)
1153 in broilers. *Journal of Animal Physiology and Animal Nutrition* **89**: 129-133.
- 1154 Henrich E., Bürkle S., Meza-Renken Z.I. & Rumpel S. (1999) Combustion and gasification
1155 kinetics of pyrolysis chars from waste and biomass. *Journal of Analytical and*
1156 *Applied Pyrolysis* **49**: 221-241.
- 1157 Hernandez A.B., Ferrasse J.-H., Chaurand P., Saveyn H., Borschneck D. & Roche N. (2011)
1158 Mineralogy and leachability of gasified sewage sludge solid residues. *Journal of*
1159 *Hazardous Materials* **191**: 219-227.
- 1160 Herrman L. (2009) Recovery of phosphorus from wastewater treatment. A review. Umwelt
1161 Wissen Nr. 0929. Bundesamt für Umwelt (BAFU). Bern.
- 1162 Herzel H., Kruger O., Hermann L. & Adam C. (2016) Sewage sludge ash - A promising
1163 secondary phosphorus source for fertilizer production. *Science of the Total*
1164 *Environment* **542**: 1136-1143.
- 1165 Hess T., Aldaya M., Fawell J., Franceschini H., Ober E., Schaub R. & Schulze-Aurich J.
1166 (2014) Understanding the impact of crop and food production on the water
1167 environment - using sugar as a model. *Journal of the Science of Food and*
1168 *Agriculture* **94**: 2-8.

- 1169 Hicks J. & Yager J. (2006) Airborne Crystalline Silica Concentrations at Coal-Fired Power
1170 Plants Associated with Coal Fly Ash. *Journal of Occupational and Environmental*
1171 *Hygiene* **3**: 448-455.
- 1172 Hilber I., Bastos A.C., Loureiro S., Soja G., Marsz A., Cornelissen G. & Bucheli T.D. (2017)
1173 The different faces of biochar: contamination risk versus remediation tool. *Journal*
1174 *of Environmental Engineering and Landscape Management* **25**: 86-104.
- 1175 Hilt K., Harrison J., Bowers K., Stevens R., Bary A. & Harrison K. (2016) Agronomic
1176 response of crops fertilized with struvite derived from dairy manure. *Water, Air, &*
1177 *Soil Pollution* **227**: 388.
- 1178 Hinsinger P. (2001) Bioavailability of soil inorganic P in the rhizosphere as affected by root-
1179 induced chemical changes: a review. *Plant and Soil* **237**: 173-195.
- 1180 Hjelm O. (1990) Leachate from land disposal of coal fly ash. *Waste Management &*
1181 *Research* **8**: 429-449.
- 1182 Hjerne O. & Hansson S. (2002) The role of fish and fisheries in Baltic Sea nutrient dynamics.
1183 *Limnology and Oceanography* **47**: 1023-1032.
- 1184 Hjorth M., Christensen K.V., Christensen M.L. & Sommer S.G. (2010) Solid—liquid
1185 separation of animal slurry in theory and practice. A review. *Agronomy for*
1186 *Sustainable Development* **30**: 153-180.
- 1187 Horrel R., Metherell A.K., Ford S. & Doscher C. (1999) Fertiliser evenness – losses and
1188 costs: A study on the economic benefits of uniform applications of fertiliser.
1189 *Proceedings of the New Zealand Grassland Association* **61**: 215-220.
- 1190 Hossain M.K., Strezov V., Yin Chan K. & Nelson P.F. (2010) Agronomic properties of
1191 wastewater sludge biochar and bioavailability of metals in production of cherry
1192 tomato (*Lycopersicon esculentum*). *Chemosphere* **78**: 1167-1171.
- 1193 Hua K., Liu L. & Bureau D.P. (2005) Determination of Phosphorus Fractions in Animal
1194 Protein Ingredients. *Journal of Agricultural and Food Chemistry* **53**: 1571-1574.
- 1195 Huang H., Liu J. & Jiang Y. (2015) Crystallization and precipitation of phosphate from swine
1196 wastewater by magnesium metal corrosion. *Scientific Reports* **5**: 16601.
- 1197 Hultman B., Levlin E., Löwén M., Mossakowska A. & Stark K. (2001) Extraction of
1198 phosphorus and other products from sludge and ash. Interim report. Stockholm
1199 Vatten AB. Vattenvårdsteknik, KTH.
- 1200 Hunsinger H., Jay K. & Vehlow J. (2002) Formation and destruction of PCDD/F inside a
1201 grate furnace. *Chemosphere* **46**: 1263-1272.
- 1202 IAEA (2003) Assessing radiation doses to the public from radionuclides in timber and wood
1203 products. IAEA-TECDOC-1376. Vienna, Austria.
- 1204 Ibrahim I.A.A. (2015) Chemical characterization and mobility of metal species in fly ash–
1205 water system. *Water Science* **29**: 109-122.
- 1206 IFA (2013) Assessment of fertiliser use by crop at the global level 2010-2010/11.
- 1207 Imtiaz M., Rizwan M.S., Xiong S., Li H., Ashraf M., Shahzad S.M., . . . Tu S. (2015)
1208 Vanadium, recent advancements and research prospects: A review. *Environment*
1209 *International* **80**: 79-88.
- 1210 Injuk J., Van Grieken R. & De Leeuw G. (1998) Deposition of atmospheric trace elements
1211 into the North Sea: Coastal, ship, platform measurements and model predictions.
1212 *Atmospheric Environment* **32**: 3011-3025.
- 1213 Inocre Biotech (2016) Inocre biotech - P-bac process [ONLINE], Available at:
1214 <http://fritzmeier-umwelttechnik.com/p-bac-process/?lang=en> [Accessed 20 May
1215 2016].
- 1216 Insam H. & Seewald M.S.A. (2010) Volatile organic compounds (VOCs) in soils. *Biology*
1217 *and Fertility of Soils* **46**: 199-213.
- 1218 Insam H. & Knapp B. (2011) *Recycling of biomass ash*. Springer-Verlag, Berlin.

- 1219 INTECUS GmbH (2013) Technical Guide on the Treatment and Recycling Techniques for
 1220 Sludge from municipal Wastewater Treatment with references to Best Available
 1221 Techniques (BAT). Federal Environment Ministry's Advisory Assistance
 1222 Programme for Environmental Protection in Central and Eastern Europe, the
 1223 Caucasus and Central Asia. Project No. FKZ 380 01 233 Report No. (UBA-FB)
 1224 001927/E,1.
- 1225 International Biochar Initiative (2016a) IBI (International Biochar Initiative). Standardized
 1226 Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil
 1227 (IBI-STD-01.1, April 11, 2013) [ONLINE]. Available at: [http://www.biochar-](http://www.biochar-international.org/sites/default/files/IBI_Biochar_Standards_V1.1.pdf)
 1228 [international.org/sites/default/files/IBI_Biochar_Standards_V1.1.pdf](http://www.biochar-international.org/sites/default/files/IBI_Biochar_Standards_V1.1.pdf) [Accessed
 1229 26 May 2016].
- 1230 International Biochar Initiative (2016b) State of the biochar industry 2015 [ONLINE],
 1231 Available at: http://www.biochar-international.org/State_of_Industry_2015
 1232 [Accessed 26 May 2016].
- 1233 International Manganese Institute (2012) Assessing the potential terrestrial risks from
 1234 manganese.
- 1235 Ippolito J.A., Spokas K.A., Novak J.M., Lentz R.D. & Cantrell K.B. (2015) Biochar
 1236 elemental composition and factors influencing nutrient retention. *Biochar*
 1237 *environmental management - science, technology and implementation*, Lehmann J.
 1238 & Joseph S. (eds.), pages. 139-163. Routledge, Oxon.
- 1239 Iqbal Y., Lewandowski I., Weinreich A., Wippel B., Pforte B., Hadai O., . . . Peters D. (2016)
 1240 Maximising the yield of biomass from residues of agricultural crops and biomass
 1241 from forestry. BIENL 15082, report for DG Energy.
- 1242 IUPAC (1990) Glossary of atmospheric chemistry terms. International Union of Pure and
 1243 Applied Chemistry, Applied Chemistry Division, Commission on Atmospheric
 1244 Chemistry. *Pure and Applied Chemistry* **62**: 2167-2219.
- 1245 Izquierdo M., Moreno N., Font O., Querol X., Alvarez E., Antenucci D., . . . Fernández-
 1246 Pereira C. (2008) Influence of the co-firing on the leaching of trace pollutants from
 1247 coal fly ash. *Fuel* **87**: 1958-1966.
- 1248 Jaison S. & Muthukumar T. (2017) Chromium Accumulation in Medicinal Plants Growing
 1249 Naturally on Tannery Contaminated and Non-contaminated Soils. *Biological Trace*
 1250 *Element Research* **175**: 223-235.
- 1251 Jala S. & Goyal D. (2006) Fly ash as a soil ameliorant for improving crop production—a
 1252 review. *Bioresource Technology* **97**: 1136-1147.
- 1253 James A., Thring R., Helle S. & Ghuman H. (2012) Ash Management Review - Applications
 1254 of Biomass Bottom Ash. *Energies* **5**: 3856.
- 1255 Janik L.J., Forrester S.T., Kirby J.K., McLaughlin M.J., Soriano-Disla J.M. & Reimann C.
 1256 (2015a) Prediction of metal and metalloid partitioning coefficients (K_d) in soil using
 1257 mid-infrared diffuse reflectance spectroscopy. *Chemistry of Europe's agricultural*
 1258 *soils – Part B: General background information and further analysis of the GEMAS*
 1259 *data set. Geologisches Jahrbuch (Reihe B 103)*, Reimann C., Birke M., Demetriades
 1260 A., Filzmoser P. & O'Connor P. (eds.), pages. 183-188. Schweizerbarth.
- 1261 Janik L.J., Forrester S.T., Soriano-Disla J.M., Kirby J.K., McLaughlin M.J., Reimann C. &
 1262 The G.P.T. (2015b) GEMAS: Prediction of solid-solution phase partitioning
 1263 coefficients (K_d) for oxoanions and boric acid in soils using mid-infrared diffuse
 1264 reflectance spectroscopy. *Environmental Toxicology and Chemistry* **34**: 235-246.
- 1265 Janssen H. & Koopman R. (2005) Total phosphorus in soil, biowaste and sewage sludge,
 1266 prepared by CEN/BT/Task Force 151 – Horizontal Standards in the Field of Sludge,
 1267 Biowaste and Soil, the secretariat of which is held by Danish Standards.

- 1268 Jayathilakan K., Sultana K., Radhakrishna K. & Bawa A.S. (2012) Utilization of byproducts
1269 and waste materials from meat, poultry and fish processing industries: a review.
1270 *Journal of Food Science and Technology-Mysore* **49**: 278-293.
- 1271 Jeffery S., Abalos D., Spokas K.A. & Verheijen F.G.A. (2015) Biochar effects on crop yield.
1272 *Biochar environmental management - science, technology and implementation*,
1273 Lehmann J. & Joseph S. (eds.), pages. 301-326. Routledge, Oxon.
- 1274 Jeffery S., Abalos D., Prodana M., Bastos A.C., van Groenigen J.W., Hungate B.A. &
1275 Verheijen F. (2017) Biochar boosts tropical but not temperate crop yields.
1276 *Environmental Research Letters* **12**: 053001.
- 1277 Jensen A., Dam-Johansen K., Wójtowicz M.A. & Serio M.A. (1998) TG-FTIR Study of the
1278 Influence of Potassium Chloride on Wheat Straw Pyrolysis. *Energy & Fuels* **12**:
1279 929-938.
- 1280 Jewell S. & Kimball S. (2014) Mineral commodity summaries. US Geological Survey, pp.
1281 83. Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/2014/mcs2014.pdf>.
- 1282 Jing C., Liu S., Korfiatis G.P. & Meng X. (2006) Leaching behavior of Cr(III) in
1283 stabilized/solidified soil. *Chemosphere* **64**: 379-385.
- 1284 Johnson C.J., Pedersen J.A., Chappell R.J., McKenzie D. & Aiken J.M. (2007) Oral
1285 Transmissibility of Prion Disease Is Enhanced by Binding to Soil Particles. *PLoS*
1286 *Pathogens* **3**: e93.
- 1287 Johnston A.E. & Steen I. (1999) Understanding Phosphorus and its use in agriculture.
1288 European Fertilizer Manufacturers' Association, Brussels.
- 1289 Johnston A.E. & Richards I.R. (2003) Effectiveness of different precipitated phosphates as
1290 phosphorus sources for plants. *Soil Use and Management* **19**: 45-49.
- 1291 Joint Research Centre (2009) Linking soil degradation processes, soil-friendly farming
1292 practices and soil-relevant policy measures. Ispra.
- 1293 Jones A., Panagos P., Barcelo S. & al E. (2010) The State of Soil in Europe: A contribution
1294 of the JRC to the European Environment Agency's Environment State and Outlook
1295 Report— SOER 2010. European Commission - Joint Research Centre, Institute for
1296 Environment and Sustainability, Ispra, Italy.
- 1297 Jordan-Meille L., Rubæk G.H., Ehlert P.A.I., Genot V., Hofman G., Goulding K., . . .
1298 Barraclough P. (2012) An overview of fertilizer-P recommendations in Europe: soil
1299 testing, calibration and fertilizer recommendations. *Soil Use and Management* **28**:
1300 419-435.
- 1301 Jossa P. & Remy C. (2015) Life Cycle Assessment of selected processes for P recovery from
1302 sewage sludge, sludge liquor, or ash. Sustainable sewage sludge management
1303 fostering phosphorus recovery and energy efficiency (P-REX report). Berlin.
- 1304 Kabata-Pendias A. (2011) *Trace elements in soils and plants - Fourth edition*. CRC Press,
1305 Boca Raton.
- 1306 Kabata-Pendias A. & Mukherjee A.B. (2007) *Trace elements from soil to human*. Springer,
1307 New York.
- 1308 Kabbe C. (2017) Overview of phosphorus recovery from the wastewater stream facilities
1309 operating or under construction (March 2017) - P-REX Document.
- 1310 Kabbe C., Kraus F. & Nattorp A. (2015) Integral guidance document for phosphorus
1311 recovery and recycling. Sustainable sewage sludge management fostering
1312 phosphorus recovery and energy efficiency (P-REX report).
- 1313 Kahiluoto H., Kuisma M., Ketoja E., Salo T. & Heikkinen J. (2015) Phosphorus in Manure
1314 and Sewage Sludge More Recyclable than in Soluble Inorganic Fertilizer.
1315 *Environmental Science & Technology* **49**: 2115-2122.
- 1316 Kalmykova Y. & Karlfeldt Fedje K. (2013) Phosphorus recovery from municipal solid waste
1317 incineration fly ash. *Waste Management* **33**: 1403-1410.

- 1318 Kalmykova Y. & Fedje K.K. (2013) Phosphorus recovery from municipal solid waste
1319 incineration fly ash. *Waste Management* **33**: 1403-1410.
- 1320 Kambo H.S. & Dutta A. (2015) A comparative review of biochar and hydrochar in terms of
1321 production, physico-chemical properties and applications. *Renewable and*
1322 *Sustainable Energy Reviews* **45**: 359-378.
- 1323 Kaplan D.I., Sajwan K.S., Adriano D.C. & Gettier S. (1990) Phytoavailability and toxicity of
1324 beryllium and vanadium. *Water, Air, and Soil Pollution* **53**: 203-212.
- 1325 Karbowska B. (2016) Presence of thallium in the environment: sources of contaminations,
1326 distribution and monitoring methods. *Environmental Monitoring and Assessment*
1327 **188**: 640.
- 1328 Karlton E., Saarsalmi A., Ingerslev M., Mandre M., Andersson S., Gaitnieks T., . . .
1329 Varnagiryte-Kabasinskiene I. (2008) Wood ash recycling - possibilities and risks.
1330 *Sustainable use of forest biomass for energy: a synthesis with focus on the*, Röser D.,
1331 Asikainen A., Raulund-Rasmussen K. & Stupak I. (eds.), pages. 79-108. Springer,
1332 Dordrecht.
- 1333 Karvelas M., Katsoyiannis A. & Samara C. (2003) Occurrence and fate of heavy metals in
1334 the wastewater treatment process. *Chemosphere* **53**: 1201-1210.
- 1335 Kasina M., Kowalski P.R. & Michalik M. (2016) Metals Accumulation During Thermal
1336 Processing of Sewage Sludge - Characterization of Fly Ash and Air Pollution
1337 Control (APC) Residues. *Energy Procedia* **97**: 23-30.
- 1338 Kataki S., West H., Clarke M. & Baruah D.C. (2016) Phosphorus recovery as struvite: Recent
1339 concerns for use of seed, alternative Mg source, nitrogen conservation and fertilizer
1340 potential. *Resources, Conservation and Recycling* **107**: 142-156.
- 1341 Katanda Y., Zvomuya F., Flaten D. & Cicek N. (2016) Hog-Manure-Recovered Struvite:
1342 Effects on Canola and Wheat Biomass Yield and Phosphorus Use Efficiencies. *Soil*
1343 *Science Society of America Journal* **80**: 135-146.
- 1344 Kemacheevakul P., Otani S., Matsuda T. & Shimizu Y. (2012) Occurrence of micro-organic
1345 pollutants on phosphorus recovery from urine. *Water Science and Technology* **66**:
1346 2194-2201.
- 1347 Kercher A.K. & Nagle D.C. (2003) Microstructural evolution during charcoal carbonization
1348 by X-ray diffraction analysis. *Carbon* **41**: 15-27.
- 1349 Kern J., Tammeorg P., Shanskiy M., Sakrabani R., Knicker H., Kammann C., . . . Glaser B.
1350 (2017) Synergistic use of peat and charred material in growing media – an option to
1351 reduce the pressure on peatlands? *Journal of Environmental Engineering and*
1352 *Landscape Management* **25**: 160-174.
- 1353 Khan M.R., Wajid & Khan M. (1996) The effect of fly ash on plant growth and yield of
1354 tomato. *Environmental Pollution* **92**: 105-111.
- 1355 Kim A.G., Kazonich G. & Dahlberg M. (2003) Relative Solubility of Cations in Class F Fly
1356 Ash. *Environmental Science & Technology* **37**: 4507-4511.
- 1357 Kim S. & Dale B.E. (2004) Global potential bioethanol production from wasted crops and
1358 crop residues. *Biomass & Bioenergy* **26**: 361-375.
- 1359 Kleber M., Hockaday W.C. & Nico P.S. (2015) Characteristics of biochar: macro-molecular
1360 properties. *Biochar environmental management - science, technology and*
1361 *implementation*, Lehmann J. & Joseph S. (eds.), pages. 11-138. Routledge, Oxon.
- 1362 Kloss S., Zehetner F., Dellantonio A., Hamid R., Ottner F., Liedtke V., . . . Soja G. (2012)
1363 Characterization of Slow Pyrolysis Biochars: Effects of Feedstocks and Pyrolysis
1364 Temperature on Biochar Properties. *Journal of Environmental Quality* **41**: 990-1000.
- 1365 Knowles O.A., Robinson B.H., Contangelo A. & Clucas L. (2011) Biochar for the mitigation
1366 of nitrate leaching from soil amended with biosolids. *Science of the Total*
1367 *Environment* **409**: 3206-3210.

- 1368 Komiyama T., Kobayashi A. & Yahagi M. (2013) The chemical characteristics of ashes from
 1369 cattle, swine and poultry manure. *Journal of Material Cycles and Waste*
 1370 *Management* **15**: 106-110.
- 1371 Kopittke P.M., Menzies N.W. & Blamey F.P.C. (2005) Rhizotoxicity of aluminate and
 1372 polycationic aluminium at high pH. *Plant and Soil* **266**: 177-186.
- 1373 Korving L. (2012) Trends in slibontwatering, STOWA Report 2012-46. p. 108.
- 1374 Koutcheiko S., Monreal C.M., Kodama H., McCracken T. & Kotlyar L. (2007) Preparation
 1375 and characterization of activated carbon derived from the thermo-chemical
 1376 conversion of chicken manure. *Bioresource Technology* **98**: 2459-2464.
- 1377 Kratz S., Schick J. & Schnug E. (2016) Trace elements in rock phosphates and P containing
 1378 mineral and organo-mineral fertilizers sold in Germany. *Science of the Total*
 1379 *Environment* **542**: 1013-1019.
- 1380 Kraus F. & Seis W. (2015) Quantitative risk assessment of potential hazards for humans and
 1381 the environment: quantification of potential hazards resulting from agricultural use
 1382 of the manufactured fertilizers. Sustainable sewage sludge management fostering
 1383 phosphorus recovery and energy efficiency (P-REX report). Berlin.
- 1384 Kremer A.M. (2013) Nutrient budgets - Methodology and Handbook, version 1.02.
 1385 Luxembourg.
- 1386 Kretschmer B., Smith C., Watkins E., Allen B., Buckwell A., Desbarats J. & Kieve D. (2013)
 1387 Technology options for feeding 10 billion people - Recycling agricultural, forestry &
 1388 food wastes and residues for sustainable bioenergy and biomaterials. Institute for
 1389 European Environmental Policy (IEEP).
- 1390 Krewski D., Yokel R.A., Nieboer E., Borchelt D., Cohen J., Harry J., . . . Rondeau V. (2007)
 1391 Human health risk assessment for aluminium, aluminium oxide and aluminium
 1392 hydroxide. *Journal of toxicology and environmental health. Part B, Critical reviews*
 1393 **10**: 1-269.
- 1394 Kröppl M., Muñoz I.L. & Zeiner M. (2011) Trace elemental characterization of fly ash.
 1395 *Toxicological & Environmental Chemistry* **93**: 886-894.
- 1396 Krüger O. & Adam C. (2015) Recovery potential of German sewage sludge ash. *Waste*
 1397 *Management* **45**: 400-406.
- 1398 Kubota (2015) Sustainable phosphorus cycle by Kubota sludge melting system. European
 1399 Sustainable Phosphorus Conference, Berlin.
- 1400 Kuligowski K., Poulsen T.G., Rubæk G.H. & Sørensen P. (2010) Plant-availability to barley
 1401 of phosphorus in ash from thermally treated animal manure in comparison to other
 1402 manure based materials and commercial fertilizer. *European Journal of Agronomy*
 1403 **33**: 293-303.
- 1404 Kuokkanen T., Pöykiö R., Nurmesniemi H. & Rämö J. (2006) Sequential leaching of heavy
 1405 metals and sulfur in bottom ash and fly ash from the co-combustion of wood and
 1406 peat at a municipal district heating plant. *Chemical Speciation & Bioavailability* **18**:
 1407 131-142.
- 1408 Kuppusamy S., Thavamani P., Megharaj M., Venkateswarlu K. & Naidu R. (2016)
 1409 Agronomic and remedial benefits and risks of applying biochar to soil: Current
 1410 knowledge and future research directions. *Environment International* **87**: 1-12.
- 1411 Kuwahara Y. & Yamashita H. (2017) Phosphate Removal from Aqueous Solutions Using
 1412 Calcium Silicate Hydrate Prepared from Blast Furnace Slag. *Isij International* **57**:
 1413 1657-1664.
- 1414 Kuzyakov Y. & Domanski G. (2000) Carbon input by plants into the soil. Review. *Journal of*
 1415 *Plant Nutrition and Soil Science* **163**: 421-431.

- 1416 Kyllonen K., Karlsson V. & Ruoho-Airola T. (2009) Trace element deposition and trends
 1417 during a ten year period in Finland. *Science of the Total Environment* **407**: 2260-
 1418 2269.
- 1419 Lal R. (2009) Soils and food sufficiency. A review. *Agronomy for Sustainable Development*
 1420 **29**: 113-133.
- 1421 Langenkamp H. & Part P. (2001) Organic contaminants in sewage sludge for agricultural use.
 1422 European Commission, Joint Research Centre, Institute for Environment and
 1423 Sustainability, Soil and Waste Unit.
- 1424 Langeveld C.P. & Ten Wolde K.W. (2013) Phosphate recycling in mineral fertiliser
 1425 production. *Proceedings of the International Fertiliser Society* **727**: 1-24.
- 1426 Lanzerstorfer C. (2015) Investigation of the contamination of a fly ash sample during sample
 1427 preparation by air classification. *International Journal of Environmental Science and*
 1428 *Technology* **12**: 1437-1442.
- 1429 Lapa N., Barbosa R., Lopes M.H., Mendes B., Abelha P., Gulyurtlu I. & Santos Oliveira J.
 1430 (2007) Chemical and ecotoxicological characterization of ashes obtained from
 1431 sewage sludge combustion in a fluidised-bed reactor. *Journal of Hazardous*
 1432 *Materials* **147**: 175-183.
- 1433 Lapuerta M., Hernandez J.J., Pazo A. & Lopez J. (2008) Gasification and co-gasification of
 1434 biomass wastes: Effect of the biomass origin and the gasifier operating conditions.
 1435 *Fuel Processing Technology* **89**: 828-837.
- 1436 Larsson M.A., Baken S., Gustafsson J.P., Hadialhejazi G. & Smolders E. (2013) Vanadium
 1437 bioavailability and toxicity to soil microorganisms and plants. *Environmental*
 1438 *Toxicology and Chemistry* **32**: 2266-2273.
- 1439 Larsson M.A., Baken S., Smolders E., Cubadda F. & Gustafsson J.P. (2015) Vanadium
 1440 bioavailability in soils amended with blast furnace slag. *Journal of Hazardous*
 1441 *Materials* **296**: 158-165.
- 1442 Lavric E.D., Konnov A.A. & De Ruyck J. (2004) Dioxin levels in wood combustion - a
 1443 review. *Biomass & Bioenergy* **26**: 115-145.
- 1444 Le Corre K.S., Valsami-Jones E., Hobbs P. & Parsons S.A. (2009) Phosphorus Recovery
 1445 from Wastewater by Struvite Crystallization: A Review. *Critical Reviews in*
 1446 *Environmental Science and Technology* **39**: 433-477.
- 1447 Lehmann J. & Joseph S. (2015) *Biochar for environmental management - science, technology*
 1448 *and implementation, 2nd edition*. Routledge, New York.
- 1449 Lehmann J., Abiven S., Kleber M., Pan G., Singh B.P., Sohi S.P. & Zimmerman A.R. (2015)
 1450 Persistence of biochar in soil. *Biochar for Environmental Management - Science,*
 1451 *Technology and Implementation, 2nd edition.*, Lehmann J. & Joseph S. (eds.), pages.
 1452 235-282. Routledge - Earthscan, London.
- 1453 Leip A., Weiss F., Lesschen J.P. & Westhoek H. (2014) The nitrogen footprint of food
 1454 products in the European Union. *Journal of Agricultural Science* **152**: S20-S33.
- 1455 Lemieux P.M., Lee C.W., Ryan J.V. & Lutes C.C. (2001) Bench-scale studies on the
 1456 simultaneous formation of PCBs and PCDD/Fs from combustion systems. *Waste*
 1457 *Management* **21**: 419-425.
- 1458 Li F., Cao X., Zhao L., Wang J. & Ding Z. (2014) Effects of Mineral Additives on Biochar
 1459 Formation: Carbon Retention, Stability, and Properties. *Environmental Science &*
 1460 *Technology* **48**: 11211-11217.
- 1461 Li J., Liu B., Zeng Y. & Wang Z. (2017a) Mineralogical determination and geo-chemical
 1462 modeling of chromium release from AOD slag: Distribution and leachability
 1463 aspects. *Chemosphere* **167**: 360-366.

- 1464 Li J., Liu B., Zeng Y., Wang Z. & Gao Z. (2017b) Maximum availability and mineralogical
1465 control of chromium released from AOD slag. *Environmental Monitoring and*
1466 *Assessment* **189**: 113.
- 1467 Li M., Wang C., Cen K., Ni M. & Li X. (2018) Emission characteristics and
1468 vapour/particulate phase distributions of PCDD/F in a hazardous waste incinerator
1469 under transient conditions. *Royal Society Open Science* **5**.
- 1470 Li Y.-x., Zhang X.-l., Li W., Lu X.-f., Liu B. & Wang J. (2013) The residues and
1471 environmental risks of multiple veterinary antibiotics in animal faeces.
1472 *Environmental Monitoring and Assessment* **185**: 2211-2220.
- 1473 Liang X., Jin Y., He M., Niyungeko C., Zhang J., Liu C., . . . Arai Y. (2017) Phosphorus
1474 speciation and release kinetics of swine manure biochar under various pyrolysis
1475 temperatures. *Environmental Science and Pollution Research*.
- 1476 Libra J.A., Ro K.S., Kammann C., Funke A., Berge N.D., Neubauer Y., . . . Emmerich K.-H.
1477 (2011) Hydrothermal carbonization of biomass residuals: a comparative review of
1478 the chemistry, processes and applications of wet and dry pyrolysis. *Biofuels* **2**: 71-
1479 106.
- 1480 Lidén G. (2006) Dustiness Testing of Materials Handled at Workplaces. *The Annals of*
1481 *Occupational Hygiene* **50**: 437-439.
- 1482 Lievens C., Carleer R., Cornelissen T. & Yperman J. (2009) Fast pyrolysis of heavy metal
1483 contaminated willow: Influence of the plant part. *Fuel* **88**: 1417-1425.
- 1484 Lillo-Ródenas M.A., Marco-Lozar J.P., Cazorla-Amorós D. & Linares-Solano A. (2007)
1485 Activated carbons prepared by pyrolysis of mixtures of carbon precursor/alkaline
1486 hydroxide. *Journal of Analytical and Applied Pyrolysis* **80**: 166-174.
- 1487 Lin Y., Munroe P., Joseph S., Henderson R. & Ziolkowski A. (2012) Water extractable
1488 organic carbon in untreated and chemical treated biochars. *Chemosphere* **87**: 151-
1489 157.
- 1490 Lindsay W.L. & De Ment J.D. (1961) Effectiveness of some iron phosphates as sources of
1491 phosphorus for plants. *Plant and Soil* **14**: 118-126.
- 1492 Liu H., Pu C., Yu X., Sun Y. & Chen J. (2018) Removal of tetracyclines, sulfonamides, and
1493 quinolones by industrial-scale composting and anaerobic digestion processes.
1494 *Environmental Science and Pollution Research*.
- 1495 Liu X., Li Z., Zhang Y., Feng R. & Mahmood I.B. (2014) Characterization of human manure-
1496 derived biochar and energy-balance analysis of slow pyrolysis process. *Waste*
1497 *Management* **34**: 1619-1626.
- 1498 Liu X., Tao Y., Wen G., Kong F., Zhang X. & Hu Z. (2016) Influence of Soil and Irrigation
1499 Water pH on the Availability of Phosphorus in Struvite Derived from Urine through
1500 a Greenhouse Pot Experiment. *Journal of Agricultural and Food Chemistry* **64**:
1501 3324-3329.
- 1502 Liu Y., Rahman M.M., Kwag J.H., Kim J.H. & Ra C. (2011) Eco-friendly Production of
1503 Maize Using Struvite Recovered from Swine Wastewater as a Sustainable Fertilizer
1504 Source. *Asian-Australasian Journal of Animal Sciences* **24**: 1699-1705.
- 1505 Locke J.C., Altland J.E. & Ford C. (2013) Gasified rice hull biochar affects nutrition and
1506 growth of horticultural crops in container substrates. *Journal of Horticultural*
1507 *Science* **31**: 195-202.
- 1508 Looft T., Johnson T.A., Allen H.K., Bayles D.O., Alt D.P., Stedtfield R.D., . . . Stanton T.B.
1509 (2012) In-feed antibiotic effects on the swine intestinal microbiome. *Proceedings of*
1510 *the National Academy of Sciences* **109**: 1691-1696.
- 1511 Lopes H., Gulyurtlu I., Abelha P., Crujeira T., Salema D., Freire M., . . . Cabrita I. (2009)
1512 Particulate and PCDD/F emissions from coal co-firing with solid biofuels in a
1513 bubbling fluidised bed reactor. *Fuel* **88**: 2373-2384.

- 1514 Lopez Anton M.A., Spears D.A., Diaz Somoano M. & Martinez Tarazona M.R. (2013)
 1515 Thallium in coal: Analysis and environmental implications. *Fuel* **105**: 13-18.
- 1516 Lou Y., Ye Z.-L., Chen S., Wei Q., Zhang J. & Ye X. (2018) Influences of dissolved organic
 1517 matters on tetracyclines transport in the process of struvite recovery from swine
 1518 wastewater. *Water Research* **134**: 311-326.
- 1519 Lövren L. (2012) Roll pelletizing of ash—Cost efficient handling and improved product with
 1520 accelerated carbonatization. In Proceedings of Conference on Ash Utilization 2012:
 1521 Ashes in a Sustainable Society, Stockholm, Sweden, 25–27.
- 1522 Lu T., Yuan H., Wang Y., Huang H. & Chen Y. (2016) Characteristic of heavy metals in
 1523 biochar derived from sewage sludge. *Journal of Material Cycles and Waste
 1524 Management* **18**: 725-733.
- 1525 Lukehurst C.T., Frost P. & Al Seadi T. (2010) Utilisation of digestate from biogas plants as
 1526 biofertiliser. IEA Bioenergy Report - Task 37.
- 1527 Lundin L. & Marklund S. (2005) Thermal Degradation of PCDD/F in Municipal Solid Waste
 1528 Ashes in Sealed Glass Ampules. *Environmental Science & Technology* **39**: 3872-
 1529 3877.
- 1530 Lundin M., Olofsson M., Pettersson G.J. & Zetterlind H. (2004) Environmental and
 1531 economic assessment of sewage sludge handling options. *Resources, Conservation
 1532 and Recycling* **41**: 255-278.
- 1533 Luo Y., Xu L., Rysz M., Wang Y., Zhang H. & Alvarez P.J.J. (2011) Occurrence and
 1534 Transport of Tetracycline, Sulfonamide, Quinolone, and Macrolide Antibiotics in the
 1535 Haihe River Basin, China. *Environmental Science & Technology* **45**: 1827-1833.
- 1536 Lynch D., Low F., Henihan A.M., Garcia A., Kwapinski W., Zhang L. & Leahy J.J. (2014)
 1537 Behavior of Heavy Metals during Fluidized Bed Combustion of Poultry Litter.
 1538 *Energy & Fuels* **28**: 5158-5166.
- 1539 Ma Y., Oliveira R.S., Freitas H. & Zhang C. (2016) Biochemical and Molecular Mechanisms
 1540 of Plant-Microbe-Metal Interactions: Relevance for Phytoremediation. *Frontiers in
 1541 Plant Science* **7**: 918.
- 1542 Ma Y.L. & Matsunaka T. (2013) Biochar derived from dairy cattle carcasses as an alternative
 1543 source of phosphorus and amendment for soil acidity. *Soil Science and Plant
 1544 Nutrition* **59**: 628-641.
- 1545 Macdonald G.K., Jarvie H.P., Withers P.J.A., Doody D.G., Keeler B.L., Haygarth P.M., . . .
 1546 Zhang T. (2016) Guiding phosphorus stewardship for multiple ecosystem services.
 1547 *Ecosystem Health and Sustainability* **2**: e01251.
- 1548 Madhiyanon T., Sathitruangsak P. & Soponronnarit S. (2009) Co-combustion of rice husk
 1549 with coal in a cyclonic fluidized-bed combustor (Psi-FBC). *Fuel* **88**: 132-138.
- 1550 Maestrini B., Nannipieri P. & Abiven S. (2015) A meta-analysis on pyrogenic organic matter
 1551 induced priming effect. *GCB Bioenergy* **7**: 577-590.
- 1552 Mahmoud A., Olivier J., Vaxelaire J. & Hoadley A.F.A. (2011) Electro-dewatering of
 1553 wastewater sludge: Influence of the operating conditions and their interactions
 1554 effects. *Water Research* **45**: 2795-2810.
- 1555 Makridis C. & Amberger A. (1996) Thallium concentration in soils and crops and critical
 1556 values with respect to food chain. *Fertilizers and Environment: Proceedings of the
 1557 International Symposium "Fertilizers and Environment", held in Salamanca, Spain,
 1558 26–29, September, 1994*, Rodriguez-Barrueco C. (ed.), pages. 443-448. Springer
 1559 Netherlands, Dordrecht.
- 1560 Mankasingh U., Choi P.-C. & Ragnarsdottir V. (2011) Biochar application in a tropical,
 1561 agricultural region: A plot scale study in Tamil Nadu, India. *Applied Geochemistry*
 1562 **26, Supplement**: S218-S221.

- 1563 Manteau U. (2012) Wood Flows in Europe. Commissioned by CEPI: Confederation of
 1564 European Paper Industries, and CEI-Bois: European Confederation of Woodworking
 1565 Industries [ONLINE]. Available at:
 1566 [http://www.cepi.org/system/files/public/documents/publications/forest/2012/CE](http://www.cepi.org/system/files/public/documents/publications/forest/2012/CEPIWoodFlowsinEurope2012.pdf)
 1567 [PIWoodFlowsinEurope2012.pdf](http://www.cepi.org/system/files/public/documents/publications/forest/2012/CEPIWoodFlowsinEurope2012.pdf).
- 1568 Marchi A., Geerts S., Weemaes M., Wim S. & Christine V. (2015) Full-scale phosphorus
 1569 recovery from digested waste water sludge in Belgium - part I: technical
 1570 achievements and challenges. *Water Science and Technology* **71**: 487-494.
- 1571 Marculescu C. & Stan C. (2012) Non-oxidant Thermal Treatment for Organic Waste
 1572 Neutralization. *Energy Procedia* **18**: 545-551.
- 1573 Marti N., Ferrer J., Seco A. & Bouzas A. (2008) Optimisation of sludge line management to
 1574 enhance phosphorus recovery in WWTP. *Water Research* **42**: 4609-4618.
- 1575 Martí N., Pastor L., Bouzas A., Ferrer J. & Seco A. (2010) Phosphorus recovery by struvite
 1576 crystallization in WWTPs: Influence of the sludge treatment line operation. *Water*
 1577 *Research* **44**: 2371-2379.
- 1578 Martinez-Sanchez V., Kromann M.A. & Astrup T.F. (2015) Life cycle costing of waste
 1579 management systems: Overview, calculation principles and case studies. *Waste*
 1580 *Management* **36**: 343-355.
- 1581 Martins Abdao dos Passos A., Milanez de Rezende P., Reis Carvalho E. & William de Avila
 1582 F. (2015) Biochar, farmyard manure and poultry litter on chemical attributes of a
 1583 Distrophic Cambissol and soybean crop. *Agrária - Revista Brasileira de Ciências*
 1584 *Agrárias* **3**: 382-388.
- 1585 Masia A.A.T., Buhre B.J.P., Gupta R.P. & Wall T.F. (2007) Characterising ash of biomass
 1586 and waste. *Fuel Processing Technology* **88**: 1071-1081.
- 1587 Massé D.I., Cata Saady N.M. & Gilbert Y. (2014) Potential of Biological Processes to
 1588 Eliminate Antibiotics in Livestock Manure: An Overview. *Animals : an Open*
 1589 *Access Journal from MDPI* **4**: 146-163.
- 1590 Massey M.S., Davis J.G., Ippolito J.A. & Sheffield R.E. (2009) Effectiveness of recovered
 1591 magnesium phosphates as fertilizers in neutral and slightly alkaline soils. *Agronomy*
 1592 *Journal* **101**: 323-329.
- 1593 Mastro R.E., Sarkar E., George J., Jyoti K., Dutta P. & Ram L.C. (2015) PAHs and potentially
 1594 toxic elements in the fly ash and bed ash of biomass fired power plants. *Fuel*
 1595 *Processing Technology* **132**: 139-152.
- 1596 Mätzing H., Baumann W., Becker B., Jay K., Paur H.-R. & Seifert H. (2001) Adsorption of
 1597 PCDD/F on MWI fly ash. *Chemosphere* **42**: 803-809.
- 1598 Mayer B.K., Baker L.A., Boyer T.H., Drechsel P., Gifford M., Hanjra M.A., . . . Rittmann
 1599 B.E. (2016) Total Value of Phosphorus Recovery. *Environmental Science &*
 1600 *Technology* **50**: 6606-6620.
- 1601 McLaren R.G., Naidu R., Smith J. & Tiller K.G. (1998) Fractionation and Distribution of
 1602 Arsenic in Soils Contaminated by Cattle Dip. *Journal of Environmental Quality* **27**:
 1603 348-354.
- 1604 McLaughlin M.J. (2002) Measuring P availability in soils fertilized with water-soluble P
 1605 fertilizers using ³²P methodologies. IAEA Tecdoc 1272. Vienna.
- 1606 Mehta C.M., Khunjar W.O., Nguyen V., Tait S. & Batstone D.J. (2015) Technologies to
 1607 recover nutrients from waste streams: a critical review. *Critical Reviews in*
 1608 *Environmental Science and Technology* **45**: 385-427.
- 1609 Meij R., Nagengast S. & te Winkel H. (2000) The Occurrence of Quartz in Coal Fly Ash
 1610 Particles. *Inhalation Toxicology* **12**: 109-116.

- 1611 Méndez A., Gómez A., Paz-Ferreiro J. & Gascó G. (2012) Effects of sewage sludge biochar
 1612 on plant metal availability after application to a Mediterranean soil. *Chemosphere*
 1613 **89**: 1354-1359.
- 1614 Merchant S.S. (2010) The Elements of Plant Micronutrients. *Plant Physiology* **154**: 512-515.
- 1615 Meyer S., Genesio L., Vogel I., Schmidt H.-P., Soja G., Someus E., . . . Glaser B. (2017)
 1616 Biochar standardization and legislation harmonization. *Journal of Environmental*
 1617 *Engineering and Landscape Management* 1-17.
- 1618 Michalowski T. & Pietrzyk A. (2006) A thermodynamic study of struvite plus water system.
 1619 *Talanta* **68**: 594-601.
- 1620 Midwest Research Institute (1998) Emission Factor Documentation for AP-42, Section 9.2.1,
 1621 Fertilizer Application, Draft Report, Midwest Research Institute (MRI) for the
 1622 Office of Air Quality Planning and Standards (OAQPS), U. S. Environmental
 1623 Protection Agency (EPA), Contract No. 68-D2-0159.
- 1624 Miles T.R., Baxter L.L., Bryers R.W., Jenkins B.M. & Oden L.L. (1996) Boiler deposits from
 1625 firing biomass fuels. *Biomass & Bioenergy* **10**: 125-138.
- 1626 Miles T.R., Miles J.T.R., Baxter L.L., Bryers R.W., Jenkins B.M. & Oden L.L. (1995) Alkali
 1627 deposits found in biomass power plants. A preliminary investigation of their extent
 1628 and nature. Report of the National Renewable Energy Laboratory (NREL/TZ-2-
 1629 11226-1; TP-433-8142). Golden, CO, USA.
- 1630 Milieu Ltd - WRc - RPA (2010a) Environmental, economic and social impacts of the use of
 1631 sewage sludge on land - Final report. Part II - Report on Options and Impacts.
 1632 Report report prepared for the European Commission, DG Environment under Study
 1633 Contract DG ENV.G.4/ETU/2008/0076r.
- 1634 Milieu Ltd - WRc - RPA (2010b) Environmental, economic and social impacts of the use of
 1635 sewage sludge on land - Final report. Part I - Overview Report. Report report
 1636 prepared for the European Commission, DG Environment under Study Contract DG
 1637 ENV.G.4/ETU/2008/0076r.
- 1638 Milieu Ltd - WRc - RPA (2010c) Environmental, economic and social impacts of the use of
 1639 sewage sludge on land - final report, Study Contract DG ENV.G.4/ETU/2008/0076r
 1640 (for the European Commission, DG Environment).
- 1641 Milosavljevic I., Oja V. & Suuberg E.M. (1996) Thermal effects in cellulose pyrolysis:
 1642 Relationship to char formation processes. *Industrial & Engineering Chemistry*
 1643 *Research* **35**: 653-662.
- 1644 Miravet R., López-Sánchez J.F. & Rubio R. (2006) Leachability and analytical speciation of
 1645 antimony in coal fly ash. *Analytica Chimica Acta* **576**: 200-206.
- 1646 Misra M.K., Ragland K.W. & Baker A.J. (1993) WOOD ASH COMPOSITION AS A
 1647 FUNCTION OF FURNACE TEMPERATURE. *Biomass & Bioenergy* **4**: 103-116.
- 1648 Mithöfer A., Schulze B. & Boland W. (2004) Biotic and heavy metal stress response in
 1649 plants: evidence for common signals. *FEBS Letters* **566**: 1-5.
- 1650 Moilanen A. (2006) Thermogravimetric characterisations of biomass and waste for
 1651 gasification processes. VTT Technical Research Centre of Finland. Publications No
 1652 607; p. 103.
- 1653 Mok W.S.L. & Antal M.J. (1983) Effects of pressure on biomass pyrolysis. II. Heats of
 1654 reaction of cellulose pyrolysis. *Thermochimica Acta* **68**: 165-186.
- 1655 Moller K. (2015) Assessment of alternative phosphorus fertilisers for organic farming - meat
 1656 and bone meal. Stuttgart.
- 1657 Moller K. (2016) Assessment of alternative phosphorus fertilisers for organic farming - chars,
 1658 ashes and slags. Stuttgart.
- 1659 Möller K. & Müller T. (2012) Effects of anaerobic digestion on digestate nutrient availability
 1660 and crop growth: A review. *Engineering in Life Sciences* **12**: 242-257.

- 1661 Moloney A., Fotoushi J. & Steiger J. (2014) Industrial water use [ONLINE], available at:
 1662 <http://www.wwdmag.com/industrial-wastewater-recyclingreuse/industrial->
 1663 [revolution.](http://www.wwdmag.com/industrial-wastewater-recyclingreuse/industrial-)
- 1664 Montag D. & Pinnekamp J. (2009) The PASH process for P-recovery and overview of the
 1665 German Funding Programme "Recycling management of plant nutrients, especially
 1666 phosphorous". BAL TIC 21 Phosphorus Recycling and Good Agricultural
 1667 Management Practice, Berlin.
- 1668 Monte M.C., Fuente E., Blanco A. & Negro C. (2009) Waste management from pulp and
 1669 paper production in the European Union. *Waste Management* **29**: 293-308.
- 1670 Montes N., Otero M., Coimbra R.N., Méndez R. & Martín-Villacorta J. (2015) Removal of
 1671 tetracyclines from swine manure at full-scale activated sludge treatment plants.
 1672 *Environmental Technology* **36**: 1966-1973.
- 1673 Moore C. (2013) Can chicken litter be economically utilised at farm scale for energy
 1674 production and improve the profitability of the chicken farmer by reducing costs and
 1675 increasing revenues? Master thesis, DCU.
- 1676 Mooshammer M., Wanek W., Zechmeister-Boltenstern S. & Richter A. (2014)
 1677 Stoichiometric imbalances between terrestrial decomposer communities and their
 1678 resources: mechanisms and implications of microbial adaptations to their resources.
 1679 *Frontiers in Microbiology* **5**.
- 1680 Morabito E., Contini D., Belosi F., Stortini A.M., Manodori L. & Gambaro A. (2014)
 1681 Atmospheric Deposition of Inorganic Elements and Organic Compounds at the
 1682 Inlets of the Venice Lagoon. *Advances in Meteorology* **2014**: 10.
- 1683 Morselli L., Brusori B., Passarini F., Bernardi E., Francaviglia R., Gataleta L., . . . Olivieri P.
 1684 (2004) Heavy metals monitoring at a Mediterranean natural ecosystem of Central
 1685 Italy. Trends in different environmental matrixes. *Environment International* **30**:
 1686 173-181.
- 1687 Morshedizad M., Panten K., Klysubun W. & Leinweber P. (2018) Bone char effects on soil:
 1688 sequential fractionations and XANES spectroscopy. *SOIL* **4**: 23-35.
- 1689 Müller-Stöver D., Ahrenfeldt J., Holm J.K., Shalatat S.G.S., Henriksen U. & Hauggaard-
 1690 Nielsen H. (2012) Soil application of ash produced by low-temperature fluidized bed
 1691 gasification: effects on soil nutrient dynamics and crop response. *Nutrient Cycling in*
 1692 *Agroecosystems* **94**: 193-207.
- 1693 Muller J., Reinhardt M., Gunther L., Dockhorn T., Dichtl N., Urban I., . . . Vesterager N.O.
 1694 (2005) Fundamentals and feasibility of nutrient recycling using the seaborne
 1695 process. Conference on the Management of Residues Emanating from Water and
 1696 Wastewater Treatment, Johannesburg, South Africa.
- 1697 Münch E.V. & Barr K. (2001) Controlled struvite crystallisation for removing phosphorus
 1698 from anaerobic digester sidestreams. *Water Research* **35**: 151-159.
- 1699 Nanzer S., Oberson A., Berger L., Berset E., Hermann L. & Frossard E. (2014) The plant
 1700 availability of phosphorus from thermo-chemically treated sewage sludge ashes as
 1701 studied by ³³P labeling techniques. *Plant and Soil* **377**: 439-456.
- 1702 Nattorp A., Remmen K. & Remy C. (2017) Cost assessment of different routes for
 1703 phosphorus recovery from wastewater using data from pilot and production plants.
 1704 *Water Science and Technology* **76**: 413-424.
- 1705 Neal C., Williams R.J., Bowes M.J., Harrass M.C., Neal M., Rowland P., . . . Jarvie H.P.
 1706 (2010) Decreasing boron concentrations in UK rivers: Insights into reductions in
 1707 detergent formulations since the 1990s and within-catchment storage issues. *Science*
 1708 *of the Total Environment* **408**: 1374-1385.

- 1709 Nelissen V., Rutting T., Huygens D., Staelens J., Ruyschaert G. & Boeckx P. (2012) Maize
1710 biochars accelerate short-term soil nitrogen dynamics in a loamy sand soil. *Soil*
1711 *Biology & Biochemistry* **55**: 20-27.
- 1712 Nelson N.O. & Janke R.R. (2007) Phosphorus sources and management in organic
1713 production systems. *Horttechnology* **17**: 442-454.
- 1714 Neupane G. & Donahoe R.J. (2013) Leachability of elements in alkaline and acidic coal fly
1715 ash samples during batch and column leaching tests. *Fuel* **104**: 758-770.
- 1716 Neves D., Thunman H., Matos A., Tarelho L. & Gómez-Barea A. (2011) Characterization
1717 and prediction of biomass pyrolysis products. *Progress in Energy and Combustion*
1718 *Science* **37**: 611-630.
- 1719 Neyroud J.A. & Lischer P. (2003) Do different methods used to estimate soil phosphorus
1720 availability across Europe give comparable results? *Journal of Plant Nutrition and*
1721 *Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde* **166**: 422-431.
- 1722 Nielsen F.H. (2014) Update on human health effects of boron. *Journal of Trace Elements in*
1723 *Medicine and Biology* **28**: 383-387.
- 1724 Nieminen J. (2010) Phosphorus recovery and recycling from municipal wastewater sludge.
1725 Thesis, Aalto University.
- 1726 NIOSH—Publications Dissemination (2002) Hazard Review: Health Effects of Occupational
1727 Exposure to Respirable Crystalline Silica. National Institutes of Occupational Safety
1728 and Health (NIOSH); Cincinnati, OH, USA.
- 1729 Novak J.M., Lima I., Xing B., Gaskin J.W., Steiner C., Das K.C., . . . Schomberg H. (2009)
1730 Characterization of Designer Biochar Produced at Different Temperatures and Their
1731 Effects on a Loamy Sand. *2009* **3**.
- 1732 Nriagu J.O. (1998) History, production and uses of thallium. In J. O. Nriagu (Ed.), *Thallium*
1733 *in the environment* 29 (pp. 1–14). New York: Wiley.
- 1734 Nutalapati D., Gupta R., Moghtaderi B. & Wall T.F. (2007) Assessing slagging and fouling
1735 during biomass combustion: A thermodynamic approach allowing for alkali/ash
1736 reactions. *Fuel Processing Technology* **88**: 1044-1052.
- 1737 Obernberger I. & Supancic K. (2009) Possibilities of ash utilisation from biomass combustion
1738 plants. Proceedings of the 17th European Biomass Conference & exhibition, 29 June
1739 - 03 July Hamburg, Germany.
- 1740 Ocheцова P., Tlustos P. & Szakova J. (2014) Wheat and Soil Response to Wood Fly Ash
1741 Application in Contaminated Soils. *Agronomy Journal* **106**: 995-1002.
- 1742 Oenema O., Chardon W., Ehlert P.A.I., Van Dijk K.C., Schoumans O. & Rulkens W.H.
1743 (2012) Phosphorus fertilisers from by-products and wastes. Proceedings 717,
1744 International Fertiliser Society, Leek, UK.
- 1745 Oosterhuis F.H., Brouwer F.M. & Wijnants H.J. (2000) A possible EU wide charge on
1746 cadmium in phosphate fertilisers: Economic and environmental implications.
1747 Institute for Environmental Studies, Report number E-00/02 commissioned by the
1748 European Commission. Amsterdam.
- 1749 Page A.L., Elseewi A.A. & Straughan I.R. (1979) Physical and chemical properties of fly ash
1750 from coal-fired power plants with reference to environmental impacts. *Residue*
1751 *Reviews: Residues of Pesticides and Other Contaminants in the Total Environment*,
1752 Gunther F.A. & Gunther J.D. (eds.), pages. 83-120. Springer New York, New York,
1753 NY.
- 1754 Pagenkopf G.K. & Connolly J.M. (1982) Retention of boron by coal ash. *Environmental*
1755 *Science & Technology* **16**: 609-613.
- 1756 Paisley L.G. & Hostrup-Pedersen J. (2005a) A quantitative assessment of the BSE risk
1757 associated with fly ash and slag from the incineration of meat-and-bone meal in a
1758 gas-fired power plant in Denmark. *Preventive Veterinary Medicine* **68**: 263-275.

- 1759 Paisley L.G. & Hostrup-Pedersen J. (2005b) A quantitative assessment of the BSE risk
 1760 associated with fly ash and slag from the incineration of meat-and-bone meal in a
 1761 gas-fired power plant in Denmark. *Preventive Veterinary Medicine* **68**: 263-275.
- 1762 Pan Y.P. & Wang Y.S. (2015) Atmospheric wet and dry deposition of trace elements at 10
 1763 sites in Northern China. *Atmospheric Chemistry and Physics* **15**: 951-972.
- 1764 Panagos P., Van Liedekerke M., Jones A. & Montanarella L. (2012) European Soil Data
 1765 Centre: Response to European policy support and public data requirements. *Land
 1766 use policy* **29**: 329-338.
- 1767 Pandelova M., Lenoir D. & Schramm K.W. (2006) Correlation between PCDD/F, PCB and
 1768 PCBz in coal/waste combustion. Influence of various inhibitors. *Chemosphere* **62**:
 1769 1196-1205.
- 1770 Pandey V.C. & Singh N. (2010) Impact of fly ash incorporation in soil systems. *Agriculture,
 1771 Ecosystems & Environment* **136**: 16-27.
- 1772 Parker D.L., Kumar H.D., Rai L.C. & Singh J.B. (1997) Potassium salts inhibit growth of the
 1773 cyanobacteria *Microcystis* spp. in pond water and defined media: Implications for
 1774 control of microcystin-producing aquatic blooms. *Applied and Environmental
 1775 Microbiology* **63**: 2324-2329.
- 1776 Paul E., Laval M.L. & Sperandio M. (2001) Excess Sludge Production and Costs Due to
 1777 Phosphorus Removal. *Environmental Technology* **22**: 1363-1371.
- 1778 Pell Frischmann Consultants Ltd (2012) Enhancement and treatment of digestates from
 1779 anaerobic digestion, WRAP Project code: OMK006 - 002, UK.
- 1780 Peng X., Deng Y., Peng Y. & Yue K. (2018) Effects of biochar addition on toxic element
 1781 concentrations in plants: A meta-analysis. *Science of the Total Environment* **616-
 1782 617**: 970-977.
- 1783 Pensis I., Luetzenkirchen F. & Friede B. (2014) SWeRF—A Method for Estimating the
 1784 Relevant Fine Particle Fraction in Bulk Materials for Classification and Labelling
 1785 Purposes. *Annals of Occupational Hygiene* **58**: 501-511.
- 1786 Peralta-Videa J.R., Lopez M.L., Narayan M., Saupe G. & Gardea-Torresdey J. (2009) The
 1787 biochemistry of environmental heavy metal uptake by plants: Implications for the
 1788 food chain. *The International Journal of Biochemistry & Cell Biology* **41**: 1665-
 1789 1677.
- 1790 Peter A.L.J. & Viraraghavan T. (2005) Thallium: a review of public health and
 1791 environmental concerns. *Environment International* **31**: 493-501.
- 1792 Petrie B., Barden R. & Kasprzyk-Hordern B. (2015) A review on emerging contaminants in
 1793 wastewaters and the environment: Current knowledge, understudied areas and
 1794 recommendations for future monitoring. *Water Research* **72**: 3-27.
- 1795 Pettersen J. & Hertwich E.G. (2008) Critical Review: Life-Cycle Inventory Procedures for
 1796 Long-Term Release of Metals. *Environmental Science & Technology* **42**: 4639-
 1797 4647.
- 1798 Petzet S. & Cornel P. (2012) Prevention of Struvite Scaling in Digesters Combined With
 1799 Phosphorus Removal and Recovery-The FIX-Phos Process. *Water Environment
 1800 Research* **84**: 220-226.
- 1801 Petzet S., Peplinski B. & Cornel P. (2012) On wet chemical phosphorus recovery from
 1802 sewage sludge ash by acidic or alkaline leaching and an optimized combination of
 1803 both. *Water Research* **46**: 3769-3780.
- 1804 Pichtel J. (2016) Oil and Gas Production Wastewater: Soil Contamination and Pollution
 1805 Prevention. *Applied and Environmental Soil Science* **2016**: 24.
- 1806 Pillay K., von Blottnitz H. & Petersen J. (2003) Ageing of chromium(III)-bearing slag and its
 1807 relation to the atmospheric oxidation of solid chromium(III)-oxide in the presence of
 1808 calcium oxide. *Chemosphere* **52**: 1771-1779.

- 1809 Pinnekamp J., Montag D. & Everding W. (2010) Recycling of plant nutrients, especially
 1810 phosphorus - overview and preliminary results of the German Funding Programme.
 1811 7. FONA-FORUM, Berlin.
- 1812 Pitman R.M. (2006) Wood ash use in forestry – a review of the environmental impacts.
 1813 *Forestry: An International Journal of Forest Research* **79**: 563-588.
- 1814 Pizzorno L. (2015) Nothing Boring About Boron. *Integrative Medicine: A Clinician's*
 1815 *Journal* **14**: 35-48.
- 1816 Plants Database (2016) Nutrient content of crops [ONLINE], Available at:
 1817 <http://plants.usda.gov/npk/main> [Accessed 22 March 2016]. United States
 1818 Department of Agriculture.
- 1819 Plaza C., Sanz R., Clemente C., Fernandez J.M., Gonzalez R., Polo A. & Colmenarejo M.F.
 1820 (2007) Greenhouse evaluation of struvite and sludges from municipal wastewater
 1821 treatment works as phosphorus sources for plants. *Journal of Agricultural and Food*
 1822 *Chemistry* **55**: 8206-8212.
- 1823 Pogue J. & Yusuf S. (1998) Overcoming the limitations of current meta-analysis of
 1824 randomised controlled trials. *Lancet* **351**: 47-52.
- 1825 Pokhrel D. & Viraraghavan T. (2004) Treatment of pulp and paper mill wastewater—a
 1826 review. *Science of the Total Environment* **333**: 37-58.
- 1827 Polubesova T., Zadaka D., Groisman L. & Nir S. (2006) Water remediation by micelle–clay
 1828 system: Case study for tetracycline and sulfonamide antibiotics. *Water Research* **40**:
 1829 2369-2374.
- 1830 Popowska M., Rzczycka M., Miernik A., Krawczyk-Balska A., Walsh F. & Duffy B. (2012)
 1831 Influence of Soil Use on Prevalence of Tetracycline, Streptomycin, and
 1832 Erythromycin Resistance and Associated Resistance Genes. *Antimicrobial Agents*
 1833 *and Chemotherapy* **56**: 1434-1443.
- 1834 Pöykiö R., Nurmesniemi H., Dahl O. & Makela M. (2014) Chemical fractionation method for
 1835 characterization of biomass-based bottom and fly ash fractions from large-sized
 1836 power plant of an integrated pulp and paper mill complex. *Transactions of*
 1837 *Nonferrous Metals Society of China* **24**: 588-596.
- 1838 Pöykiö R., Rönkkömäki H., Nurmesniemi H., Perämäki P., Popov K., Välimäki I. & Tuomi
 1839 T. (2009) Chemical and physical properties of cyclone fly ash from the grate-fired
 1840 boiler incinerating forest residues at a small municipal district heating plant (6 MW).
 1841 *Journal of Hazardous Materials* **162**: 1059-1064.
- 1842 Prabakar J., Dendorkar N. & Morchhale R.K. (2004) Influence of fly ash on strength
 1843 behavior of typical soils. *Construction and Building Materials* **18**: 263-267.
- 1844 Press F. & Siever R. (1974) *Earth*. Freeman, W.H. and co., San Francisco.
- 1845 Priester T., Köster R. & Eberle S.H. (1996) *Charakterisierung kohlenstoffhaltiger*
 1846 *Bestandteile in Hausmüllverbrennungsschlacken unter besonderer Berücksichtigung*
 1847 *organischer Stoffe*. In: *Müll und Abfall*. Institut für Technische Chemie - Bereich
 1848 Wasser- und Geotechnologie (ITC-WGT) (ITC-WGT), Karlsruhe.
- 1849 Proctor D.M., Fehling K.A., Shay E.C., Wittenborn J.L., Green J.J., Avent C., . . . Zak M.A.
 1850 (2000) Physical and Chemical Characteristics of Blast Furnace, Basic Oxygen
 1851 Furnace, and Electric Arc Furnace Steel Industry Slags. *Environmental Science &*
 1852 *Technology* **34**: 1576-1582.
- 1853 PYREG (2016) PYREG GmbH [ONLINE], Available at: <http://www.pyreg.de/home.html>
 1854 [Accessed 26 May 2016].
- 1855 Qadir S., Qureshi M.I., Javed S. & Abdin M.Z. (2004) Genotypic variation in
 1856 phytoremediation potential of Brassica juncea cultivars exposed to Cd stress. *Plant*
 1857 *Science* **167**: 1171-1181.

- 1858 Quintana M., Colmenarejo M.F., Barrera J., García G., García E. & Bustos A. (2004) Use of
1859 a Byproduct of Magnesium Oxide Production To Precipitate Phosphorus and
1860 Nitrogen as Struvite from Wastewater Treatment Liquors. *Journal of Agricultural
1861 and Food Chemistry* **52**: 294-299.
- 1862 Rahman M.M., Salleh M.A.M., Rashid U., Ahsan A., Hossain M.M. & Ra C.S. (2014)
1863 Production of slow release crystal fertilizer from wastewaters through struvite
1864 crystallization – A review. *Arabian Journal of Chemistry* **7**: 139-155.
- 1865 Ravi S., Sharratt B.S., Li J.R., Olshevski S., Meng Z.J. & Zhang J.G. (2016) Particulate
1866 matter emissions from biochar-amended soils as a potential tradeoff to the negative
1867 emission potential. *Scientific Reports* **6**.
- 1868 RecoPhos (2016) RecoPhos, Close the circle, Wie Phoenix aus der Asche [ONLINE],
1869 Available at: <http://www.recophos.de/index.php?id=12> [Accessed 17 May 2016].
- 1870 Regenig - Bio Energie Technologie (2016) MAX Pyrolysereaktor Available at:
1871 <http://www.rewenergy.de/produkte/max-pyrolysereaktor.html#content>
1872 [Accessed 26 May 2016].
- 1873 Rehder D. (2015) The role of vanadium in biology. *Metallomics* **7**: 730-742.
- 1874 Reibe K., Roß C.-L. & Ellmer F. (2015) Hydro-/Biochar application to sandy soils: impact on
1875 yield components and nutrients of spring wheat in pots. *Archives of Agronomy and
1876 Soil Science* **61**: 1055-1060.
- 1877 Reijkonen I. (2017) Chemical bioavailability of chromium and vanadium species in soil: risk
1878 assessment of the use of steel industry slags as liming materials. PhD thesis,
1879 University of Helsinki, Finland.
- 1880 Reijonen I. (2017) Chemical bioavailability of chromium and vanadium species in soil: Risk
1881 assessment of the use of steel industry slags as liming materials. PhD thesis,
1882 University of Helsinki.
- 1883 Reijonen I., Metzler M. & Hartikainen H. (2016) Impact of soil pH and organic matter on the
1884 chemical bioavailability of vanadium species: The underlying basis for risk
1885 assessment. *Environmental Pollution* **210**: 371-379.
- 1886 Reiter M.S. & Middleton A. (2016) Nutrient availability from poultry litter co-products -
1887 Appendix F. Virginia.
- 1888 Remondis Aqua (2016) Phoenix from the ashes - Remondis Aqua paves the way for
1889 recovering phosphorus from sewage sludge ashes [ONLINE], Available at:
1890 [http://www.remondis-aktuell.com/en/remondis-aktuell/032014/water/phoenix-
1891 from-the-ashes/](http://www.remondis-aktuell.com/en/remondis-aktuell/032014/water/phoenix-from-the-ashes/) [Accessed 20 May 2016].
- 1892 Repetto G., del Peso A. & Repetto M. (1998) Human thallium toxicity. In J. O. Nriagu
1893 (Ed.), *Thallium in the environment* 29 (pp. 167–199). New York: Wiley.
- 1894 Reuter H.I., Lado L.R., Hengl T. & Montanarella L. (2008) Continental-scale digital Soil
1895 Mapping using European Soil Profile Data: Soil pH. *SAGA – Seconds Out.
1896 Hamburger Beiträge zur Physischen Geographie und Landschaftsökologie*, Vol. 19,
1897 Böhner J., Blaschke T. & Montanarella L. (eds.), pages. 113-126. Universität
1898 Hamburg Institut für Geographie, Hamburg.
- 1899 Rex M., Drissen P., Bartsch S., Breuer J. & Pischke J. (2013) Pflanzenverfügbarkeit von
1900 Phosphaten aus Klärschlamm- und Tiermehlaschen nach Aufschluss in flüssiger
1901 Konverterschlacke. VDLUFA Schriftenreihe 69.
- 1902 Rey-Salgueiro L., Omil B., Merino A., Martínez-Carballo E. & Simal-Gándara J. (2016)
1903 Organic pollutants profiling of wood ashes from biomass power plants linked to the
1904 ash characteristics. *Science of the Total Environment* **544**: 535-543.
- 1905 Richard F.C. & Bourg A.C.M. (1991) Aqueous geochemistry of chromium: A review. *Water
1906 Research* **25**: 807-816.

- 1907 Rigby H., Dowding A., Fernandes A., Humphries D., Petch R., Reynolds C., . . . Smith S.
 1908 (2015) Organic Contaminant Content and Physico-Chemical Characteristics of
 1909 Waste Materials Recycled in Agriculture. *Agriculture* **5**: 1289.
- 1910 Risnes H., Fjellerup J., Henriksen U., Moilanen A., Norby P., Papadakis K., . . . Sorensen
 1911 L.H. (2003) Calcium addition in straw gasification. *Fuel* **82**: 641-651.
- 1912 Ro K.S., Cantrell K.B. & Hunt P.G. (2010) High-Temperature Pyrolysis of Blended Animal
 1913 Manures for Producing Renewable Energy and Value-Added Biochar. *Industrial &*
 1914 *Engineering Chemistry Research* **49**: 10125-10131.
- 1915 Rodríguez-Reinoso F. & Molina-Sabio M. (1992) Activated carbons from lignocellulosic
 1916 materials by chemical and/or physical activation: an overview. *Carbon* **30**: 1111-
 1917 1118.
- 1918 Rohr A.C., Campleman S.L., Long C.M., Peterson M.K., Weatherstone S., Quick W. &
 1919 Lewis A. (2015) Potential Occupational Exposures and Health Risks Associated
 1920 with Biomass-Based Power Generation. *International Journal of Environmental*
 1921 *Research and Public Health* **12**: 8542-8605.
- 1922 Römbke J., Moser T. & Moser H. (2009) Ecotoxicological characterisation of 12 incineration
 1923 ashes using 6 laboratory tests. *Waste Management* **29**: 2475-2482.
- 1924 Römheld V. & Marschner H. (1986) Mobilization of iron in the rhizosphere of different plant
 1925 species. *Advances in Plant Nutrition, Volume 2*, Tinker B. & Läuchli A. (eds.),
 1926 pages. 155-204. Praeger Scientific, New York.
- 1927 Ronteltap M., Maurer M. & Gujer W. (2007) The behaviour of pharmaceuticals and heavy
 1928 metals during struvite precipitation in urine. *Water Research* **41**: 1859-1868.
- 1929 Ross J.J., Zitomer D.H., Miller T.R., Weirich C.A. & McNamara P.J. (2016) Emerging
 1930 investigators series: pyrolysis removes common microconstituents triclocarban,
 1931 triclosan, and nonylphenol from biosolids. *Environmental Science-Water Research*
 1932 *& Technology* **2**: 282-289.
- 1933 Rossell J.B. (2001) *Frying: improving quality*. Woodhead, Cambridge, England.
- 1934 Roy R.N., Finck A., Blair G.J. & Tandon H.L.S. (2006) Nutrient management guidelines for
 1935 some major field crops. *Plant nutrition for food productivity - A guide for integrated*
 1936 *nutrient management*, FAO (ed.), pages. 235-348. FAO, Rome.
- 1937 Ruamrungsri S., Bundithya W., Potapohn N., Ohtake N., Sueyoshi K. & Ohyama T. (2011)
 1938 Effect of NPK Levels on Growth and Bulb Quality of Some Geophytes in Substrate
 1939 Culture. *X International Symposium on Flower Bulbs and Herbaceous Perennials*,
 1940 Vol. 886, VanDenEnde J.E., Krikke A.T. & DenNijs A.P.M. (eds.), pages. 213-218.
- 1941 Ruiz Diaz D.A., Mueller N.D., Heller K. & Nelson N.O. (2010) Phosphorus recovered from
 1942 feedlot manure as fertilizer source for corn and soybean. Kansas City.
- 1943 Ruschetta S., Mosello R. & Carcano A. (2003) Trace metal measurements in atmospheric
 1944 depositions at three sites in Northern Italy. Methodology and preliminary results.
 1945 *Forest Snow and Landscape Research* **802**: 191-200.
- 1946 Rutherford D.W., Wershaw R.L. & Cox L.G. (2004) Changes in Composition and Porosity
 1947 Occurring During the Thermal Degradation of Wood and Wood Components. US
 1948 Geological Survey, Scientific Investigation Report 2004-5292.
- 1949 Saarsalmi A., Smolander A., Kukkola M. & Arola M. (2010) Effect of wood ash and nitrogen
 1950 fertilization on soil chemical properties, soil microbial processes, and stand growth
 1951 in two coniferous stands in Finland. *Plant and Soil* **331**: 329-340.
- 1952 Sahlstrom L., Bagge E., Emmoth E., Holmqvist A., Danielsson-Tham M.L. & Albihn A.
 1953 (2008) A laboratory study of survival of selected microorganisms after heat
 1954 treatment of biowaste used in biogas plants. *Bioresource Technology* **99**: 7859-7865.
- 1955 Sardans J. & Peñuelas J. (2015) Trees increase their P:N ratio with size. *Global ecology and*
 1956 *biogeography : a journal of macroecology* **24**: 147-156.

- 1957 Sartaj M. & Fernandes L. (2005) Adsorption of boron from landfill leachate by peat and the
 1958 effect of environmental factors. *Journal of Environmental Engineering and Science*
 1959 **4**: 19-28.
- 1960 Sarteel M., Tostivint C., Landowski A. & et al (2016) Resource Efficiency in Practice –
 1961 Closing Mineral Cycles. Final report. BIO by Deloitte, Ecologic Institute, AMEC,
 1962 Milan University, DTU, LEI. Report for European Commission, DG Environment.
 1963 Brussels, Belgium.
- 1964 Saunders S.E., Bartelt-Hunt S.L. & Bartz J.C. (2008) Prions in the environment: Occurrence,
 1965 fate and mitigation. *Prion* **2**: 162-169.
- 1966 Scarlat N., Martinov M. & Dallemand J.-F. (2010) Assessment of the availability of
 1967 agricultural crop residues in the European Union: Potential and limitations for
 1968 bioenergy use. *Waste Management* **30**: 1889-1897.
- 1969 Schaum C. (2007) Processes for future sewage sludge treatment - sewage sludge conditioning
 1970 and phosphorus recovery from sewage sludge ash. Thesis, Technische Universitat
 1971 Darmstadt, Darmstadt, Germany.
- 1972 Scheidig K. (2009) Economic and energy aspects of phosphorus recycling from sewage
 1973 sludge. *Korrespondenz Abwasser Abfall* **56**: 1138-1146.
- 1974 Schiemenz K. & Eichler-Löbermann B. (2010) Biomass ashes and their phosphorus
 1975 fertilizing effect on different crops. *Nutrient Cycling in Agroecosystems* **87**: 471-
 1976 482.
- 1977 Schiemenz K., Kern J., Paulsen H.-M., Bachmann S. & Eichler-Löbermann B. (2011)
 1978 Phosphorus fertilizing effects of biomass ashes. *Recycling of Biomass Ashes*, Insam
 1979 H. & Knapp B.A. (eds.), pages. 17-31. Springer Berlin Heidelberg, Berlin,
 1980 Heidelberg.
- 1981 Schimmelpfennig S. & Glaser B. (2012) One Step Forward toward Characterization: Some
 1982 Important Material Properties to Distinguish Biochars. *Journal of Environmental*
 1983 *Quality* **41**: 1001-1013.
- 1984 Schimmelpfennig S., Müller C., Grünhage L., Koch C. & Kammann C. (2014) Biochar,
 1985 hydrochar and uncarbonized feedstock application to permanent grassland—Effects
 1986 on greenhouse gas emissions and plant growth. *Agriculture, Ecosystems &*
 1987 *Environment* **191**: 39-52.
- 1988 Schmidt H.P. & Wilson K. (2016) The 55 uses of biochar - the Biochar Journal 2014, Arbaz,
 1989 Switzerland. [ONLINE], Available at: www.biochar-journal.org/en/ct/2 [Accessed
 1990 26 May 2016].
- 1991 Schoderboeck L., Mühlegger S., Losert A., Gausterer C. & Hornek R. (2011) Effects
 1992 assessment: Boron compounds in the aquatic environment. *Chemosphere* **82**: 483-
 1993 487.
- 1994 Schönberg A., Samiei K., Kern H. & Raupenstrauch H. (2014) The recophos process:
 1995 recovering phosphorus from sewage. *Österreichische Wasser- und Abfallwirtschaft*
 1996 **66**: 403-407.
- 1997 Schoumans O.F., Rulkens W.H., Oenema O. & Ehlert P.A.I. (2010) Phosphorus recovery
 1998 from animal manure - technical opportunities and agro-economical perspectives.
 1999 Alterra report 2158. Wageningen.
- 2000 Schoumans O.F., Bouraoui F., Kabbe C., Oenema O. & van Dijk K.C. (2015) Phosphorus
 2001 management in Europe in a changing world. *Ambio* **44**: S180-S192.
- 2002 Schulze M., Mumme J., Funke A. & Kern J. (2016) Effects of selected process conditions on
 2003 the stability of hydrochar in low-carbon sandy soil. *Geoderma* **267**: 137-145.
- 2004 Schuurmans Stekhoven S. (2015) Memo energie en grondstoffenfabriek. Utrecht, RVO.
- 2005 Schwarzer G., Carpenter J.R. & Rücker G. (2015) An Introduction to meta-analysis in R.
 2006 *Meta-Analysis with R*, pages. Springer International Publishing, Cham.

- 2007 Scurlock J.M.O., Dayton D.C. & Hames B. (2000) Bamboo: an overlooked biomass
2008 resource? *Biomass & Bioenergy* **19**: 229-244.
- 2009 Searle S. & Malins C. (2013) Availability of cellulosic residues and wastes in the EU. New
2010 York.
- 2011 Secretariat of the Stockholm Convention on Persistent Organic Pollutants (2008) Waste
2012 incinerators - guidelines on best available techniques and provisional guidance on
2013 best environmental practices relevant to Article 5 and Annex C of the Stockholm
2014 Convention on Persistent Organic Pollutants. Geneva.
- 2015 Seufert V. & Ramankutty N. (2017) Many shades of gray—The context-dependent
2016 performance of organic agriculture. *Science Advances* **3**.
- 2017 Severin M., Breuer J., Rex M., Stemann J., Adam C., Weghe H.v.d. & Kücke M. (2014)
2018 Phosphate fertilizer value of heat treated sewage sludge ash. *Plant, Soil and*
2019 *Environment* **60**: 555-561.
- 2020 Shackley S., Sohi S., Ibarrola R., Hammond J., Mašek O., Brownsort P., . . . Haszeldine S.
2021 (2013) Biochar, Tool for Climate Change Mitigation and Soil Management.
2022 *Geoengineering Responses to Climate Change: Selected Entries from the*
2023 *Encyclopedia of Sustainability Science and Technology*, Lenton T. & Vaughan N.
2024 (eds.), pages. 73-140. Springer New York, New York, NY.
- 2025 Shahid M., Shamshad S., Rafiq M., Khalid S., Bibi I., Niazi N.K., . . . Rashid M.I. (2017)
2026 Chromium speciation, bioavailability, uptake, toxicity and detoxification in soil-
2027 plant system: A review. *Chemosphere* **178**: 513-533.
- 2028 Sheppard S., Long J., Sanipelli B. & Sohlenius G. (2009) Solid/liquid partition coefficients
2029 (Kd) for selected soils and sediments at Forsmark and Laxemar-Simpevarp. SKB
2030 Rapport R-09-27. Swedish Nuclear Fuel and Waste Management Commission.
- 2031 Shibamoto T., Yasuhara A. & Katami T. (2007) Dioxin Formation from Waste Incineration.
2032 *Reviews of Environmental Contamination and Toxicology: Continuation of Residue*
2033 *Reviews*, Ware G.W., Whitacre D.M. & Gunther F.A. (eds.), pages. 1-41. Springer
2034 New York, New York, NY.
- 2035 Shigeru M., Hideto F., Emi Y., Takayoshi K., Akira O. & Kensuke N. (1997)
2036 Bioaccumulation of Antimony by *Chlorella vulgaris* and the Association Mode of
2037 Antimony in the Cell. *Applied Organometallic Chemistry* **11**: 393-396.
- 2038 Siciliano A. (2016) Assessment of fertilizer potential of the struvite produced from the
2039 treatment of methanogenic landfill leachate using low-cost reagents. *Environmental*
2040 *Science and Pollution Research* **23**: 5949-5959.
- 2041 Siddiqui S. & Adams W.A. (2002) The fate of diesel hydrocarbons in soils and their effect on
2042 the germination of perennial ryegrass. *Environmental Toxicology* **17**: 49-62.
- 2043 Siebers N., Godlinski F. & Leinweber P. (2014) Bone char as phosphorus fertilizer involved
2044 in cadmium immobilization in lettuce, wheat, and potato cropping. *Journal of Plant*
2045 *Nutrition and Soil Science* **177**: 75-83.
- 2046 SIFCO (2017) Rapport d'activité 2015 - Syndicat des Industries Françaises des COproduits.
- 2047 Sigurnjak I., Michels E., Crappé S., Buysens S., Tack F.M.G. & Meers E. (2016) Utilization
2048 of derivatives from nutrient recovery processes as alternatives for fossil-based
2049 mineral fertilizers in commercial greenhouse production of *Lactuca sativa* L.
2050 *Scientia Horticulturae* **198**: 267-276.
- 2051 Silva F.C., Borrego C., Keizer J.J., Amorim J.H. & Verheijen F.G.A. (2015) Effects of
2052 moisture content on wind erosion thresholds of biochar. *Atmospheric Environment*
2053 **123, Part A**: 121-128.
- 2054 Singer A.C., Shaw H., Rhodes V. & Hart A. (2016) Review of Antimicrobial Resistance in
2055 the Environment and Its Relevance to Environmental Regulators. *Frontiers in*
2056 *Microbiology* **7**: 1728.

- 2057 Singh R., Gautam N., Mishra A. & Gupta R. (2011a) Heavy metals and living systems: An
2058 overview. *Indian Journal of Pharmacology* **43**: 246-253.
- 2059 Singh S., Ram L.C., Masto R.E. & Verma S.K. (2011b) A comparative evaluation of
2060 minerals and trace elements in the ashes from lignite, coal refuse, and biomass fired
2061 power plants. *International Journal of Coal Geology* **87**: 112-120.
- 2062 Six L., Hoxha A. & Langeveld K. (2014) Is there a potential for P recycling in the mineral
2063 fertilizer industry? Sustainable Phosphorus Summit, 1-3 September, Le Corum,
2064 Montpellier, France.
- 2065 Skodras G., Prokopidou M. & Sakellaropoulos G.P. (2006) Leaching and toxicity behavior of
2066 coal-biomass waste cocombustion ashes. *Environmental Toxicology* **21**: 317-323.
- 2067 Smit C.E. (2012) *Environmental risk limits for vanadium in water - A proposal for water*
2068 *quality standards in accordance with the Water Framework Directive*. . RIVM
2069 Letter Report 601714021/2012, Bilthoven, the Netherlands.
- 2070 Smith C.R., Buzan E.M. & Lee J.W. (2013a) Potential Impact of Biochar Water-Extractable
2071 Substances on Environmental Sustainability. *ACS Sustainable Chemistry &*
2072 *Engineering* **1**: 118-126.
- 2073 Smith C.R., Hatcher P.G., Kumar S. & Lee J.W. (2016) Investigation into the Sources of
2074 Biochar Water-Soluble Organic Compounds and Their Potential Toxicity on Aquatic
2075 Microorganisms. *ACS Sustainable Chemistry & Engineering* **4**: 2550-2558.
- 2076 Smith P.G., Boutin C. & Knopper L. (2013b) Vanadium Pentoxide Phytotoxicity: Effects of
2077 Species Selection and Nutrient Concentration. *Archives of Environmental*
2078 *Contamination and Toxicology* **64**: 87-96.
- 2079 Smith S. & Kwan M.K.H. (1989) Use of aquatic macrophytes as a bioassay method to assess
2080 relative toxicity, uptake kinetics and accumulated forms of trace metals.
2081 *Hydrobiologia* **188**: 345-351.
- 2082 Smith S.R. (2009) Organic contaminants in sewage sludge (biosolids) and their significance
2083 for agricultural recycling. *Philosophical Transactions of the Royal Society A:*
2084 *Mathematical, Physical and Engineering Sciences* **367**: 4005-4041.
- 2085 Sokka L., Antikainen R. & Kauppi P. (2004) Flows of nitrogen and phosphorus in municipal
2086 waste: a substance flow analysis in Finland. *Progress in Industrial Ecology* **1**: 165-
2087 186.
- 2088 Someus E. (2015) Risk of biochar use - organic pollutants: PCBs and PCDDs/PCDFs.
2089 Refertil Newsletter - Issue 2015.
- 2090 Song W., Ding Y., Chiou C.T. & Li H. (2010) Selected Veterinary Pharmaceuticals in
2091 Agricultural Water and Soil from Land Application of Animal Manure. *Journal of*
2092 *Environmental Quality* **39**: 1211-1217.
- 2093 Spellman F.R. & Whiting N.E. (2007) *Environmental Management of Concentrated Animal*
2094 *Feeding Operations (CAFOs)*. Taylor and Francis, Boca Raton.
- 2095 Spokas K.A., Novak J.M., Stewart C.E., Cantrell K.B., Uchimiya M., DuSaire M.G. & Ro
2096 K.S. (2011) Qualitative analysis of volatile organic compounds on biochar.
2097 *Chemosphere* **85**: 869-882.
- 2098 Srivastava S., Tripathi R.D. & Dwivedi U.N. (2004) Synthesis of phytochelatins and
2099 modulation of antioxidants in response to cadmium stress in *Cuscuta reflexa* – an
2100 angiospermic parasite. *Journal of Plant Physiology* **161**: 665-674.
- 2101 Staroń P., Kowalski Z., Staroń A., Seidlerová J. & Banach M. (2016) Residues from the
2102 thermal conversion of waste from the meat industry as a source of valuable macro-
2103 and micronutrients. *Waste Management* **49**: 337-345.
- 2104 Steenari B.M., Schelander S. & Lindqvist O. (1999) Chemical and leaching characteristics of
2105 ash from combustion of coal, peat and wood in a 12 MW CFB – a comparative
2106 study. *Fuel* **78**: 249-258.

- 2107 Steiner C., Sanchez-Monedero M.A. & Kammann C. (2015) biochar as an additive to
 2108 compost. *Biochar environmental management - science, technology and*
 2109 *implementation*, Lehmann J. & Joseph S. (eds.), pages. 717-738. Routledge, Oxon.
- 2110 Steinhauser G., Brandl A. & Johnson T.E. (2014) Comparison of the Chernobyl and
 2111 Fukushima nuclear accidents: A review of the environmental impacts. *Science of the*
 2112 *Total Environment* **470–471**: 800-817.
- 2113 Stenmark A., Jense C., AQuested T. & Moates G. (2016) Estimates of European food waste
 2114 levels. FUSIONS EU project.
- 2115 Steppich D. (2015) The thermo-reductive RecoPhos process – From sewage sludge ashes to
 2116 elementary phosphorus for industrial applications. RecoPhos – Demonstration Event
 2117 Leoben, Leoben, Austria.
- 2118 Storer N.L. & Nelson T.S. (1968) The effect of various aluminum compounds on chick
 2119 performance. *Poultry Science* **47**: 244-246.
- 2120 STOWA (2011) Fosfaatterugwinning in communale afvalwaterzuiveringsinstallaties.
 2121 STOWA Report 24/2011.
- 2122 STOWA (2015) Verkenning van de kwaliteit van struviet uit de communale afvalwaterketen
 2123 (in dutch). STOWA Report 2015-35, Amersfoort, NL.
- 2124 STOWA (2016a) Levenscyclusanalyse van grondstoffen uit rioolwater. STOWA Rapport
 2125 22.2016, Amersfoort.
- 2126 STOWA (2016b) Struviet en struviethoudende producten uit communaal afvalwater.
 2127 STOWA 2016-12. Amersfoort, NL.
- 2128 Straughan I.R., Elseewi A.A. & Page A.L. (1978) Mobilization of selected trace elements in
 2129 residues from coal combustions with a special reference to fly ash. *Trace Substances*
 2130 *and Environmental Health* **12**: 389-402.
- 2131 Styles D., Adams P., Thelin G., Vaneekhaute C., Chadwick D. & Withers P.J.A. (2018) Life
 2132 Cycle Assessment of Biofertilizer Production and Use Compared with Conventional
 2133 Liquid Digestate Management. *Environmental Science & Technology* **52**: 7468-
 2134 7476.
- 2135 Subbarao G.V., Ito O., Berry W.L. & Wheeler R.M. (2003) Sodium—A Functional Plant
 2136 Nutrient. *Critical Reviews in Plant Sciences* **22**: 391-416.
- 2137 Sutton M.A., Howard C.M., Erisman J.W., Billen G., Bleeker A., Grennfelt P., . . . Grizetti B.
 2138 (2011) *The European Nitrogen Assessment*. Cambridge University Press,
 2139 Cambridge.
- 2140 Świetlik R., Trojanowska M., Karbowska B. & Zembruski W. (2016) Speciation and
 2141 mobility of volatile heavy metals (Cd, Pb, and Tl) in fly ashes. *Environmental*
 2142 *Monitoring and Assessment* **188**: 637.
- 2143 Syers J.K., Johnston A.E. & Curtin D. (2008) Efficiency of soil and fertilizer phosphorus use
 2144 - Reconciling changing concepts of soil phosphorus behaviour with agronomic
 2145 information. FAO Fertilizer and plant nutrition bulletin No18. FAO, Rome.
- 2146 Takahashi M., Kato S., Shima H., Sarai E., Ichioka T., Hatyakawa S. & Miyajiri H. (2001)
 2147 Technology for recovering phosphorus from incinerated wastewater treatment
 2148 sludge. *Chemosphere* **44**: 23-29.
- 2149 Talboys P.J., Heppell J., Roose T., Healey J.R., Jones D.L. & Withers P.J.A. (2016) Struvite:
 2150 a slow-release fertiliser for sustainable phosphorus management? *Plant and Soil*
 2151 **401**: 109-123.
- 2152 Tan Z. & Lagerkvist A. (2011) Phosphorus recovery from the biomass ash: A review.
 2153 *Renewable and Sustainable Energy Reviews* **15**: 3588-3602.
- 2154 The Ellen MacArthur Foundation (2014) Towards the circular economy - Accelerating the
 2155 scale-up across global supply chains. Cowes, UK.

- 2156 The Weinberg Group Inc. (2000) Health risk evaluation of select metals in inorganic
 2157 fertilizers post application. Report prepared for the Fertilizer Institute (TFI).
 2158 Washington, 140 pp.
- 2159 Theis M., Skrifvars B.J., Hupa M. & Tran H.H. (2006) Fouling tendency of ash resulting
 2160 from burning mixtures of biofuels. Part 1: Deposition rates. *Fuel* **85**: 1125-1130.
- 2161 Thompson L.B. (2013) Field evaluation of the availability for corn and soybean of
 2162 phosphorus recovered as struvite from corn fiber processing for bioenergy. Graduate
 2163 Theses and Dissertations. Paper 13173.
- 2164 Thornberg D. (2015) Genanvendelse af fosfor fra aske og rejektivand - projekt EDASK og
 2165 GAFOKIR. EDASK Project Meeting, Copenhagen.
- 2166 Thy P., Leshar C.E. & Jenkins B.M. (2000) Experimental determination of high-temperature
 2167 elemental losses from biomass slag. *Fuel* **79**: 693-700.
- 2168 Thy P., Jenkins B.M., Grundvig S., Shiraki R. & Leshar C.E. (2006) High temperature
 2169 elemental losses and mineralogical changes in common biomass ashes. *Fuel* **85**:
 2170 783-795.
- 2171 Thy P., Leshar C.E., Jenkins B.M., Gras M.A. & Shiraki R. (2008) Trace mobilization during
 2172 comustion of biomass fuels. Pier final project report. Commission contract No 500-
 2173 02-004. Davis.
- 2174 Tillman D.A. (2000) Biomass cofiring: the technology, the experience, the combustion
 2175 consequences. *Biomass & Bioenergy* **19**: 365-384.
- 2176 Titirici M.-M., Antonietti M. & Baccile N. (2008) Hydrothermal carbon from biomass: a
 2177 comparison of the local structure from poly- to monosaccharides and
 2178 pentoses/hexoses. *Green Chemistry* **10**: 1204-1212.
- 2179 Tomasi Morgano M., Leibold H., Richter F., Stapf D. & Seifert H. (2018) Screw pyrolysis
 2180 technology for sewage sludge treatment. *Waste Management* **73**: 487-495.
- 2181 Tong L., Li P., Wang Y. & Zhu K. (2009) Analysis of veterinary antibiotic residues in swine
 2182 wastewater and environmental water samples using optimized SPE-LC/MS/MS.
 2183 *Chemosphere* **74**: 1090-1097.
- 2184 Tortosa Masiá A.A., Buhre B.J.P., Gupta R.P. & Wall T.F. (2007) Characterising ash of
 2185 biomass and waste. *Fuel Processing Technology* **88**: 1071-1081.
- 2186 Tóth G., Guicharnaud R.-A., Tóth B. & Hermann T. (2014) Phosphorus levels in croplands of
 2187 the European Union with implications for P fertilizer use. *European Journal of*
 2188 *Agronomy* **55**: 42-52.
- 2189 Tschan M., Robinson B. & Schulin R. (2008) Antimony uptake by *Zea mays* (L.) and
 2190 *Helianthus annuus* (L.) from nutrient solution. *Environmental Geochemistry and*
 2191 *Health* **30**: 187-191.
- 2192 Twining B.S., Twiss M.R. & Fisher N.S. (2003) Oxidation of Thallium by Freshwater
 2193 Plankton Communities. *Environmental Science & Technology* **37**: 2720-2726.
- 2194 Tyler G. (1978) Leaching rates of heavy metal ions in forest soil. *Water, Air, and Soil*
 2195 *Pollution* **9**: 137-148.
- 2196 Uchimiya M. (2014) Changes in Nutrient Content and Availability During the Slow Pyrolysis
 2197 of Animal Wastes. *Applied Manure and Nutrient Chemistry for Sustainable*
 2198 *Agriculture and Environment*, He Z. & Zhang H. (eds.), pages. 53-68. Springer
 2199 Netherlands, Dordrecht.
- 2200 Uchimiya M., Cantrell K.B., Hunt P.G., Novak J.M. & Chang S. (2012) Retention of Heavy
 2201 Metals in a Typic Kandiodult Amended with Different Manure-based Biochars.
 2202 *Journal of Environmental Quality* **41**: 1138-1149.
- 2203 Udikovic-Kolic N., Wichmann F., Broderick N.A. & Handelsman J. (2014) Bloom of
 2204 resident antibiotic-resistant bacteria in soil following manure fertilization.
 2205 *Proceedings of the National Academy of Sciences* **111**: 15202-15207.

- 2206 Ueno Y. & Fujii M. (2001) Three Years Experience of Operating and Selling Recovered
2207 Struvite from Full-Scale Plant. *Environmental Technology* **22**: 1373-1381.
- 2208 Umantahaswaran K. & Batra V.S. (2008) Physico-chemical characterisation of Indian
2209 biomass ashes. *Fuel* **87**: 628-638.
- 2210 UMK-AG (2000) Arbeitsgruppe der Umweltministerkonferenz "Ursachen der
2211 Klärschlammbelastung mit gefährlichen Stoffen, Maßnahmenplan" (2000):
2212 Abschlussbericht "Ursachen der Klärschlammbelastung mit gefährlichen Stoffen,
2213 Maßnahmenplan". Preprint, 350 p.
- 2214 UNEP (2000) Cleaner production assessment in fish processing. Paris, France.
- 2215 UNEP (2004) General Technical Guideline on the Environmentally Sound Management of
2216 Wastes Consisting of, Containing or Contaminated with Persistent Organic
2217 Pollutants. Open-ended Working Group Report of the Basel Convention on the
2218 Control of Transboundary Movements of Hazardous Wastes and Their Disposal.
- 2219 United Nations Economic Commission for Europe (UN ECE) (2009) Recent Results and
2220 Updating of Scientific and Technical Knowledge: Health Risks of Air Pollution
2221 from Biomass Combustion. Report by the Task Force on Health, Executive Body for
2222 the Convention on Long-range Transboundary Air Pollution,
2223 ECE/EB.AIR/WG.1/2009/12. United Nations Economic Commission for Europe
2224 (UN ECE); Geneva, Switzerland: p. 12.
- 2225 Uysal A. & Kuru B. (2015) The fertilizer effect of struvite recovered from dairy industry
2226 wastewater on the growth and nutrition of maize plant. *Fresenius Environmental*
2227 *Bulletin* **24**: 3155-3162.
- 2228 Uysal A., Yilmazel Y.D. & Demirer G.N. (2010) The determination of fertilizer quality of the
2229 formed struvite from effluent of a sewage sludge anaerobic digester. *Journal of*
2230 *Hazardous Materials* **181**: 248-254.
- 2231 Uysal A., Demir S., Sayilgan E., Eraslan F. & Kucukyumuk Z. (2014) Optimization of
2232 struvite fertilizer formation from baker's yeast wastewater: growth and nutrition of
2233 maize and tomato plants. *Environmental Science and Pollution Research* **21**: 3264-
2234 3274.
- 2235 Valeur I. (2011) Speciation of heavy metals and nutrient elements in digestate. PhD thesis,
2236 Norwegian University of Life Sciences.
- 2237 Vamvuka D. & Zografos D. (2004) Predicting the behaviour of ash from agricultural wastes
2238 during combustion. *Fuel* **83**: 2051-2057.
- 2239 Vamvuka D. & Kakaras E. (2011) Ash properties and environmental impact of various
2240 biomass and coal fuels and their blends. *Fuel Processing Technology* **92**: 570-581.
- 2241 Vamvuka D., Hahladakis J. & Pentari D. (2005) Leaching of toxic elements from lignite and
2242 agrosidue ashes in cultivated soils of Crete. *Energy & Fuels* **19**: 807-812.
- 2243 Van Caneghem J. & Vandecasteele C. (2014) Characterisation of polycyclic aromatic
2244 hydrocarbons in flue gas and residues of a full scale fluidized bed combustor
2245 combusting non-hazardous industrial waste. *Waste Management* **34**: 2407-2413.
- 2246 Van Caneghem J., Block C., Vermeulen I., Van Brecht A., Van Royen P., Jaspers M., . . .
2247 Vandecasteele C. (2010) Mass balance for POPs in a real scale fluidized bed
2248 combustor co-incinerating automotive shredder residue. *Journal of Hazardous*
2249 *Materials* **181**: 827-835.
- 2250 van der Voet E., Lifset R.J. & Luo L. (2010) Life-cycle assessment of biofuels, convergence
2251 and divergence. *Biofuels* **1**: 435-449.
- 2252 van Dijk K.C., Lesschen J.P. & Oenema O. (2016) Phosphorus flows and balances of the
2253 European Union Member States. *Science of the Total Environment* **542**: 1078-1093.
- 2254 Van Eijk R.J., te Winkel H. & Stam A.F. (2011) Van Eijk R.J., te Winkel H., Stam A.F.
2255 Environmental and health aspects of coal and biomass co-combustion ashes;

- 2256 Proceedings of the World of Coal Ash (WOCA) Conference; Denver, CO, USA. 9–
2257 12 May; p. 11.
- 2258 van Eijk R.J., Obernberger I. & Supancic K. (2012) Options for increased utilization of ash
2259 from biomass combustion and co-firing. IEA Bioenergy Task 32 Deliverable D4 -
2260 Document number 30102040-PGR/R&E 11-2142.
- 2261 Van Grinsven H.J.M., Holland M., Jacobsen B.H., Klimont Z., Sutton M.a. & Jaap Willems
2262 W. (2013) Costs and Benefits of Nitrogen for Europe and Implications for
2263 Mitigation. *Environmental Science & Technology* **47**: 3571-3579.
- 2264 Van Loo S. & Koppejan J. (2008) *The Handbook of Biomass Combustion and Co-Firing*.
2265 Earthscan, London.
- 2266 van Vlaardingen P.L.A., Posthumus R. & Posthuma-Doodema C.J.A.M. (2005)
2267 Environmental Risk Limits for Nine Trace Elements, RIVM report 601501029/2005.
- 2268 Van Wesenbeeck S., Prins W., Ronsse F. & Antal M.J. (2014) Sewage Sludge Carbonization
2269 for Biochar Applications. Fate of Heavy Metals. *Energy & Fuels* **28**: 5318-5326.
- 2270 Vaneekhaute C., Janda J., Vanrolleghem P.A., Tack F.M.G. & Meers E. (2016) Phosphorus
2271 use efficiency of bio-based fertilizers: bioavailability and fractionation. *Pedosphere*
2272 **26**: 310-325.
- 2273 Vaněk A., Grösslová Z., Mihaljevič M., Trubač J., Ettler V., Teper L., . . . Ash C. (2016)
2274 Isotopic Tracing of Thallium Contamination in Soils Affected by Emissions from
2275 Coal-Fired Power Plants. *Environmental Science & Technology* **50**: 9864-9871.
- 2276 Vanhoof C. & Tirez K. (2014) Analyse methode voor het bepalen van de zuiverheid van
2277 struviet. OVAM - Study Report 2014/SCT/R/26.
- 2278 Vassilev S.V. & Braekman-Danheux C. (1999) Characterization of refuse-derived char from
2279 municipal solid waste - 2. Occurrence, abundance and source of trace elements. *Fuel*
2280 *Processing Technology* **59**: 135-161.
- 2281 Vassilev S.V. & Vassileva C.G. (2007) A new approach for the classification of coal fly
2282 ashes based on their origin, composition, properties, and behaviour. *Fuel* **86**: 1490-
2283 1512.
- 2284 Vassilev S.V. & Vassileva C.G. (2009) A new approach for the combined chemical and
2285 mineral classification of the inorganic matter in coal. 1. Chemical and mineral
2286 classification systems. *Fuel* **88**: 235-245.
- 2287 Vassilev S.V., Braekman-Danheux C. & Laurent P. (1999) Characterization of refuse-derived
2288 char from municipal solid waste - 1. Phase-mineral and chemical composition. *Fuel*
2289 *Processing Technology* **59**: 95-134.
- 2290 Vassilev S.V., Eskenazy G.M. & Vassileva C.G. (2000) Contents, modes of occurrence and
2291 origin of chlorine and bromine in coal. *Fuel* **79**: 903-921.
- 2292 Vassilev S.V., Baxter D., Andersen L.K. & Vassileva C.G. (2010) An overview of the
2293 chemical composition of biomass. *Fuel* **89**: 913-933.
- 2294 Vassilev S.V., Baxter D., Andersen L.K. & Vassileva C.G. (2013a) An overview of the
2295 composition and application of biomass ash.: Part 2. Potential utilisation,
2296 technological and ecological advantages and challenges. *Fuel* **105**: 19-39.
- 2297 Vassilev S.V., Baxter D., Andersen L.K. & Vassileva C.G. (2013b) An overview of the
2298 composition and application of biomass ash. Part 1. Phase–mineral and chemical
2299 composition and classification. *Fuel* **105**: 40-76.
- 2300 Vehlow J., Bergfeldt B. & Hunsinger H. (2006) PCDD/F and related compounds in solid
2301 residues from municipal solid waste incineration - a literature review. *Waste*
2302 *Management & Research* **24**: 404-420.
- 2303 Venderbosch R.H. & Prins W. (2010) Fast pyrolysis technology development. *Biofuels*,
2304 *Bioproducts and Biorefining* **4**: 178-208.

- 2305 Vesterinen P. (2003) Wood ash recycling - state of the art in Finland and Sweden, VTT
2306 Processes, PRO2/6107/03.
- 2307 Visioli G., Conti F.D., Menta C., Bandiera M., Malcevschi A., Jones D.L. & Vamerali T.
2308 (2016) Assessing biochar ecotoxicology for soil amendment by root phytotoxicity
2309 bioassays. *Environmental Monitoring and Assessment* **188**: 166.
- 2310 Vogel T., Nelles M. & Eichler-Löbermann B. (2015) Phosphorus application with recycled
2311 products from municipal waste water to different crop species. *Ecological*
2312 *Engineering* **83**: 466-475.
- 2313 Vollaro M., Galioto F. & Viaggi D. (2016) The circular economy and agriculture: new
2314 opportunities for re-using Phosphorus as fertilizer. *Bio-Based and Applied*
2315 *Economics* **5**: 267-285.
- 2316 vom Eyser C., Schmidt T.C. & Tuerk J. (2016) Fate and behaviour of diclofenac during
2317 hydrothermal carbonization. *Chemosphere* **153**: 280-286.
- 2318 Waligora J., Bulteel D., Degrugilliers P., Damidot D., Potdevin J.L. & Measson M. (2010)
2319 Chemical and mineralogical characterizations of LD converter steel slags: A multi-
2320 analytical techniques approach. *Materials Characterization* **61**: 39-48.
- 2321 Wallace J.S., Garner E., Pruden A. & Aga D.S. (2018) Occurrence and transformation of
2322 veterinary antibiotics and antibiotic resistance genes in dairy manure treated by
2323 advanced anaerobic digestion and conventional treatment methods. *Environmental*
2324 *Pollution* **236**: 764-772.
- 2325 Wang H., Yan B.J. & Li F. (2015) Analysis of Cr with Various Valence States in Industrial
2326 EAF Slag for Making Stainless Steel. *Isij International* **55**: 1425-1431.
- 2327 Wang L. & Nancollas G.H. (2008) Calcium Orthophosphates: Crystallization and
2328 Dissolution. *Chemical Reviews* **108**: 4628-4669.
- 2329 Wang L., Li A. & Chang Y. (2016) Hydrothermal treatment coupled with mechanical
2330 expression at increased temperature for excess sludge dewatering: Heavy metals,
2331 volatile organic compounds and combustion characteristics of hydrochar. *Chemical*
2332 *Engineering Journal* **297**: 1-10.
- 2333 Wang L., Hustad J.E., Skreiberg Ø., Skjevraak G. & Grønli M. (2012a) A Critical Review on
2334 Additives to Reduce Ash Related Operation Problems in Biomass Combustion
2335 Applications. *Energy Procedia* **20**: 20-29.
- 2336 Wang S. & Shi X. (2001) Molecular mechanisms of metal toxicity and carcinogenesis. *Mol*
2337 *Cell Biochem* **222**: 3-9.
- 2338 Wang T., Camps-Arbestain M., Hedley M. & Bishop P. (2012b) Predicting phosphorus
2339 bioavailability from high-ash biochars. *Plant and Soil* **357**: 173-187.
- 2340 Wang Z., Wang F., Cao J. & Wang J. (2010) Pyrolysis of pine wood in a slowly heating
2341 fixed-bed reactor: Potassium carbonate versus calcium hydroxide as a catalyst. *Fuel*
2342 *Processing Technology* **91**: 942-950.
- 2343 Wanty R.B. & Goldhaber M.B. (1992) Thermodynamics and kinetics of reactions involving
2344 vanadium in natural systems: Accumulation of vanadium in sedimentary rocks.
2345 *Geochimica Et Cosmochimica Acta* **56**: 1471-1483.
- 2346 WCA environment (2014) Assessment of Risks to Soil Quality and Human Health from
2347 Organic Contaminants in Materials Commonly Spread on Land in Scotland: Final
2348 Report.
- 2349 Wei X., Schnell U. & Hein K.R.G. (2005) Behaviour of gaseous chlorine and alkali metals
2350 during biomass thermal utilisation. *Fuel* **84**: 841-848.
- 2351 Weideler A., Brechtel K., Maier W., Krampe J. & Rott U. (2005) Recovery of phosphorus
2352 from sewage sludge as MAP. IWA-/WISA-Conference on the Management of
2353 Residues Emanating from Water and Wastewater Treatment, 9–12 August 2005,
2354 Johannesburg, South Africa.

- 2355 Weigand H., Bertau M., Huebner W., Bohndick F. & Bruckert A. (2013) RecoPhos: Full-
2356 scale fertilizer production from sewage sludge ash. *Waste Management* **33**: 540-544.
- 2357 Weiner B., Baskyr I., Poerschmann J. & Kopinke F.-D. (2013) Potential of the hydrothermal
2358 carbonization process for the degradation of organic pollutants. *Chemosphere* **92**:
2359 674-680.
- 2360 Weinfurter K., Gäth S., Kördel W. & Waida C. (2009) Ecological testing of products from
2361 phosphorus recovery processes - first results. International conference on nutrient
2362 recovery from wastewater streams. IWA Publishing, London, UK.
- 2363 Wells D.E. (2013) Poultry litter ash as a phosphorus source for greenhouse crop production.
2364 PhD thesis, Louisiana State University.
- 2365 Werther J., Saenger M., Hartge E.U., Ogada T. & Siagi Z. (2000) Combustion of agricultural
2366 residues. *Progress in Energy and Combustion Science* **26**: 1-27.
- 2367 WHO (1990) Environmental Health Criteria 107: Barium. International Programme on
2368 Chemical Safety, Geneva: 121.
2369 <http://www.inchem.org/documents/ehc/ehc/ehc107.htm>
- 2370 WHO (1996) Thallium, International programme on chemical safety, Environmental Health
2371 Criteria, 182. Geneva.
- 2372 WHO (2006) Guidelines for drinking-water quality, third edition, incorporating first
2373 addendum. Volume 1 — Recommendations. Geneva.
- 2374 WHO (2018) Circular economy and health: opportunities and risks. WHO Regional Office
2375 for Europe, Copenhagen, Denmark.
- 2376 Widen P. (1993) Composting of sorted household waste in Uppsala. Thesis, Sveriges
2377 Lantbruksinstitute, Uppsala.
- 2378 Wiechmann B., Dienemann C., Kabbe C., Vogel I. & Roskosch A. (2013a) Sewage sludge
2379 management in Germany. Umweltbundesamt (UBA).
- 2380 Wiechmann B., Dienemann C., Christian Kabbe C., Simone Brandt S., Ines Vogel I. &
2381 Andrea Roskosch A. (2013b) Sewage sludge management in Germany.
2382 Umweltbundesamt (UBA), Dessau-Roßlau, Germany.
- 2383 Wieck-Hansen K., Overgaard P. & Larsen O.H. (2000) Cofiring coal and straw in a 150
2384 MWe power boiler experiences. *Biomass & Bioenergy* **19**: 395-409.
- 2385 Wigley F., Williamson J., Malmgren A. & Riley G. (2007) Ash deposition at higher levels of
2386 coal replacement by biomass. *Fuel Processing Technology* **88**: 1148-1154.
- 2387 Wijnands J.H.M. & Linders G.-J. (2013) Competitiveness Proofing - Fertilising Materials
2388 Ex ante evaluation of competitiveness impacts of the European Commission's policy
2389 proposal Review of Regulation (EC) no 2003/2003 relating to fertilisers. Technical
2390 report, ECORYS & WUR, Den Haag, Netherlands.
- 2391 Wilfert P., Kumar P.S., Korving L., Witkamp G.-J. & van Loosdrecht M.C.M. (2015) The
2392 Relevance of Phosphorus and Iron Chemistry to the Recovery of Phosphorus from
2393 Wastewater: A Review. *Environmental Science & Technology* **49**: 9400-9414.
- 2394 Wilken V., Zapka O. & Muskolus A. (2015) Product quality: fertilizing efficiency, results of
2395 pot and field tests. Report of the P-REX project - Sustainable sewage sludge
2396 management fostering phosphorus recovery and energy efficiency. Institute of
2397 Agricultural and Urban Ecological Projects affiliated to Berlin Humboldt University
2398 (IASP).
- 2399 Wilson S.C., Lockwood P.V., Ashley P.M. & Tighe M. (2010) The chemistry and behaviour
2400 of antimony in the soil environment with comparisons to arsenic: A critical review.
2401 *Environmental Pollution* **158**: 1169-1181.
- 2402 Winship K.A. (1987) Toxicity of antimony and its compounds. *Adverse Drug Reactions and
2403 Toxicological Reviews* **6**: 67-90.

- 2404 Wojtkowiak T., Karbowska B., Zembrzuski W., Siepak M. & Lukaszewski Z. (2016)
 2405 Miocene colored waters: A new significant source of thallium in the environment.
 2406 *Journal of Geochemical Exploration* **161**: 42-48.
- 2407 Woolf D., Amonette J.E., Street-Perrott F.A., Lehmann J. & Joseph S. (2010) Sustainable
 2408 biochar to mitigate global climate change. *Nature Communications* **1**.
- 2409 Wopenka B. & Pasteris J.D. (2005) A mineralogical perspective on the apatite in bone.
 2410 *Materials Science & Engineering C-Biomimetic and Supramolecular Systems* **25**:
 2411 131-143.
- 2412 World Health Organization (1996) *Trace elements in human nutrition and health*. Geneva.
- 2413 World Health Organization (2004) Manganese and its compounds : environmental aspects.
 2414 (Concise international chemical assessment document ; 63). Stuttgart.
- 2415 Wragge V. (2015) Product quality and fertiliser value of recovered products. P-REX project
 2416 final meeting, Berlin.
- 2417 Wu H., Lai C., Zeng G., Liang J., Chen J., Xu J., . . . Wan J. (2017) The interactions of
 2418 composting and biochar and their implications for soil amendment and pollution
 2419 remediation: a review. *Critical Reviews in Biotechnology* **37**: 754-764.
- 2420 Wuana R.A. & Okieimen F.E. (2011) Heavy Metals in Contaminated Soils: A Review of
 2421 Sources, Chemistry, Risks and Best Available Strategies for Remediation. *ISRN*
 2422 *Ecology* **2011**: 20.
- 2423 Xia W., Du X., Zheng T., Zhang B., Li Y., Bassig B.A., . . . Xu S. (2016) A Case-Control
 2424 Study of Prenatal Thallium Exposure and Low Birth Weight in China.
 2425 *Environmental Health Perspectives* **124**: 164-169.
- 2426 Xiao T., Guha J., Boyle D., Liu C.-Q., Zheng B., Wilson G.C., . . . Chen J. (2004) Naturally
 2427 occurring thallium: a hidden geoenvironmental health hazard? *Environment*
 2428 *International* **30**: 501-507.
- 2429 Xiao X., Chen Z. & Chen B. (2016) H/C atomic ratio as a smart linkage between pyrolytic
 2430 temperatures, aromatic clusters and sorption properties of biochars derived from
 2431 diverse precursory materials. *Scientific Reports* **6**: 22644.
- 2432 Xu C., Salsali H., Weese S. & Warriner K. (2015) Inactivation of *Clostridium difficile* in
 2433 sewage sludge by anaerobic thermophilic digestion. *Canadian Journal of*
 2434 *Microbiology* **62**: 16-23.
- 2435 Yao F.X., Arbestain M.C., Virgel S., Blanco F., Arostegui J., Maciá-Agulló J.A. & Macías F.
 2436 (2010) Simulated geochemical weathering of a mineral ash-rich biochar in a
 2437 modified Soxhlet reactor. *Chemosphere* **80**: 724-732.
- 2438 Yao Z.T., Ji X.S., Sarker P.K., Tang J.H., Ge L.Q., Xia M.S. & Xi Y.Q. (2015) A
 2439 comprehensive review on the applications of coal fly ash. *Earth-Science Reviews*
 2440 **141**: 105-121.
- 2441 Ye Z.-L., Deng Y., Lou Y., Ye X. & Chen S. (2018) Occurrence of veterinary antibiotics in
 2442 struvite recovery from swine wastewater by using a fluidized bed. *Frontiers of*
 2443 *Environmental Science & Engineering* **12**: 7.
- 2444 Ye Z.-L., Deng Y., Lou Y., Ye X., Zhang J. & Chen S. (2017) Adsorption behavior of
 2445 tetracyclines by struvite particles in the process of phosphorus recovery from
 2446 synthetic swine wastewater. *Chemical Engineering Journal* **313**: 1633-1638.
- 2447 Yildirim I.Z. & Prezzi M. (2011) Chemical, Mineralogical, and Morphological Properties of
 2448 Steel Slag. *Advances in Civil Engineering* **2011**: 13.
- 2449 Zepke F. & Klose S. (2017) Vom Klärschlamm zum Phosphat – Dünger Das EuPhoRe®-
 2450 Verfahren. .
- 2451 Zevenhoven-Onderwater M., Blomquist J.P., Skrifvars B.J., Backman R. & Hupa M. (2000)
 2452 The prediction of behaviour of ashes from five different solid fuels in fluidised bed
 2453 combustion. *Fuel* **79**: 1353-1361.

- 2454 Zevenhoven M., Yrjas P., Skrifvars B.-J. & Hupa M. (2012) Characterization of Ash-
2455 Forming Matter in Various Solid Fuels by Selective Leaching and Its Implications
2456 for Fluidized-Bed Combustion. *Energy & Fuels* **26**: 6366-6386.
- 2457 Zhang H.-L., Fang W., Wang Y.-P., Sheng G.-P., Zeng R.J., Li W.-W. & Yu H.-Q. (2013)
2458 Phosphorus Removal in an Enhanced Biological Phosphorus Removal Process:
2459 Roles of Extracellular Polymeric Substances. *Environmental Science & Technology*
2460 **47**: 11482-11489.
- 2461 Zhang S., Herbell J.-D. & Gaye-Haake B. (2004) Biodegradable organic matter in municipal
2462 solid waste incineration bottom ash. *Waste Management* **24**: 673-679.
- 2463 Zheng H., Wang Z., Deng X., Zhao J., Luo Y., Novak J., . . . Xing B. (2013) Characteristics
2464 and nutrient values of biochars produced from giant reed at different temperatures.
2465 *Bioresource Technology* **130**: 463-471.
- 2466 Zöttle H.W., Stahr K. & Hädrich F. (1979) Umsatz von Spurenelementen in der Bärhalde und
2467 ihren Ökosystemen. *Mitteilung der Deutschen Bodenkundlichen Gesellschaft* **29**:
2468 569-576.
- 2469 Zwetsloot M.J., Lehmann J., Bauerle T., Vanek S., Hestrin R. & Nigussie A. (2016)
2470 Phosphorus availability from bone char in a P-fixing soil influenced by root-
2471 mycorrhizae-biochar interactions. *Plant and Soil* **408**: 95-105.
- 2472 Zwick T.C., Arthur M.F., Tolle D.A. & Van Voris P. (1984) A unique laboratory method for
2473 evaluating agro-ecosystem effects of an industrial waste product. *Plant and Soil* **77**:
2474 395-399.
- 2475
- 2476