INVENTORY REPORT FOR A PROFESSIONAL USER GROUP ON BIOMASS PROCESSING

WPT1_Activity 1_Deliverable 1.1

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List of Abbreviations

3R: Recycle – Reduce – Reuse

ABC: Animal bone char

AD: Anaerobic digestion

$Ca(OH)_2$: Calcium hydroxide

CaP: Calcium phosphate

CH_4: Methane

CO: Carbon monoxide

CO_2: Carbon dioxide

COD: Chemical oxygen demand

CSTR: Continuous stirred tank reactor

CW: Constructed wetland

DAF: Dissolved air flotation

DEMA: Direct Ethanol from Microalgae

DM: Dry matter

ESP: Electrostatic precipitators

EU: European Union

GDP: Gross domestic product

H_2: Hydrogen gas

HNO_3: Nitric acid

H_2SO_4: Sulphuric acid

HTC: Hydrothermal carbonization

IX: Ion exchange

K_2O: Potassium oxide

LF: Liquid fraction

LT-CFB: Low-temperature circulating fluidized bed

MBM: Meat and bone meal

MC: Moisture content

MF: Microfiltration

$MgCl_2$: Magnesium chloride

MWCO: Molecular weight cut off

N_2: Nitrogen gas

NaOH: Sodium hydroxide

NH_3: Ammonia

NH_4-N: Ammonium nitrogen

NF: Nanofiltration

NO_2-N: Nitrite nitrogen

NO_3-N: Nitrate nitrogen

NVZ: Nitrate Vulnerable Zone

NWE: North West Europe

OM: Organic matter

P_2O_5: Phospohorus pentoxide

RDF: Recycling derived fertilizer

RO: Reverse osmosis

SABANA: Sustainable Algae Biorefinery for Agriculture and Aquaculture

SF: Solid fraction

UF: Ultrafiltration

VGF: Vegetable, garden, and fruit

WWTP: Wastewater treatment plant

1 Introduction

Agricultural development is an important measure toward ending global poverty and feeding a projected 10 billion people by the year 2050 (FAO, 2017). Estimated to account for one-third of the global gross domestic product (GDP), it is also crucial for economic growth. Among many factors that stimulate agricultural development, the affordable availability of effective fertilizers is pivotal. The global fertilizer demand for 2018 was forecasted to be 194 Mt and is projected to increase to 201 Mt by 2020 (FAO, 2015) and 263 Mt by 2050 (Alexandratos and Bruinsma, 2012). Europe has also followed the same trend of agricultural intensification and over the last few decades evolved to intensive plant production resulting in an increasing demand for mineral fertilizers. In 2016, the total production of mineral fertilizers in Europe reached 16.6 Mt, out of which 73% of the produced fertilizers comprised of nitrogen (N), 16% of potassium oxide (K_2O) and 11% of phosphorus pentoxide (P_2O_5) (Fertilizers Europe, 2018).

Currently, the N used in fertilizers is synthesized via the fossil-fuel intensive Haber-Bosch process, whereas phosphorus (P) is mined from finite phosphate rock deposits that are largely concentrated in certain parts of the world like China, United States of America, Russia and Morocco among a few other places. Assessments on nutrient budgets also state a deficit in potassium (K) and indicate that a global doubling of potash fertilizer production would be required to balance inputs and offtake (Manning, 2010). Moreover, there is a looming threat of the depletion of the mineral reserves along with an increase in its price. The quality of the ores has been diminishing and geopolitical concerns further cast doubts onto its uninhibited supply (Coppens et al., 2016).

It is therefore inevitable to have alternative processes that can manufacture fertilizers and maintain food security in a sustainable manner. Implementation of nutrient recovery from different waste streams for the production of fertilizers would not only help in the management of excess biomass, but also enable the recycling of valuable nutrients that would otherwise end up being lost into the ecosystem. Moreover, it would form an important part of the circular economy concept which aims to keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each lifespan.

Despite the existence of market-ready recovery techniques, recycling derived fertilizers (RDFs) are not yet extensively used due to certain barriers like legal constraints on the raw materials used in RDFs, initial investment costs of recovery plants, lack of awareness amongst the different stakeholders involved, lack of product-safety guarantee and other product information, and unavailability of suitable application techniques. These barriers need to be overcome to attain a larger market for RDFs and the first step is to provide an inventory report on existing nutrient recovery techniques.

ReNu2Farm is an Interreg North West Europe (NWE) project that focusses on nutrient recycling and upscaling from pilot level to farms and fields. Its priority specific objective is to optimise the reuse of material and natural resources in NWE. One of the project tasks is to deliver an inventory report that

represents an actualization on the progress of market-ready techniques, building on previous benchmark reports published under projects like ARBOR and BIOREFINE. The report at first briefly describes the three main biomass streams of focus for ReNu2Farm, and secondly elaborates on biomass processing and nutrient recovery processes.

2 Nutrient rich biomass

The current use of nutrients is observed to be inefficient and wasteful. The inadequate utilization of nutrients can cause some of the most damaging side effects (e.g. eutrophication, air pollution, soil acidification, etc.) to our environmental systems. The use of nutrients from a linear to a circular pattern is of absolute necessity. An intelligent diversification of the sources of nutrient supply is brought by the recovery and reuse of nutrients from waste streams, adding resilience in an event of disruption of the import and supply of conventional mineral fertilizers. In this chapter, we elaborate on the form, content, available quantities, legislation, and the current use in agriculture of the three largest biomass streams in Europe that have a high potential to supply nutrients for European Union (EU) agriculture. These streams are animal manure, sewage sludge and food waste. At the moment around 60-80% of N and 76% of P is recycled from total production of animal manure, sewage sludge, and food waste, leaving 2-5 Mt of N and 0.6 Mt of P unrecycled for EU agricultural use. The unrecycled part could fulfil 18-46% of N and 43% of P synthetic fertilizer needs for EU crop production (Buckwell and Nadeu, 2016).

2.1 Animal manure

Animal manure is composed of animal excreta mixed with water and/or straw. It is considered as a beneficial soil amendment and fertilizer due to its high nutrient content and ability to improve the physical and biological properties of the soil by contribution of organic matter (OM). Table 1 provides an overview of the total NPK, dry matter (DM) and OM content in different types of manure.

In 2016, the total amount of N excreted as manure in Northern and Western Europe was estimated at 924.5 and 1567 million kg of N, respectively (FAO, 2017). NWE is known for its historical application of animal manure and high livestock densities which have led to over-application of N and nitrate leaching, as well as P accumulation in agricultural soils. In order to safeguard the water quality and protect the environment from agricultural pressure, the Nitrates Directive was implemented in 1991 with a limitation on application of N from animal manure up to 170 kg N ha^{-1} y^{-1} in the Nitrate Vulnerable Zones[1] (NVZ) (European Commission, 1991a). This limitation, in combination with a decline in arable land, has led to the current situation where certain regions in NWE (e.g. Brittany (France), Flanders (Belgium), the Netherlands) are confronted with excess of animal manure and the need to process manure in a sustainable manner.

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[1] The NVZs are areas of land which drain into polluted waters (i.e. exceeding a concentration of 50 mg NO_3^- l^{-1} in surface waters or groundwater bodies) or waters at risk of pollution and which contribute to NO_3^- pollution.

When it comes to the use of N in EU-27, the largest singular source of N inputs (51%) to croplands comes from synthetic N mineral fertilizers. The second largest N input can be attributed to the use of animal manure amounting to 34%. Smaller contributions of N (15%) occur from crop residues, atmospheric deposition, and biological fixation (Buckwell and Nadeu, 2016). In the case of P inputs, animal manure contributes 53% in comparison to the 43% derived from synthetic P mineral fertilizers.

Table 1. *Average composition of DM (dry matter), OM (organic matter), N (nitrogen), P_2O_5 (phosphorus pentoxide), K_2O (potassium oxide) in different types of animal manure. Data retrieved from Grassland and Fodder Fertilization Committee (2019).*

Type of manure	DM (%)	OM (%)	N (%)	P_2O_5 (%)	K_2O (%)
Liquid manure					
Cattle	2.50	1.00	0.40	0.02	0.80
Fattening pig	2.00	0.50	0.65	0.09	0.45
Sow	1.00	1.00	0.20	0.09	0.25
Slurry					
Cattle	9.20	7.10	0.40	0.15	0.54
Fattening pig	11	7.90	0.70	0.39	0.47
Sow	6.70	2.50	0.50	0.35	0.49
Solid manure					
Cattle	27	16	0.77	0.43	0.88
Pigs	26	15	0.79	0.79	0.85
Poultry	62	39	3.30	2.60	2.10

2.2 Sewage sludge

Sewage sludge can be defined as any solid, semisolid or liquid residue that is generated during the treatment process of municipal wastewater and sewage. It contains substantial amounts of nutrients especially N and P, among other micronutrients, which exist mainly in the form of proteins (Tyagi and Lo, 2016).

In 2012, approximately 23% of sewage sludge was incinerated in Europe, whereas 49% was applied on land for agricultural use (Huygens and Saveyn, 2018). In some parts of NWE, currently, more than half of the nutrients required for agricultural soils come from sewage sludge by means of direct land application and composting (Delvigne et al., 2015). The sewage sludge utilization comes along with criticisms that sewage sludge not only contains beneficial plant nutrients, but also can contain significant concentrations of heavy metals and other elements. Their repeated application to soil may cause the accumulation of these toxic elements, which can contaminate the soil for up to 20 years after its application (Delvigne et al., 2015). Thus, presence of pathogens, pharmaceuticals, heavy metals and other complex organic compounds needs to be determined before sewage sludge can be used on agricultural soils. In the case of high concentrations of undesired compounds, it is necessary to have nutrient recovery techniques that can deal with these issues and generate an efficient and marketable

product. Table 2 provides characterization of sewage sludge for various parameters analyzed in different studies.

Table 2. Characterization of sewage sludge for various parameters. Values given in dry weight of sample. Modified according to Tchobanoglous and Burton (1991), Hsiau and Lo (1998) and Fytili and Zabanitov (2008).

Parameters	Unit	Range
pH	-	5.0 – 8.0
Volatile solids	%	60 – 80
DM	%	2.0 – 8.0
N	%	15 – 4.0
P_2O_5	%	08 – 2.8
K_2O	%	0 – 1.0
Arsenic (As)	mg/kg	11 – 230
Cadmium (Cd)	mg/kg	10 – 3.4
Chromium (Cr)	mg/kg	10 – 990000
Cobalt (Co)	mg/kg	11 – 2490
Copper (Cu)	mg/kg	84 – 17000
Iron (Fe)	mg/kg	1000 – 154000
Lead (Pb)	mg/kg	13 – 26000
Manganese (Mn)	mg/kg	32 – 9870
Nickel (Ni)	mg/kg	2.0 – 5300
Zinc (Zn)	mg/kg	101 – 49000

In 2014 there were 26 487 active wastewater treatment plants (WWTP) in Europe (EU-28, Iceland, Norway and Switzerland), out of which 8 520 operated with N and P removal systems and 1 609 only with P removal system (EEA, 2017). These WWTP generate approximately 2.3-3.1 Mt of N and 0.23 Mt of P annually in the form of sewage sludge, whose production has increased by more than 80% compared to the values from 1992 (Buckwell and Nadeu, 2016). This increase can be owed to the implementation of the Urban Waste Water Treatment Directive (91/271/EEC), which made it mandatory for towns housing a population of over 2000 residents to collect and treat their sewage (European Commission, 1991b).

2.3 Food waste

Food waste can be defined as 'any potential source of food that has knowingly been discarded or destroyed (e.g. food discarded in factories, food not sold in shops or restaurants, kitchen scraps and plate waste) (Hunt, 2003). Other biodegradable waste like municipal solid waste, waste from agri-industry, waste garden cuttings, etc., are also included in this category. Food waste characterizes a large and currently underutilized source of potentially available and reusable nutrients as they contain notable amounts of N, P and K (Idowu et al., 2017). There is a large uncertainty in the total amount of waste generated by the food industry in the EU. The current estimations indicate that food waste

generation by the food industry reached approx. 88 Mt in 2012, resulting in 143 billion euros of costs associated with it (Stenmarck et al., 2016). The highest generation of food waste originates from households (Figure 1).

Food waste

Figure 1. Split of EU-27 food waste in 2012 (based on total of 88 Mt in 2012) by sector; includes food and inedible parts associated with food (Stenmarck et al., 2016).

The nutrient composition and DM of food waste varies considerably due to a wide range of food waste sectors from different types of food industries. Food waste from vegetable industries contains approx. 5% DM, whereas waste from olive oil industry (values for Spain, Italy, Greece and Portugal) and sugarbeet industry (EU-15) can contain 25-60% and 50% DM, respectively. Out of the 88 Mt of waste produced in EU-27, 0.11 Mt are in the form of P and 0.55 Mt in the form of N (Buckwell and Nadeu, 2016). Generally waste from the food industry is landfilled, and only a small part is used for animal feed purposes or for production of biogas and compost (Tronina and Bubel, 2008; Sydney et al., 2014; Wu et al., 2016). The recovery of nutrients from food waste is a relatively new, albeit a very promising concept to manage the colossal quantities of waste and derive value-added products (e.g. fertilizers) from it. Due to its early developmental stages, literature lacks substantial data about it.

3 Biomass processing and nutrient recovery techniques

There are different techniques that may be suitable for biomass processing, but not all of them aid in nutrient recovery. This report focusses on those biomass processing techniques that can act as a precursor to nutrient recovery and on techniques that aim at nutrient recovery. Figure 2 gives an overview of biomass processing and nutrient recovery techniques that are discussed in this report. Though there is no unambiguous definition to nutrient recovery techniques, in the current report, we consider nutrient recovery techniques as *techniques that create a nutrient enriched end-product, fit for use as fertilizers in agriculture and/or that replaces the use of mineral fertilizers by concentrating the nutrients from the biomass stream.*
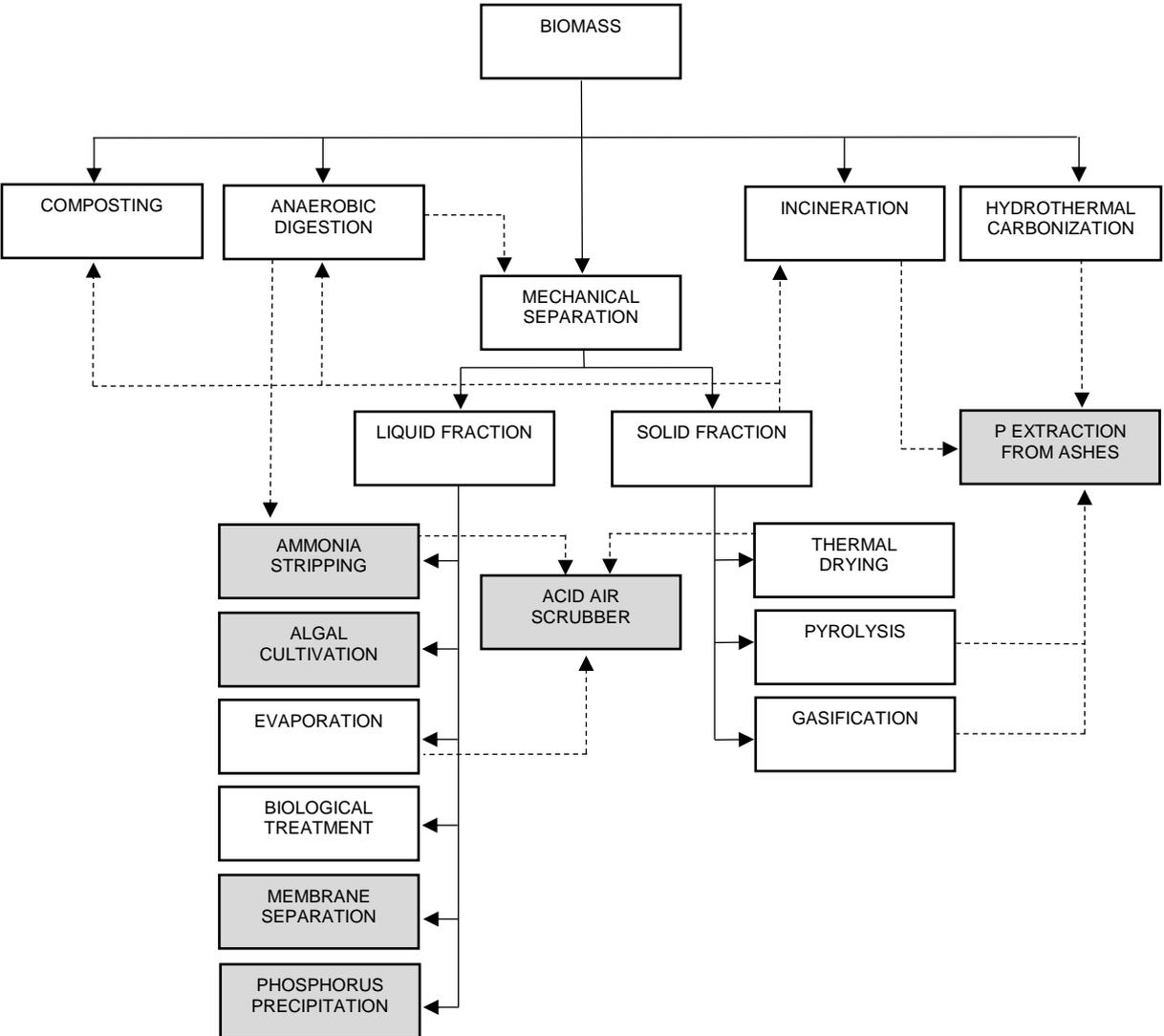
Figure 2. Overview of the biomass processing and nutrient recovery techniques (in grey)

3.1 Raw Biomass

Biomass that has not undergone any level of processing is termed as raw biomass. In this report, the term raw biomass applies to manure collected from farms and stables, raw sewage sludge, food waste from households and food sector, and other biodegradable waste. The most commonly used processing techniques for raw biomass are described in this section.

3.1.1 Anaerobic digestion

Anaerobic digestion (AD) is a process that utilizes microorganisms to breakdown organic biodegradable waste (e.g. animal manure, sewage sludge, food waste, etc.) into valuable biogas and nutrient-rich digestate. The breakdown of the complex organic substances is done in a series of steps and in the absence of oxygen, after which the produced biogas is combusted into heat and/or electricity (Figure 3). The number of biogas plants in Europe has increased from 6 227 in 2009 to 17 662 in 2016 (EBA, 2017). In 2017, 12 609 AD plants in EU-28 operated on agricultural substrates, whereas 2 346 AD plants used sewage sludge as their main feedstock (EBA, 2018).
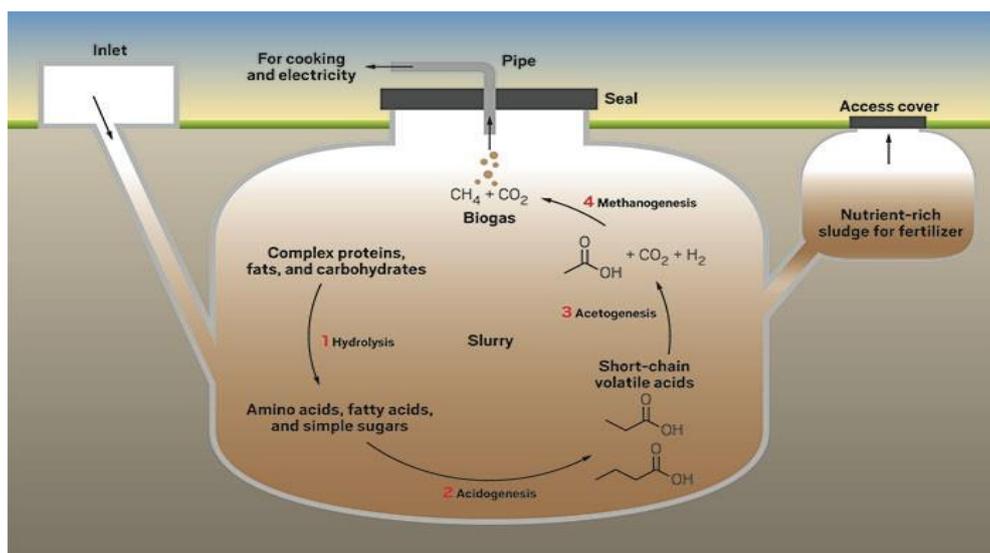
Figure 3. *A diagrammatic representation of the processes in an anaerobic digestion (AD) unit (Lim, 2016).*

The nutrient rich digestate contains the undigested resilient organic fraction, water, macro- and micronutrients. The composition of the digestate depends entirely on the treated feedstock. The total carbon (C) content of digestate can vary from 28-47% of DM (Tambone et al., 2010; Fouda, 2011; Möller and Schultheiß, 2014).

Nowadays some researchers refer to digestate as a new mine for the recovery of fertilizers in the vision of circular economy (Flotats et al., 2013). The use of digestate as a fertilizer is considered beneficial since it provides nutrients and improves the structure of the soil with the addition of OM (Nkoa, 2014).

Also, numerous studies have indicated a presence of higher amounts of N in the plant available ammonium nitrogen (NH_4-N) form in digestate as compared to manure (European Commission, 2014; Insam et al., 2015, Sigurnjak, 2017). Finally, some field studies on the performance of digestate as a fertilizer have reported similar crop N use efficiencies with digestate and those with synthetic mineral fertilizers (Vaneeckhaute et al., 2013; European Commission, 2014; Tampio et al., 2016; Sigurnjak et al., 2017).

AD plants in NWE that use an animal manure as a feedstock and are located in NVZ, are obliged to comply with the Nitrates Directive which limits application of N from animal manure on arable land (and grasslands) even in its processed form (European Commission, 1991a). These AD plants are obliged to treat their digestate further if there is no option to apply digestate up to 170 kg N ha^{-1} y^{-1}. Consequently, the digestate in NWE often undergoes a mechanical separation (section 3.1.5) wherein it is separated into a P-rich solid fraction (SF) and NK-rich liquid fraction (LF). These fractions can be used on its own as fertilizers outside of NVZ or further undergo different processing techniques that will be discussed in detail in the latter part of this report.

An example of an AD plant is Groot Zevert Vergisting (GZV) located in Beltrum, the Netherlands. The plant has been operational since 2004 and has a treatment capacity of 135 kt per year making it one of the largest AD plants in the Netherlands. Animal manure is the major substrate, comprising more than 70% of the total feedstock for which pig manure is collected from 55 pig farms. The other 30% includes dairy and slaughterhouse manure, glycerine, and waste from the dairy and feed industry. Around 10 Mm^3 of biogas is produced in this plant annually. GZV is currently installing the nutrient recovery and reuse (NRR) system to obtain higher added value from digestate by its further processing. More specifically, digestate will be treated in GENIUS-NK process where it will undergo mechanical separation by means of decanter, resulting into LF and SF of digestate. The NK-rich LF will be further processed into a NK-concentrate and clean water through a combination of dissolved air flotation (DAF) and membrane filtration system: microfiltration (MF), reverse osmosis (RO) and ion-exchange (IX). Results from pilot scale experiments, conducted by Wageningen University, indicated nutrient recovery efficiencies of 50% of total N and 56% of NH_4-N, 56% of K and 3% of P. The P-rich SF will be treated with a P-stripper called "Re-P-eat" through a process of acid (i.e. sulphuric acid (H_2SO_4)) and base (calcium hydroxide ($Ca(OH)_2$)) addition. The products of "Re-P-eat" process will be mineral calcium phosphate (Ca-P) and a P-poor organic soil conditioner. The implementation of NRR system is expected to reduce the digestate volume by 60-80%, leading to a reduction of digestate transport cost over longer distances and in volume reduction of concentrated minerals that are applied on fields (Systemic, 2018a). The mentioned NRR technology that is used at GZV will be explained in detail in the following sections.

3.1.2 Composting

Composting refers to conversion of the biodegradable OM into carbon dioxide (CO_2), water, heat, and compost with stabilized OM. The produced heat causes the water to evaporate, which helps in achieving a considerable reduction in mass and volume. The formed compost is used as a soil amendment owing to the stability of the product. Mineral ions, humic substances, and microbes in compost considerably influence the immobilization of heavy metals and cause reduction of the ecological and environmental risks of heavy metals in agricultural soils (de la Fuente et al., 2011; Udovic and McBride, 2012). However, depending on the source of biomass used for its manufacture, compost can itself contain heavy metals. Therefore, a thorough characterization of the product must be done before its use.

Composting can be carried out on animal manure, digestate, sewage sludge, food waste and the SF obtained after mechanical separation, among others. If digestate from AD is used for composting, then it is often mixed with bulking agents such as wood shavings, straw, dried chicken manure, etc., to optimize the C:N ratio. The addition of a bulking agent during the composting process can reduce the gaseous N losses that occur when manure or residues from manure are composted. Bulking agents are also very important to maintain the moisture content (MC) and C:N ratio (Batham et al., 2013). The MC of composting systems differs according to their raw materials. For pig manure with corncob, the optimal MC was found to be <80% (Zhu 2006), for pig manure with sawdust 50-60% (Tiquia et al., 1996) and for sewage sludge 60-70% (Liang et al., 2003).

The C:N ratio has a direct impact on residue decomposition and N cycling in the soil, making it an important factor to be taken into consideration. Microorganisms that decompose OM use C as a source of energy and N for building cell structure. If the C:N ratio is high, then the decomposition slows down because available N has been consumed by microorganisms. To complete the N cycle and continue decomposition, the microbial cells will draw any available soil N in the proper proportion to make use of remaining C. When the soil is depleted of N, the availability of N for plant uptake is delayed. Whereas, when the C:N ratio is low, not all of the available N will be mineralized and taken up by the microbes. It is therefore crucial to maintain the ideal C:N ratio of 25-30:1 (Pace et al., 1995).

Nowadays composting is a widely spread business. For example, Attero (the Netherlands) is an environmental company that converts nearly half of all Dutch vegetable, garden, and fruit waste (VGF) into more than 250 000 tonnes of compost. The VGF waste is first digested and then composted at Attero sites in Wijster, Wilp, Tilburg and Venlo. The generated compost is heat-treated to remove weed seeds and pathogens, and subsequently distributed in the EU market (Aterro, n.d.).

3.1.3 Incineration

Incineration is one of the mature thermochemical technologies of biomass processing that involves direct controlled burning of waste in the presence of oxygen at temperatures of 800°C and above, resulting in heat energy, gases and ash. The Directive on waste incineration (2000/76/EC) requires for the flue gases to reach a temperature of at least 850°C for at least two seconds in order to ensure complete combustion except when halogenated organic compounds are present (European Commission, 2000). The net energy yield produced via incineration depends on the density and composition of the biomass input. About 65-80% of the energy content of the OM can be recovered as heat energy and subsequently utilized for direct thermal applications or for producing power by using steam-turbine generators (Patil et al., 2014).

Incineration can be applied on dewatered sewage sludge, and some types of animal manure and food waste. For sewage sludge it is considered as the most commonly used treatment process as it significantly reduces the volume of the disposed sewage sludge (Cieślik et al., 2015). Both, mono- and co-incineration of sewage sludge are done in practice. The conventional incineration process of sewage sludge is preceded by a drying process, wherein the sludge is dried to 18-35% of DM (Donatello and Cheeseman, 2013). Inert materials in the solid waste stream are incinerated with the biomass fraction, but are not combustible. These materials usually fall through the grate slits of the furnace and end up in the bottom ash at the end of the incineration process. This ash is termed as the bottom/bed ash or slag. On the other hand, fly ashes are the small dust particles in flue gases which are captured by electrostatic precipitators (ESP-filters) after the flue gases leave the boiler. They are also known as ESP-ash (IPEN, 2005). In general, sewage sludge ashes have a P recovery potential of 70%, and P content between 2-12% has been observed in mono-incinerated ash (Buckwell and Nadeu, 2016). It is believed that P from incineration of municipal solid waste can meet up to 10% of EU demands for P (Kalmykova and Fedje, 2013).

Outotec GmbH & Co., a partner in the ReNu2Farm project, is a company located in Germany that treats municipal and industrial sludge in their sewage sludge incineration plants. They utilize the Outotec fluidized bed technology which is a self-sustaining thermal treatment requiring no external fuel sources (apart from natural gas during the start-up phase) when in continuous operation. Depending on the required capacity, Outotec offers two different plant solutions, 'The Outotec Sewage Sludge Incineration Plant 100' (treating 100 000 tonnes sludge y^{-1}), and 'The Outotec Sewage Sludge Incineration Plant 30 and 50' (treating 30 000 and 50 000 tonnes sludge y^{-1}, respectively). In both cases, the sludge is first dewatered and stored in a bunker and then partly dried by the steam from the process before being fed into a fluidized bed incinerator (Figure 4) (Outotec, n.d.). Outotec also offers the AshDec® process by which inorganic calcined phosphates (thermophosphates) are produced from phosphate-rich ashes remaining from incineration. The AshDec® process complements Outotec's existing biomass incineration solutions based on fluidized bed technology. In this process alkaline compounds, K and/or

Na-based admixed to the ash decompose at a temperature of approximately 900°C and react with the ash-borne phosphates to form bioavailable (ammonium citrate-soluble) alkaline phosphate compounds (Hermann and Schaaf, 2019). The P concentration in the end-product is 15-25%, with a P recovery performance of 98% from the incinerated sewage sludge (P-REX, 2015a).
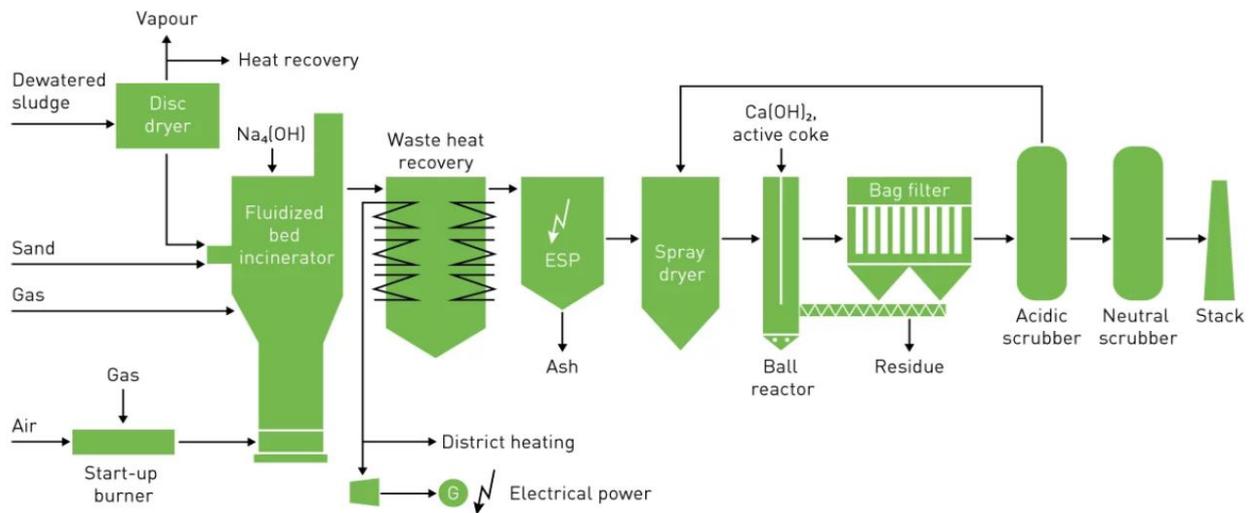
Figure 4. *Diagrammatic representation of the Outotec sewage sludge incineration plant 100 (Outotec, n.d.)*

Food waste is also a major source of P that contains on average 4 g P kg^{-1} of total solids (Kalmykova and Fedje, 2013). Incineration of food waste is primarily carried out on meat and bone meal (MBM). The FLUID-PHOS technology used by the SARIA group in England is an example where incineration of animal carcasses from slaughterhouses (part of biomass from the food chain) results in production of 12 000 tonnes of calcium phosphate fertilizer. The recovered fertilizer is a mixture of the bed ash and fly ash, and is considered as a slow release fertilizer that contains primarily 22% P and other nutrients in smaller amounts (Buckwell and Nadeu, 2016).

Animal manure can also be incinerated, more specifically poultry litter since it is known for its high DM content. In the Netherlands, BMC Moerdijk power plant incinerates poultry litter at temperatures exceeding 1000°C to produce poultry litter ash with an efficacy that is comparable to artificial fertilizers. The ash also contains secondary nutrients and trace elements. BMC processes 430 000 tonnes of poultry litter on an annual basis. The manure that arrives at the plant from 400 poultry farmers is first mixed thoroughly to obtain a homogenous feedstock prior to incineration. The incineration process generates 290 000 MWh electricity and 55 000 tonnes of P and K rich ash that is mainly exported to England, France and some other countries (BMC Moerdijk, 2019).

3.1.4 Hydrothermal carbonization

Hydrothermal carbonization (HTC; also called wet torrefaction) is a thermal conversion process that converts wet feedstock into a gaseous, liquid or solid (hydrochar) product. It takes place at low temperatures (<350°C) and a pressure of 25 atm with relatively lower energy inputs, in the presence of water and an absence of air (Krylova and Zaitchenko, 2018). The main gaseous products formed are carbon monoxide (CO), CO_2, hydrogen gas (H_2), and methane (CH_4), with CO_2 having the highest fraction (Wang et al., 2018). Water is used as a reaction medium for the conversion of wet biomass into a solid product with high C content. The process takes about 16 hours to carbonize and dehydrate the biomass. At the end of the process, a thick suspension consisting of powdered coal and water is formed in the reactor (Figure 5).
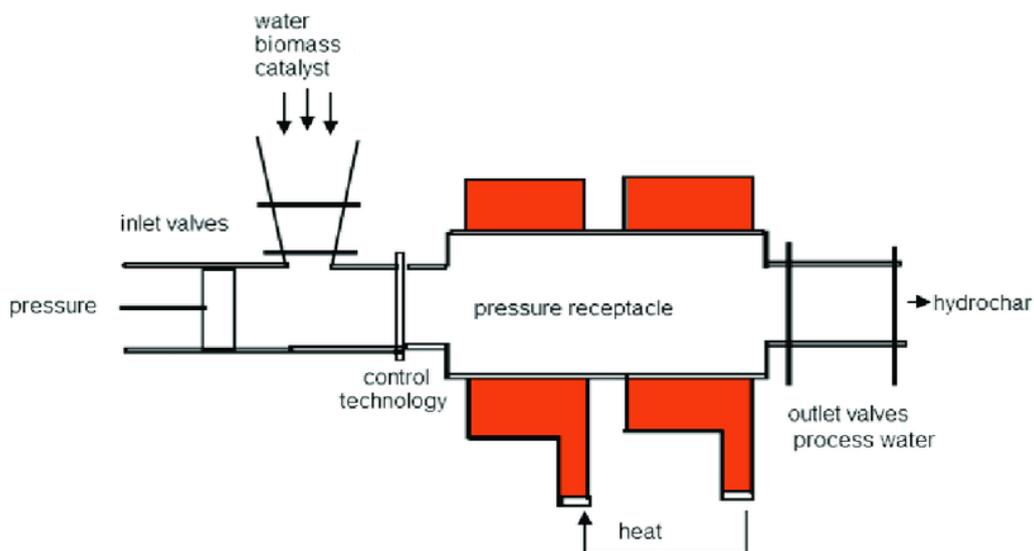
Figure 5. *A diagrammatic representation of a HTC reactor (principal components of the Artec Hydrothermal Carbonization plant) (Glaser, 2015).*

The formed hydrochar, regarded as the main product of HTC, has a crystalline structure and it can be separated from the suspension easily due to its high hydrophobicity and homogenous properties (Hoekman et al., 2013). The C efficiency of HTC is very high, because most of the C of the feed remains in the end-product, with the formation of minimal C-containing gases. If the course of process is interrupted after the first 6 hours, humus can be obtained from the reactor (Krylova and Zaitchenko, 2018). The majority of the N, calcium (Ca) and magnesium (Mg) are integrated in the solid phase after carbonization, whereas, the majority of the K and sodium (Na) are in the liquid phase. The fate of P on the other hand, depends on the reaction time and temperature inside the HTC chamber, with solid-phase integration increasing with higher temperature and longer time (Idowu et al., 2017). The HTC process may have a positive effect on the migration of heavy metals from bioavailable fractions into the

more stable fractions (Liu et al., 2018). However, the acid-soluble and exchangeable/reducible fractions of Zn, Ni and Cd can be high, presenting a potential risk to the environment.

Its ability to transform wet biomass into energy without pre-drying, makes HTC an attractive biomass treatment process. The treated substrate must be milled and mixed with water since its MC prior to the treatment needs to reach approximately 85% (De Mena Pardo et al., 2016). HTC is now applied to a wide range of biomass like sewage sludge, municipal solid waste, food wastes, etc. A study on treating different types of manure using HTC has shown that >90% of initial P can recovered in the hydrochar (Heilmann et al., 2014). An establishment of the effect of temperature, process time, particle size, MC, and pH of the medium is necessary to optimize the conditions for HTC. The MC of raw material and the liquid to solid ratio has an effect on the process because this ratio is responsible for the ability of reactants (H_3O+) to penetrate into the material. The non-uniform distribution of liquid over the volume of the solid material can lead to the decomposition of the external surface of the material, whereas the internal portion remains almost unchanged. The water enters the process from the humidity of the biomass or is produced by chemical dehydration of the biomass. In some cases when the humidity of the biomass is low, process water may be recycled to the reactor to guarantee pumpability of the feed. After the process, water is not evaporated but separated by filter pressing down to approxiately 50%. This mechanical dewatering is energy efficient and removes already large amounts of water. After the mechanical water removal, hydrochar can be dried by thermal drying (De Mena Pardo et al., 2016).

Ingelia is a company in Spain (with a capacity to process 14 000 tonnes y^{-1} of biomass) that uses HTC to process various biomass streams, like municipal biowaste and food waste, into hydrochar and liquid fertilizers (Ingelia, n.d.). Hydrochar is a source of C for the soil, and it has already been used as a growing media/soil conditioner on different plant species with great advantages in terms of plant mass increase, fruit production, and growth rate. Hydrochar improves the soil water retention capacity, reducing the water demand of farming activities and increasing their sustainability. It contains other plant nutrients like N, P, K and Ca. After the HTC process the water-soluble nutrients, previously contained in the fresh processed material, are dissolved in the HTC process water. Nutrients can thus be concentrated and used as a basis to produce liquid complex fertilizers applicable for crop fertigation. The existing commercial plant developed by Ingelia demonstrates that HTC is viable and competitive in different conditions and can process all types of organic wastes without significant process changes (De Mena Pardo et al., 2016).

3.1.5 Mechanical separation

Mechanical separation is performed usually as a pre-treatment for nutrient recovery techniques, wherein the separation of raw biomass results into a LF (concentrated in N and K) and SF (concentrated in P and OM). Separation can be achieved by various means including screw press, belt press, drum filters, filter belt presses, centrifuge and flocculation/coagulation that is applied with or without addition of polymers. Table 3 enlists the commonly used techniques for animal manure (applicable also for digestate) separation and the total number of plants in Europe that utilized them in 2011.

Table 3. Livestock manure processing separation techniques and number of plants using these techniques in Europe for 2011 according to Foged et al. (2012).

Separation technique used	Number of plants in Europe using the technology
Coagulation - Flocculation	29
Grate	24
Screw press	3668
Sieves	1995
Filter press	118
Centrifugation	244
Air floatation	2
Drum filters	4635
Natural settling	415

The performance of mechanical separation can be improved by the addition of chemicals like flocculants/coagulants as they allow reduction of the P content in the LF, reduction of the water content in the SF, and/or the enhancement of the capacity of separation equipment (Hjorth et al., 2008). Separation by centrifugation uses centrifugal force to separate solids and liquids into a layer with high DM concentrations (Christensen et al., 2013). It is considered as one of the most effective separation techniques, although, it is relatively expensive. In comparison to the costs for screw press, centrifugation was found to be 5 times more expensive (Møller et al., 2000).

Flocculation is also an effective step, but the attitude of farmers towards it is influenced by the economy of the process as it involves the cost of polymers, additional equipment, etc. (Popovic et al., 2017). The best mechanical separation techniques for flocculated slurry are screens or filter belts (Hjorth et al., 2011). The separation efficiency of mechanical separators for the removal of DM and P is ranked as follows: centrifugation > sedimentation > non-pressurized filtration > pressurized filtration (Table 4). The separation of total N and NH_4^+ also follows the same pattern, but the separation efficiency is lower than for DM and P (Hjorth et al., 2011).

Separation technique	Separation Index (%)			
	DM	TN	NH$_4$-N	P
Sedimentation	56	33	28	52
Centrifugation	61	28	16	71
Non-pressurized filtration	44	27	23	34
Pressurized filtration	37	15	-	17

Nowadays, there is also development in animal manure separation at source. Vermeulen Construct, one of the associated partners of ReNu2Farm, together with Beton Dobbelaere has developed an innovative VeDoWS stabling system for primary manure separation (Figure 6). The VeDoWS system ensures efficient separation of animal excreta and urine, aiming to counteract the formation of urease, which is harmful to both, humans and animals due to the emission of ammonia (NH$_3$). By using a manure and liquid manure gutter with manure scraper, the VeDoWS stabling system separates the drainage of manure and urine. Underneath the slatted floor, a shallow cellar is constructed which enables the separation of urine and solid manure. Using a scraper, the solid manure is removed from the manure gutter daily. This primary separation of manure in the cellar helps in lowering the NH$_3$ emissions thus lowering loss of N by volatilization.

a)   b)   c)
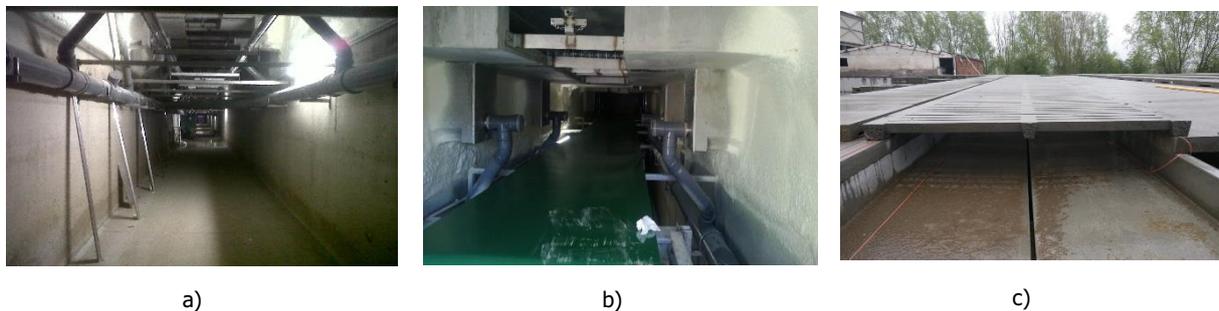
Figure 6. *The VeDoWS system for manure separation: a) pipeline which collects urine from all the stable units; b) conveyor belt to transfer the SF from the slatted floor to the manure storage area; c) gutter for urine collection (Vermeulen Construct, n.d.).*

In case of sewage sludge, thickening and dewatering are the two main processes for water removal. Thickening is a low energy process that relies on gravity as a separation force, and which increases the DM content of sludge from 0.8-1% to 3-7%. Centrifuges, belt press, flotation, etc., can also be used for thickening of sewage sludge (Fytili and Zabaniotou, 2008). Dewatering also utilises mechanical force to remove water and increases DM content usually to around 25% (Sharma, 2017). Plate press, belt press, centrifuge, drying bed, etc., can also be used for sludge dewatering. The mechanically separated biomass, in the form of SF or LF, can undergo further treatment.

3.2 Treatment of solid fraction

SF after mechanical separation contains significant amounts of P and OM. The possibility of recovering nutrients from the SF is limited in comparison to the LF, due to the nature of the organic binding of the nutrients in it. SF usually has a median DM value of 26 w% with an OM content of 17 w% (VLACO, 2012). Depending on regional nutrient demand, the SF can undergo further treatment. The most common processing techniques for SF are described hereinafter.

3.2.1 Drying

Drying of biomass can be done by thermal drying or by using belt, drum and fluidbed drying systems (Figure 7). SF, and in some cases even the raw digestate, is dried using the excess heat that is produced during the AD process. It is one of the most commercially available post-treatment options for SF of digestate as it facilitates the storage and transportation by volume reduction, nutrient upconcentration and sanitation of the solids from mechanical separation. The dried SF is usually exported either in its pure form or after pelletisation to reduce transport costs and facilitate its application on the fields.

Figure 7. *Three types of drying systems in use by Andritz Dryers based on temperatures and heat source (Andritz, 2012).*

The NH_4-N, present in SF and/or digestate, is prone to losses by volatilization during the drying process. There are strategies developed to combat this issue like the treatment of the exhaust air, for example, by air scrubbing to capture the volatilized NH_3 in acidic solution. Another option is to acidify the SF

before thermal drying in order to minimize NH_3 volatilization. In a study by Derikx et al. (1994) it was reported that acidification (to a pH 6) of pig manure and cattle manure prior to drying has resulted respectively in 80% and 60% of NH_4-N recovery. In case of sewage sludge, drying can be done by belt dryers, drum dryers and fluidbed dryers (Figure 7).

3.2.2 Gasification

Gasification involves conversion of carbonaceous feedstock into gas (syngas) accompanied by formation of biochar and/or ash as a by-product. It is considered as one of the key conversion technologies of biomass to produce electricity, fuels and chemical products (Ptasinski, 2008). All the three biomass streams, animal manure, sewage sludge and food waste (as a part of municipal solid waste; MSW), can undergo the process of gasification.

The gasifier operates at close to atmospheric pressure and typically between 850-900°C and utilizes air as the gasification/fluidizing agent (Morris and Waldheim, 1998). The biochar/ash that is produced at the end of the process has a high content of P and K and can be used as a fertilizer. A study by Li et al., (2017) showed that the biochar from pig and poultry manure gasification can have higher P extractability relative to triple super phosphate (TSP) as compared to sewage sludge-based biochar. The reducing conditions maintained in gasification process are expected to lower the level of pollutants that might be present in the sludge. The high temperatures destroy the harmful dioxins and furans and the lack of oxygen prevents their formation in the syngas cleaning stage. In addition, the emissions of NO_x are low in the gasification process (Sharma, 2017). However, biomass with high contents of straw, manure, and sewage sludge (having low melting point ashes) often causes problems related to ash melt during gasification at higher temperatures >800°C (Thomsen et al., 2015). These issues can be mostly avoided with the low-temperature circulating fluidized bed (LT-CFB) gasifier, where the maximum process temperature does not exceed 750°C (Ahrenfeldt et al., 2013; Hansen et al., 2015).

At Soil-Concept (Dierkirch, Luxembourg), one of the project partners of ReNu2Farm, sewage sludge compost is converted into thermal and electrical energy using a stationary atmospheric fluidised bed gasifier (Figure 8). The gasifer is operated with preheated air and superheated steam to produce a low Btu synthesis gas. The gross capacity (fuel input) of the gasifier is 2 MW thermal. Fluidized bed gasification leads to good heat transfer within the reactor, as fluid material (i.e. solid particles) and fluid medium (i.e. gas or liquid) come in close contact. The high heat capacity of the bed inventory leads to a relatively homogeneous temperature field in the reactor and keeps level of pollutants in the gasification process low. In sewage sludge compost, however, the exhaust gases must be filtered because they contain heavy metals and tar. The synthesis gas produced during gasification is used in a subsequent process for combustion in a combined heat and power plant or for operating a steam turbine. The electricity generated is fed into the grid and the heat is used internally. The plant-available P from the sewage sludge compost settles in the bed ash which can either be processed into a fertilizer or applied

directly to the field. The plant-available P after the gasification of pure sewage sludge is 6-7% of an initial value of 9-10%. The heavy metal concentration also falls significantly, usually by 50%. The fly ash from the process goes to the cement industry due to its high concentration of heavy metals. The sewage sludge compost has an ash content of 19% at a temperature of 815°C. The calorific value is given as 12 200 kJ kg^{-1} (Soil - Concept, personal communication).
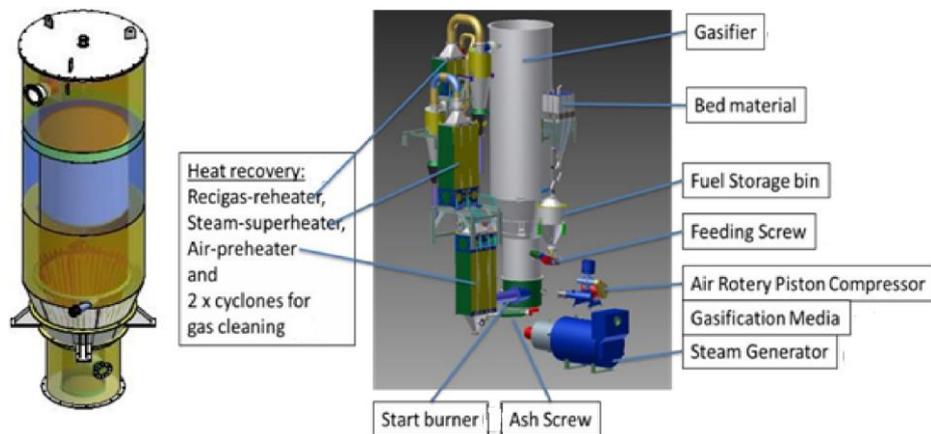
Figure 8. Overview of the gasification components at Soil Concept (Soil Concept, personal communication).

3.2.3 Pyrolysis

Pyrolysis involves the thermochemical decomposition of OM into non-condensable gases, condensable liquids (bio-oil), and a solid residual co-product (pyrolysis char/pyrochar/biochar), performed in the absence of oxygen. The end-products of pyrolysis can be controlled by optimizing the parameters such as temperature and residence time. The process can be applied to different types of biomass like animal manure, sewage sludge, food wastes, agricultural residues, municipal solid waste, etc. There are two types of pyrolysis: slow and fast. The slow pyrolysis is a low-temperature (300-550°C) process where biomass can be less finely crushed and subjected to longer residence times and low heating rates (0.01-2°C s^{-1}), resulting in higher quantities of biochar. On the other hand, fast pyrolysis requires the feed to be finely ground to allow fast heat transfer (Mandal et al., 2016). This finely ground feedstock is subjected to a moderate temperature (>600°C) with shorter residence time to produce high-quality ethylene-rich gases (syngas).

An innovative pyrolysis technology for the production of Animal bone char (ABC) bio-phosphate, an organic fertilizer, is employed by company Terra Humana (Figure 9). The 3R (Recycle-Reduce-Reuse) Zero Emission Pyrolysis Technology is a complex reductive thermal processing system for industrialized processing of category 3 food grade animal bone grist at <850°C under specific processing conditions for the production of ABC bio-phosphate. Cattle bones and parts of pig bones are the input materials for this technology. ABC bio-phosphate granulate contains 30% P_2O_5 and is a specific material with

macroporous surface characteristics. For agricultural applications, the material is bio NPK-C formulated, including biotechnological formulations with P-mobilization selected fungus strains and adapted by product-specific solid state fermentation and formulation technology. The current capacity of the plant is 2 000 tonnes y^{-1} with bio-phosphate production of 1 200 tonnes y^{-1} (Terra Humana, n.d.).

Figure 9. Pyrolysis reactor at Terra Humana (Terra Humana, n.d.)

3.3 Treatment of liquid fraction

LF after mechanical separation contains significant amounts of N and K. It has a median DM content of 6,6 w% and an OM content of 3,3 w% (VLACO, 2012). Depending on the regional nutrient status, the LF can be applied on the field or further treated. The most common processing techniques for LF are explained hereinafter.

3.3.1 Biological treatment

Biological treatment converts N in LF to N gas (N_2) via two sequential steps, nitrification followed by denitrification (Figure 10). During the nitrification process NH_4-N in the LF is oxidized to nitrite nitrogen (NO_2-N) and then to nitrate nitrogen (NO_3-N). In the denitrification process the NO_3-N is converted further to N_2 under anaerobic conditions.

Figure 10. Biological nitrification/denitrification tank (VCM, n.d.)

The effluent after biological treatment is either applied onto the field directly or after an evaporation step to reduce the water content (Lebuf et al., 2013). It can also be further treated in constructed wetland (CW) as a polishing step. The CWs are treatment systems that use natural processes involving wetland vegetation, soils, and their associated microbial assemblages to improve water quality. In CWs, the effluent after biological treatment is introduced at one end and flows through the whole wetland surface to be discharged at the other end. Interaction of biotic and abiotic factors along with the maintenance of controlled operating conditions allows the removal of particulate and dissolved OM, as well as organic and inorganic pollutants (Kadlec et al., 2000). The effluent of CW contains low nutrient and chemical oxygen demand (COD) levels, after which it can be discharged into surface or ground waters if it complies with national discharge limits (Meers et al., 2008). The biological treatment is mostly used in animal manure (and digestate) and sewage sludge processing.

3.3.2 Membrane filtration

Membrane filtration is a nutrient recovery technique that employs the use of membranes of various pore sizes to concentrate the N and K in the end-product. The membranes are categorized on the basis of the size of their pores, as follows (Yoon, 2006):

- Microfiltration (MF) pore size = 0.1-10 µm
- Ultrafiltration (UF) pore size = 0.01-0.1 µm
- Nanofiltration (NF) pore size = 0.001-0.01 µm
- Reverse osmosis (RO) = 0.0001-0.001 µm

These membrane processes selectively separate constituents from waste streams without bringing any phase transformation using semipermeable membranes and selective pressure (Figure 11). The waste stream volumes can be reduced by 4-6 times while retaining all the nutrients (Mehta et al., 2015). After MF, suspended solids are retained in the concentrate/retentate, whereas UF also retains the macromolecules. Both, MF and UF can be used as a predecessor step to RO so that neither the suspended solids nor macromolecules clog the RO membrane. NF is also emerging as a pressurized membrane filtration technology. With a pore size of 1nm, it can be used as a step between UF and RO. The permeate after the RO process can be discharged as it consists mostly of water along with small ions, or it can be used as process water. A polishing step can be added prior to the discharge, if necessary. The concentrate after the RO contains significant amount of N and K, which ranges between 7-9 g N kg^{-1} and 3-16 g K kg^{-1} (Velthof, 2011; Hoeksma et al., 2012; Vaneeckhaute et al., 2012). Hence, the concentrate is often used in crop production as a NK-fertilizer. In practice, the concentrate is referred to as a mineral concentrate since 90-100% of total N in concentrate is present in mineral N form (Schröder et al., 2014; Velthof, 2015; Sigurnjak, 2017).
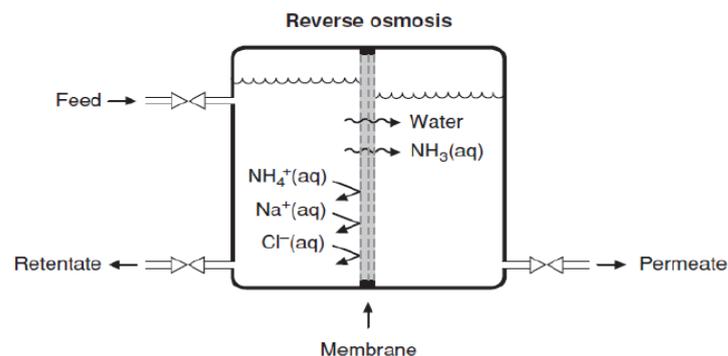
Figure 11. *Reverse osmosis filtration for concentration of ions in liquid manure (Christensen et al., 2013).*

One of the important issues with membrane filtration is the occurrence of membrane fouling. Generally fouling is the accumulation of undesired deposits on the membrane surface or inside the membrane pores, causing decrease of permeation flux and salt rejection (Malaeb and Ayoub, 2011). Inorganic scaling of membranes can be avoided by maintaining the pH range of the processes between 6-8 (Hainaut, 2018). Only properly pre-treated streams are used for membrane processes to prevent fouling and clogging of the membranes. This approach also helps in prolonging the life of the membrane and increasing the flux rates. Mostly ceramic or organo-polymeric membranes are used. Though the organo-polymeric membranes are cheaper, it is more difficult to clean them and they are also unable to withstand high pressure. The higher the separation potential of a membrane, the higher is its energy consumption, due to the high pressures required to achieve the separation. This is a limitation of this technique.

3.3.3 P - precipitation

Precipitation is a phase change process that converts soluble components in the LF into a particulate, insoluble compound for separation from the bulk liquid. Chemical precipitation of P from the LF is achieved by optimizing conditions like pH, temperature, addition of calcium/magnesium/potassium (Ca/Mg/K) ions which leads to the formation of P crystals. The crystallization of struvite ($MgNH_4PO_4.6H_2O$), a slow release fertilizer, is the most common example of P-precipitation. Struvite precipitation is enhanced when the pH is between 7-11, since alkaline conditions decrease the solubility of struvite and hence increase the level of precipitation (Burns and Moody, 2002).

Struvite typically contains 12% P and 5% N with minimal heavy metal or biological contamination (Antonini et al., 2012). Different ions can be added to a solution containing orthophosphate (the soluble form) to induce this precipitation reaction. If CaO is added to the phosphate solution, then the end-product will be calcium phosphate ($Ca_3(PO_4)_2$), whereas if K is added, then the precipitate will be K-struvite ($K_2NH_4PO_4.6H_2O$). Most of the times, struvite is produced by adding magnesium oxide (MgO), but even magnesium chloride ($MgCl_2$) can be added which requires less energy than the former. However, disadvantages of using $MgCl_2$ are residual chloride ions in the solution and a slower and incomplete reaction.

Veolia Water, the water division of the French company Veolia Environment, owns STRUVIA™ process that was originally developed by the Japanese company Showo Kankyo Systems K.K. (SKS) (P-REX, 2015b). In this process, struvite is recovered from sewage sludge liquor in a continuous stirred tank reactor (CSTR) combined with a lamellar settler on top after dewatering in a WWTP. Rapid mixing in the CSTR is enabled by a special mixing technology (Turbomix®). After dosing of $MgCl_2$ and sodium hydroxide (NaOH) for pH adjustment to 8-9, struvite is precipitated and can be harvested as a clean powder at the bottom of the reactor (Figure 12). Granular particles of 100-200 µg are formed which are

easily dewatered by gravity. The end-product contains N/P/Mg in the ratio of 5.7/12.6/9.9 (Cunha et al., 2016).
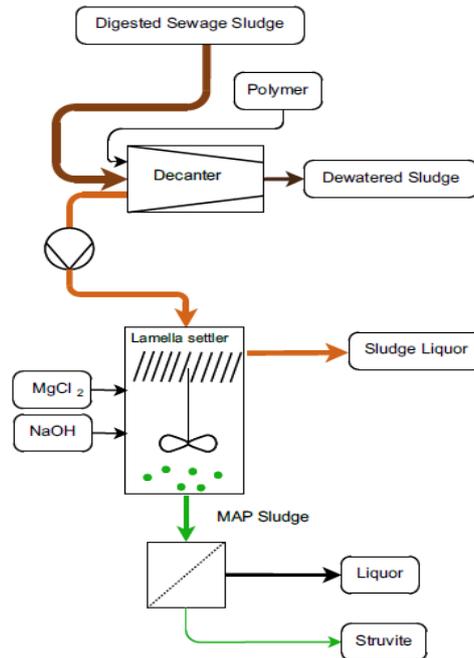
Figure 12. *Process scheme of the STRUVIA™ struvite crystallization by Veolia Water (P-REX, 2015b).*

Since struvite crystallization focuses more on P removal, the residual solution is left with a considerable quantity of N. A recent study by Amini et al. (2017), introduces ion exchange with zeolites as a technique that can recover the remaining N from the solution after precipitation. Ion exchange with zeolites has the potential to recover both N and K as a solid fertilizer. Used in agriculture and environmental remediation (Chmielewska, 2003; Mumpton, 1999; Polat et al., 2004; Tian et al., 2004), natural zeolites are hydrated aluminosilicates that have an affinity for NH_4 and K (Jorgensen et al., 1976). When applied as a fertilizer, zeolite also reduces the overall fertilizer requirements by increasing the soil IX capacity, allowing for a slower release of fertilizer into the soil (Mumpton, 1999). When zeolites are added to water, the pH is raised due to a hydrolysis reaction. This can enable struvite recovery and IX in a single reactor. Several studies have evaluated this combined process and concluded that with this process 80-90% of nutrients from swine and municipal wastewaters can be recovered (Huang et al., 2014; Lin et al., 2014; Amini et al., 2017).

3.3.4 Ammonia stripping and scrubbing

NH_3 stripping is a physiochemical process that involves mass transfer of NH_3 from the liquid to the gaseous phase. The transfer of NH_3 occurs by stripping the dissolved NH_3 with an extractant gas (mostly air) and is usually applied in situations where the input stream has a relatively high NH_3 concentration (>2000 mg/L) (Mehta et al., 2015). After stripping, the NH_3 rich air is scrubbed in a second reactor by

getting into contact with a strong acidic solution such as H_2SO_4 or nitric acid (HNO_3). Depending on the used sorbent, an end-product can be ammonium sulfate or ammonium nitrate. Both end-products are currently used in crop production as N-fertilizers.

For high stripping efficiency, the process is carried out in a packed tower, as it provides large mass transfer area (Sengupta et al., 2015). Various factors such as NH_4 concentration of feed, hydraulic loading, air flow rate, packing, pH, temperature, etc., can affect the process. Among these parameters pH and temperature are defined as the most crucial ones (Norddahl et al., 2006; Quan et al., 2009; Guo et al., 2010). Usually lime or caustic soda is used to maintain the pH. Several studies have established a pH value of 11-12 for optimum economic recovery of NH_3 from the process (Norddahl et al., 2006; Quan et al., 2009). A pH of 11 has shown a recovery rate of 92-97% NH_3 (Guo et al., 2010; Guštin and Marinšek-Logar, 2011). At a temperature higher than 80°C, the process becomes independent of pH (Bonmati and Flotats, 2003). The process can be applied as an end-of-pipe technology on LFs, but it can also be coupled to AD and hence applied on raw digestate (Sigurnjak et al., 2019).

Detricon (Gistel, Belgium), one of the associated partners of ReNu2Farm, is a Belgian SME constructing environmental technologies for the valorisation of organic waste streams. They focus on nutrient recovery from manure and digestate to produce bio-based fertilizers for local use. Their stripping and scrubbing process recovers the nutrient N in an energy efficient way, producing a bio-based liquid fertilizer with 180 kg N per tonnes (Digesmart, 2016). In Figure 13, a mass balance of the DETRICON pilot plant is given.
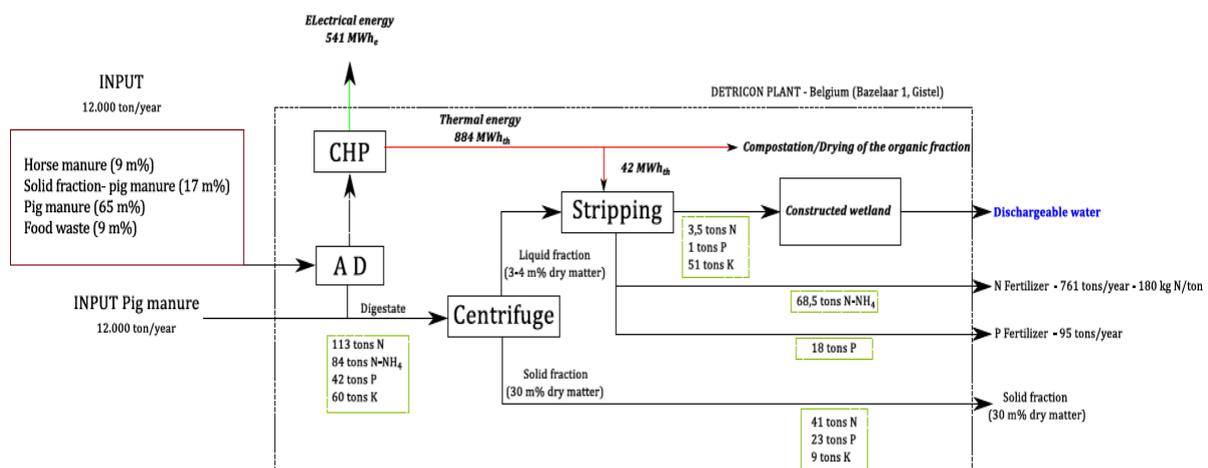
Figure 13*. Schematic diagram of the nutrient recovery and reuse technology involving anaerobic digestion (AD) and NH$_3$ stripping/scrubbing by Detricon (Detricon, personal communication).*

The AD plant 'Acqua and Sole' (Italy) treats sewage sludge and digestate from anaerobic treatment of source-segregated domestic food waste. They recover nutrients by an NH_3 stripping unit, whereby biogas acts as the stripping agent. NH_3 is extracted using H_2SO_4 as ammonium sulphate. Approximately

22% of NH_4-N from the digestate in that process is recovered from the stripping process (Systemic, 2018a; Sigurnjak et al., 2019).

3.3.5 Evaporation

Evaporation is used to up-concentrate nutrients present in LF by producing a condensate and an evaporation residue. This condensate comprises mainly of NH_3 and certain volatiles. The technique is interesting to AD plants where excess heat is available in sufficient amounts or where excess heat from other sources near the AD plant can be used. Since evaporation results in loss of NH_3 by volatilization, the LF can be acidified first. Acidification to pH of 4.5 would allow for N to remain as NH_4-N in the evaporation residue. However, acidification could cause foaming due to the production of carbonic acid (Lebuf et al., 2013). The produced evaporation residue can be further treated, dried or used as a fertilizer.

Group op de Beeck (Olen, Belgium) processes various types of organic waste. They employ an evaporation technique in one of their final steps of waste processing with the aim to recover nutrients. The energy produced on their site from AD is utilized to evaporate the LF of digestate and subsequently to produce two end-products: NH_3 water and an evaporation residue containing P (0.2%) and K (1.7%). The LF of digestate is first evaporated and the produced condensate passes through an NH_3 stripper, recovering the NH_3 present in the condensate (Figure 14). This generates NH_3 water (of 20% N) and a purified water as a concentrate which is then used as process water at site plant for cleaning or pre-treatment (Group op de Beeck, 2019).
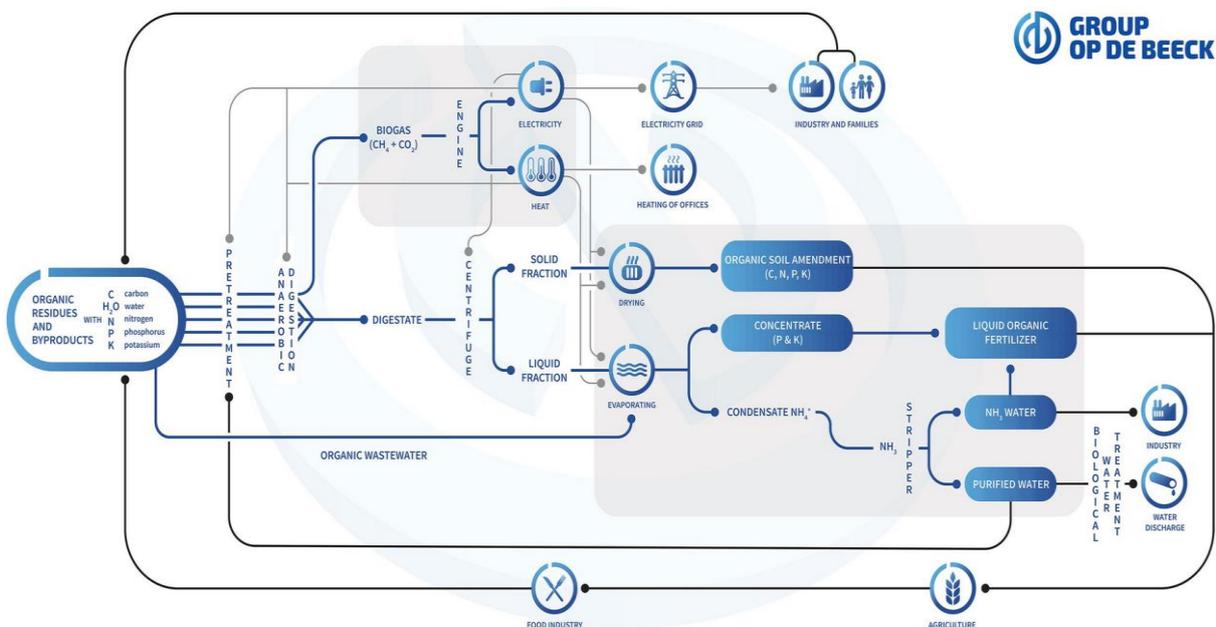
Figure 14. *Schematic diagram of the nutrient recovery and reuse technology at Group op de Beeck (Group op de Beeck, 2019)*

3.3.6 Algal Cultivation

Since the current legislative framework in NWE limits application rates of N coming from animal manure and its derivatives (European Commission, 1991a) on agricultural lands, alternative uses for these streams have been currently investigated (Stiles et al., 2018). One of them is to utilize LF as a growth medium for the photosynthetic algae. The nutrients present in the LF are taken up by the algae and converted to biomass. This cultivated algal biomass is rich in proteins and other useful compounds that can be utilized in agriculture (e.g. production of sustainable animal feed products), green chemistry and bioenergy sectors (Pulz and Gross, 2004).

Microalgae are currently being researched increasingly on a global scale to remediate the nutrients that are present in organic wastes and to produce biomass and energy (Sivakumar et al., 2012; Abinandan and Shanthakumar, 2015). European Union's Horizon 2020 Project SABANA (Sustainable Algae Biorefinery for Agriculture and Aquaculture; 01/12/2016 - 30/11/2020) aims at developing a large-scale integrated microalgae-based biorefinery for the production of biostimulants, biopesticides and feed additivies, in addition to biofertilizers and aquafeed, using only marine water and nutrients from wastewaters (sewage sludge, digestate and pig manure). Development of suitable technologies for the efficient harvesting and processing of the biomass to obtain valuable products, allowing an integral valorization of the biomass, are the main focus of the SABANA project. Another EU funded project, DEMA (Direct Ethanol from Microalgae; 23/01/2013 – 05/2017), has demonstrated a competitive technology for the direct production of bioethanol from microalgae utilising low-cost scalable photobioreactors. The Interreg NWE project ALG-AD (20/09/2017 – 30/03/2021) also focusses on similar aspects, but with the main focus to couple algal technology to AD sites where LF of digestate can be used as a growing medium. This will be achieved by cultivating algal production on LF digestate as a growing medium at three pilot facilities for algal cultivation at Devon (UK), Ghent (Belgium) and Brittany (France). Local conditions in each of these places will be utilized for the algal growth and results will be recorded.

4 Overview of end-products

Biomass processing technique	Starting from	End-product(s)	Characteristics of end-product(s)			References
			N	P	K	
Anaerobic digestion	Raw biomass	Digestate	0.12 - 0.91 %	0.04 - 0.26 %	0.12 - 1.1 %	Lebuf et al., 2013; Sigurnjak, 2017a
Composting	Raw biomass	Compost	1.4 - 2.6 %	0.81 - 0.69 %	0.69 - 1.5 %	ReNu2Farm, unpublished data
Incineration	Raw biomass	Ash	-	6.3 - 9.4 %	0.8 - 1.5 %	P-REX, 2015c; Hermann and Schaaf, 2019
HTC	Raw biomass	Hydrochar	0.1 - 4.02 %	0.001 - 3.91 %	0.01 - 0.54 %	Jandl et al., 2012; Heilmann, et al., 2014; Pucini et al., 2017; Diequez-Alonso et al., 2018
Gasification	Raw biomass, solid fraction	Biochar/ash	-	0.30 - 0.51%	0.86 - 1.6 %	ReNu2Farm, unpublished data
Pyrolysis	Raw biomass, solid fraction	Biochar/ash	0.1 - 2.4 %	2.6 - 3.03 %	1.1 - 1.3 %	Diequez-Alonso et al., 2018
Membrane filtration	Liquid fraction	NK-concentrate	0.3 - 0.9 %	-	0.23 - 1.6 %	Velthof, 2011; Hoeksma et al., 2012; Vaneeckhaute et al., 2012; ReNu2Farm, unpublished results
P-precipitation	Liquid fraction	Struvite, Ca-P	5.0 - 5.7 % 2 %	4.9 - 10.6 % 6.1 %	0.021 - 1.2 % 0.41 %	ReNu2Farm, unpublished results; Systemic, 2018b
Ammonia stripping and scrubbing	Liquid fraction	NH_4SO_4, NH_4NO_3	3.0 - 8.6 % 13.2 - 19.8 %	- -	- -	Systemic, 2018b; Sigurnjak et al., 2019
Evaporation	Liquid fraction	Ammonia water, Evaporation residue	10.7 - 20 % 0.54 %	- 0.1 - 0.2 %	- 0.99 - 1.7 %	Group op de Beeck, 2019; ReNu2Farm, unpublished results
Algal cultivation	Liquid fraction	Algal biomass	Further research needed			
Biological treatment	Liquid fraction	Effluent	300 - 1500 mg/L	44 - 480 mg/L	2045 - 3070 mg/L	Smet et al., 2003; Devlamynck et al., 2018

5 Conclusion

Managing biomass arising from various sectors as a step towards sustainability is becoming a matter of crucial importance in the present day. Processing biomass to recover and recycle the large pool of nutrients contained in them, and thus following the principal of circular economy, is an efficient step towards sustainable agriculture and waste management. Animal manure, sewage sludge, and food chain waste have a tremendous potential for nutrient recovery, and technologies to facilitate their recovery and recycling have been under constant scrutiny and development.

As shown from the report, the biomass processing and nutrient recovery techniques are currently being employed at the installations across the EU. Their further market uptake will depend on the marketing value of the produced end-products and what kind of value they bring to the end-users. Economic profitability must be established for all the stakeholders. The prices allocated to the bio-based fertilizers should be at par as for the synthetic mineral fertilizers to be able to successfully commercialize the products. Care should be taken to create an end-product with NPK values in accordance to the mineral fertilizers and to have toxic contaminants under the limits prescribed by the EU Fertilizer Regulations.

REFERENCES

Abinandan, S. and Shanthakumar, S., 2015. Challenges and opportunities in application of microalgae (Chlorophyta) for wastewater treatment: a review. *Renewable and Sustainable Energy Reviews*, *52*, 123-132. https://doi.org/10.1016/j.rser.2015.07.086

Ahrenfeldt, J., Thomsen, T.P., Henriksen, U. and Clausen, L.R., 2013. Biomass gasification cogeneration – a review of state of the art technology and near future perspectives. *Applied Thermal Engineering* 50(2), 1407–1417. https://doi.org/10.1016/j.applthermaleng.2011.12.040

Alexandratos, N. and Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO. Available from: http://www.fao.org/3/a-ap106e.pdf

ALG-AD, n.d. Project website. Available at: http://www.nweurope.eu/projects/project-search/alg-ad-creating-value-from-waste-nutrients-by-integrating-algal-and-anaerobic-digestion-technology/

Amini, A., Aponte-Morales, V., Wang, M., Dilbeck, M., Lahav, O., Zhang, Q., Cunningham, J.A. and Ergas, S.J., 2017. Cost-effective treatment of swine wastes through recovery of energy and nutrients. *Waste Management* 69, 508-517. https://doi.org/10.1016/j.wasman.2017.08.041

Andritz, 2012. *Drying technologies for sewage sludge.* Andritz AG. Available from: http://www.centrivit.cz/download/andritz_dryers_en.pdf

Antonini, S., Arias, M.A., Eichert, T. and Clemens, J., 2012. Greenhouse evaluation and environmental impact assessment of different urine-derived struvite fertilizers as phosphorus sources for plants. *Chemosphere* 89(10), 1202-1210. https://doi.org/10.1016/j.chemosphere.2012.07.026

Attero, n.d. Attero Energiek en milieu, company webiste. Available at: https://www.attero.nl/en/our-waste-management/your-organic-waste-is-converted-into-compost-and-energy/our-processing-technology/

Batham, M., Gupta, R. and Tiwari, A., 2013. Implementation of Bulking Agents in Composting: A Review. *Journal of Bioremediation and Biodegradation,* 4(7). doi:10.4172/2155-6199.1000205

BMC Moerdijk, 2019. High quality fertilizer. Available from: https://www.bmcmoerdijk.nl/en/ process/high-quality-fertilizer.htm

Bonmati, A., and Flotats, X., 2003. Air stripping of ammonia from pig slurry: characterisation and feasibility as a pre-or post-treatment to mesophilic anaerobic digestion. *Waste management*, *23*(3), 261-272. https://doi.org/10.1016/S0956-053X(02)00144-7

Buckwell, A., and Nadeu, E., 2016. Nutrient recovery and reuse (NRR) in European agriculture. A review of the issues, opportunities, and actions. RISE Foundation, Brussels. Available from: http://www.risefoundation.eu/images/files/2016/2016_RISE_NRR_Full_EN.pdf

Burns, R.T. and Moody, L., 2002. Phosphorus Recovery from Animal Manures using Optimized Struvite Precipitation. *Proceedings of Coagulants and Flocculants: Global Market and Technical Opportunities for Water Treatment Chemicals,* Chicago, Illinois. May 22-24, 2002.

Chmielewska, E., 2003. Remediation of specifically polluted waste effluents using natural zeolites. *Environment Protection Engineering* 29(1), 35-44.

Christensen, M., Christensen, K. and Sommer, S., 2013. Solid–Liquid Separation of Animal Slurry. In: *Animal Manure Recycling.* John Wiley & Sons Ltd, pp. 105-129.

Cieślik, B. M., Namieśnik, J., and Konieczka, P., 2015. Review of sewage sludge management: standards, regulations and analytical methods. *Journal of Cleaner Production* 90, 1-15. https://doi.org/10.1016/ j.jclepro.2014.11.031

Coppens, J., Meers, E., Boon, N., Buysse, J., and Vlaeminck, S. E., 2016. Follow the N and P road: high-resolution nutrient flow analysis of the Flanders region as precursor for sustainable resource management. *Resources, Conservation and Recycling* 115, 9-21. https://doi.org/10.1016/j.resconrec. 2016.08.006

Cunha, M., Paillard, H. and Oudouh, B., 2016. *Struvia technology for Phosphorus recovery as struvite-PHORater Workshop - CPE Lyon, 12/05/2016.* Lyon, pp. 1-20.

de la Fuente, C., Clemente, R., Martínez-Alcalá, I., Tortosa, G., and Bernal, M. P., 2011. Impact of fresh and composted solid olive husk and their water-soluble fractions on soil heavy metal fractionation; microbial biomass and plant uptake. *Journal of Hazardous Materials* 186(2-3), 1283-1289. https://doi.org/10.1016/j.jhazmat.2010.12.004

De Mena Pardo, B., Doyle, L., Renz, M. and Salimbeni, A., 2016. Industrial Scale Hydrothermal Carbonization: New Applications for Wet Biomass Waste; ttz Bremerhaven: Bremerhaven, Germany.

Devlamynck, R., Coudron, C., Meers, E. and Leenknegt, J., 2018. Evaluatieverslag: Agrarische nevenstromen en hun inzetbaarheid als secundaire grondstof bij eendenkroos- en spirulina-teelt. De Blauwe Keten project, Interreg V-programma Vlaanderen-Nederland. Available from: https://www.biorefine.eu/sites/default/files/publication-uploads/evaluatieverslag_ valorisatievanreststromen_1.pdf

Delvigne, F., Destain, J., Maesen, P., Meers, E., Michels, E., Tarayre, C. and Tarayre, N., 2015. *Inventory of wastes produced in Belgium, Germany, France, the Netherlands and the United Kingdom*. Gembloux Agro-Bio Tech.

DEMA, n.d. Project website. Available at: http://www.dema-etoh.eu/en/

Derikx, P.J.L., Willers, H.C. and Ten Have, P.J.W., 1994. Effect of pH on the behaviour of volatile compounds in organic manures during dry-matter determination. *Bioresource Technology* 49(1), 41-45. https://doi.org/10.1016/0960-8524(94)90171-6

Detricon, n.d. Company website. Available at: https://detricon.eu/

Dieguez-Alonso, A., Funke, A., Anca-Couce, A., Rombola, A.G., Ojeda, G., Bachmann, J. and Behrendt, F., 2018. Towards biochar and hydrochar engineering-influence of process conditions on surface physical and chemical properties, thermal stability, nutrient availability, toxicity and wettability. *Energies* 11, 1-26. https://doi.org/10.3390/en11030496

Digesmart, n.d. Project website. Available at: http://www.digesmart.eu/eng/descripcion.html

Donatello, S. and Cheeseman, C.R., 2013. Recycling and recovery routes for incinerated sewage sludge ash (ISSA): A review. *Waste Management* 33(11), 2328-2340. https://doi.org/10.1016/j.wasman .2013.05.024

EBA, 2017. EBA Statistical Report 2017. European Biogas Association, Brussels, Belgium.Available from: http://european-biogas.eu/2017/12/14/eba-statistical-report-2017-published-soon/

EBA, 2018. European Biogas Association's Statistical report. European Biogas Association, Brussels, Belgium.

EEA, 2017. Urban waste waste directive treatment plants data viewer. European Environment Agency, published on 20 Dec 2017. Available from: https://www.eea.europa.eu/themes/water/european-

waters/water-use-and-environmental-pressures/uwwtd/data-viewer-urban-wastewater-treatment-directive-1/urban-waste-water-directive-treatment [Accessed on April 12th 2019]

European Commission, 1991a. Directive of the Council of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EC). *Official Journal of the European Communities,* L375, 1-8.

European Commission, 1991b. Directive of the Council of 21 May 1991 concerning urban waste-water treatment (91/271/EEC). *Official Journal of the European Communities,* L135, 40-52.

European Commission, 2000. Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on incineration of waste. Available from: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2000L0076:20001228:EN:PDF

European Commission, 2014. Task 2.11 Study on the behaviour of digestate in agricultural soils."Providing support in relation to the implementation of the Nitrates Directive (91/676/EEC)". Cluster 2: The production of studies concerning the scientific, technical and socio-economic issues related to the Nitrates Directive. European Commission, pp. 1-28.

FAO, 2015. World fertilizer trends and outlook to 2018. Food and Agricuture Organization of the United Nations, Rome (Italy), 1-66. Available from: http://www.fao.org/3/a-i4324e.pdf

FAO, 2017. The future of food and agriculture – Trends and challenges. Food and Agricuture Organization of the United Nations, Rome (Italy), 11-163. Available from: http://www.fao.org/3/a-i6583e.pdf

Fertlizers Europe, 2018. Industry facts and figures 2018. Available from: https://www.fertilizerseurope.com/uploads/media/Industry_Facts_and_Figures_2018_Fertilizers_Europe_Web_version.pdf

Flotats, X., Bonmatí, A., Palatsi, J. and Foged, H.L., 2013. Trends on manure processing in Europe. In Book of Proceedings, 2nd International Conference of WASTES: solutions, treatments and opportunities. Centro para a Valorizaçao de Residuos, Braga, Portugal, 11-13.

Foged, H., Flotats Ripoll, X., Bonmatí Blasi, A., Palatsi Civit, J., Magrí Aloy, A. and Schelde, K.M., 2012. Inventory of manure processing activities in Europe. Available from: https://upcommons. upc.edu/handle/2117/18943

Fouda, S., 2011. Nitrogen availability of biogas residues. Doctoral dissertation, Technische Universität München.

Fytili, D. and Zabaniotou, A., 2008. Utilization of sewage sludge in EU application of old and new methods—a review. *Renewable and Sustainable Energy Reviews* 12(1), 116-140. https://doi.org/10.1016/j.rser.2006.05.014

Glaser, B., 2015. Biochar as soil amendment: facts and myths. Tuhh, A., Gfeu ev, Wecf (Ed.), Terra preta sanitation 1: background, principles and innovation. Deutsche Bundesstiftung Umwelt, Hamburg, 16-29.

Grassland and Fodder Fertilization Committee, 2019. Report on Fertilization Advice. Available at: http://edepot.wur.nl/413891

Group op de Beeck, 2019. Energy Production and Nutrient Recovery-Op de Beeck NV. Available from: . https://www.groupopdebeeck.com/en/ennu_nutrientrecuperatie/

Guo, J.S., Abbas, A.A., Chen, Y.P., Liu, Z.P., Fang, F. and Chen, P., 2010. Treatment of landfill leachate using a combined stripping, Fenton, SBR, and coagulation process. *Journal of Hazardous Materials* 178 (1-3), 699-705. https://doi.org/10.1016/j.jhazmat.2010.01.144

Guštin, S. and Marinšek-Logar, R., 2011. Effect of pH, temperature and air flow rate on the continuous ammonia stripping of the anaerobic digestion effluent. *Process Safety and Environmental Protection* 89(1), 61-66. https://doi.org/10.1016/j.psep.2010.11.001

Hainaut, R., 2018. Rejection performance and stability of MF/UF ceramic membranes towards TiO2 photocatalyst in PMRs. Available from: https://dial.uclouvain.be/memoire/ucl/en/object/thesis%3A14873/datastream/PDF_01/view

Hansen, V., Müller-Stöver, D., Ahrenfeldt, J., Holm, J.K., Henriksen, U.B. and Hauggaard-Nielsen, H., 2015. Gasification biochar as a valuable by-product for carbon sequestration and soil amendment. *Biomass and Bioenergy* 72, 300-308. https://doi.org/10.1016/j.biombioe.2014.10.013

Heilmann, S.M., Molde, J.S., Timler, J.G., Wood, B.M., Mikula, A.L., Vozhdayev, G.V., Colosky, E.C., Spokas, K.A. and Valentas, K.J., 2014. Phosphorus reclamation through hydrothermal carbonization of animal manures. *Environmental Science & Technology* 48(17), 10323-10329. doi: 10.1021/es501872k

Hermann, L. and Schaaf, T., 2019. Outotec (AshDec®) Process for P Fertilizers from Sludge Ash. In: H. Ohtake and S. Tsuneda, Hrsg. *Phosphorus Recovery and Recycling.* Singapore: Springer, 221-233. https://doi.org/10.1007/978-981-10-8031-9_15

Hjorth, M., Christensen, K. V., Christensen, M. L. and Sommer, S., 2011. Solid–Liquid Separation of Animal Slurry in Theory and Practice. *Sustainable Agriculture* 2, 953-986. https://doi.org/10.1007/978-94-007-0394-0_43

Hjorth, M., Christensen, M. and Christensen, P., 2008. Flocculation, coagulation, and precipitation of manure affecting three separation techniques. *Bioresource Technology* 99(18), 8598-8604. https://doi.org/10.1016/j.biortech.2008.04.009

Hoekman, S.K., Broch, A., Robbins, C., Zielinska, B. and Felix, L., 2013. Hydrothermal carbonization (HTC) of selected woody and herbaceous biomass feedstocks. *Biomass Conversion and Biorefinery* 3(2), 113-126. https://doi.org/10.1007/s13399-012-0066-y

Hoeksma, P., de Buisonjé, F.E. and Aarnink, A.A., 2012. Full-scale production of mineral concentrates from pig slurry using reverse osmosis. In *Ninth International Livestock Environment Symposium, Valencia Spain*, pp. 8-12.

Hsiau, P.C. and Lo, S.L., 1998. Extractabilities of heavy metals in chemically-fixed sewage sludges. *Journal of Hazardous Materials, 58* (1-3), 73-82. https://doi.org/10.1016/S0304-3894(97) 00121-0

Huang, H., Xiao, D., Pang, R., Han, C. and Ding, L., 2014. Simultaneous removal of nutrients from simulated swine wastewater by adsorption of modified zeolite combined with struvite crystallization. *Chemical Engineering Journal* 256, 431-438. https://doi.org/10.1016/j.cej.2014.07.023

Hunt, C., 2003. Wastage of food. Encyclopedia of Food Sciences and Nutrition. Available from: https://www.elsevier.com/books/encyclopedia-of-food-sciences-and-nutrition-ten-volume-set/caballero/978-0-12-227055-0

Huygens, D. and Saveyn, H., 2018. DRAFT STRUBIAS Interim Report- DRAFT market study for recovered phosphate salts, ash-based materials and pyrolysis materials in view of their possible inclusion as Component Material Categories in the Revised Fertiliser Regulation. Available from: https://phosphorusplatform.eu/images/download/STRUBIAS-draft-MARKET-report-20_12_2018.pdf

Idowu, I., Li, L., Flora, J., Pellechia, P., Darko, S., Ro, K. and Berge, N., 2017. Hydrothermal carbonization of food waste for nutrient recovery and. *Waste Management* 69, 480-491. https://doi.org/10.1016/j.wasman.2017.08.051

Ingelia, n.d. Products, Ingelia company website. Available from: https://ingelia.com/index.php/sostenibilidad-medioambiental/?lang=en

Insam, H., Gómez-Brandón, M. and Ascher, J., 2015. Manure-based biogas fermentation residues– Friend or foe of soil fertility? *Soil Biology and Biochemistry* 84, 1-14. https://doi.org/10.1016/j.soilbio.2015.02.006

IPEN, 2005. After Incineration: The Toxic Ash Problem. Prague-Manchester. Available from: https://ipen.org/sites/default/files/documents/After_incineration_the_toxic_ash_problem_2015.pdf

Jandl, G., Eckhardt, K.U., Bargmann, I., Kucke, M., Greef, J.M., Knicker, H. and Leinweber, P., 2012. Hydrothermal carbonization of biomass residues: mass spectrometric characterization for ecoological effects in the soil-plant system. *Journal of Environmental Quality* 42, 199-207. doi:10.2134/jeq2012.0155

Jorgensen, S.E., Libor, O., Graber, K.L. and Barkacs, K., 1976. Ammonia removal by use of clinoptilolite. *Water Research*, 10(3), 213-224. https://doi.org/10.1016/0043-1354(76)90130-5

Kadlec, R.H., Knight, R.L., Vymazal, J., Brix, H., Cooper, P. and Haberl, R., 2000. Constructed wetlands for pollution control. IWA scientific and technical report 8. Available at: http://www.oapen.org/viewer/web/viewer.html?file=http://www.oapen.org/document/640696

Kalmykova, Y. and Fedje, K., 2013. Phosphorus recovery from municipal solid waste incineration fly ash. *Waste Management* 33(6), 1403-1410. https://doi.org/10.1016/j.wasman.2013.01.040

Krylova, A.Y. and Zaitchenko, V.M., 2018. Hydrothermal Carbonization of Biomass: A Review. *Solid Fuel Chemistry* 52(2), 91-103. https://doi.org/10.3103/S0361521918020076

Lebuf, V., Accoe, F., Van Elsacker, S., Vaneeckhaute, C., Michels, E., Meers, E., Ghekiere, G. and Ryckaert, B., 2013. Techniques for nutrient recovery from digestate: inventory. Available from: https://biblio.ugent.be/publication/7010573

Li, X., Rubæk, G.H., Müller-Stöver, D.S., Thomsen, T.P., Ahrenfeldt, J. and Sørensen, P., 2017. Plant availability of Phosphorus in Five gasification Biochars. *Frontiers in Sustainable Food Systems* 1 (2), 1-12. https://doi.org/10.3389/fsufs.2017.00002

Liang, C., Das, K.C. and McClendon, R.W., 2003. The influence of temperature and moisture contents regimes on the aerobic microbial activity of a biosolids composting blend. *Bioresource Technology* 86(2), 131-137. https://doi.org/10.1016/S0960-8524(02)00153-0

Lim, X., 2016. Uphill climb for biogas in Asia. Chemical and Engineering News. Available from: https://cen.acs.org/content/cen/articles/94/i19/Uphill-climb-biogas-Asia.html

Lin, L., Wan, C., Lee, D.J., Lei, Z. and Liu, X., 2014. Ammonium assists orthophosphate removal from high-strength wastewaters by natural zeolite. *Separation and Purification Technology* 133, 351-356. https://doi.org/10.1016/j.seppur.2014.07.010

Liu, M., Duan, Y., Bikane, K. and Zhao, L., 2018. The Migration and Transformation of Heavy Metals in Sewage Sludge during Hydrothermal Carbonization Combined with Combustion. *BioMed Research International*, *2018*. https://doi.org/10.1155/2018/1913848

Malaeb, L. and Ayoub, G.M., 2011. Reverse osmosis technology for water treatment: state of the art review. *Desalination* 267(1), 1-8. https://doi.org/10.1016/j.desal.2010.09.001

Mandal, S., Kunhikrishnan, A., Bolan, N.S., Wijesekara, H. and Naidu, R., 2016. Chapter 4-Application of Biochar Produced From Biowaste Materials for Environmental Protection and Sustainable Agriculture Production. In *Environmental Materials and Waste*. Academic Press, pp. 73-89. https://doi.org/10.1016/B978-0-12-803837-6.00004-4

Manning, D.A., 2010. Mineral sources of potassium for plant nutrition. A review. *Agronomy for Sustainable Development* 30(2), 281-294. https://doi.org/10.1051/agro/2009023

Meers, E., Tack, F.M.G., Tolpe, I. and Michels, E., 2008. Application of a Full-scale Constructed Wetland for Tertiary Treatment of Piggery Manure: Monitoring Results. *Water Air Soil Pollution* 193, 15-24. https://doi.org/10.1007/s11270-008-9664-5

Mehta, C.M., Khunjar, W.O., Nguyen, V., Tait, S. and Batstone, D.J., 2015. Technologies to recover nutrients from waste streams: a critical review. *Critical Reviews in Environmental Science and Technology* 45(4), 385-427. https://doi.org/10.1080/10643389.2013.866621

Møller, H.B., Lund, I. and Sommer, S.G., 2000. Solid–liquid separation of livestock slurry: efficiency and cost. *Bioresource technology* 74 (3), 223-229. https://doi.org/10.1016/S0960-8524(00)00016-XMöller, K. and Schultheiß, U., 2014. Organische Handelsdüngemittel im ökologischen Landbau. KTBL-Schrift, 499.Møller, H.B., Lund, I. and Sommer, S.G., 2000. Solid–liquid separation of livestock slurry: efficiency and cost. *Bioresource technology* 74 (3), 223-229. https://doi.org/10.1016/S0960-8524(00)00016-X

Morris, M. and Waldheim, L., 1998. Energy recovery from solid waste fuels using advanced gasification technology. *Waste Management* 18(6-8), 557-564. https://doi.org/10.1016/S0956-053X(98)00146-9

Mumpton, F., 1999. La roca mágica: Uses of natural zeolites in agriculture and industry. *Proceedings of the National Academy of Science USA,* 3463-3470. https://doi.org/10.1073/pnas.96.7.3463

Norddahl, B., Horn, V.G., Larsson, M., Du Preez, J.H. and Christensen, K., 2006. A membrane contactor for ammonia stripping, pilot scale experience and modeling. *Desalination* 199(1), 172-174. doi:10.1016/j.desal.2006.03.037

Nkoa, R., 2014. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review. *Agronomy for Sustainable Development* 34(2), 473-492. doi: 10.1007/s13593-013-0196-z

Outotec, n.d. Outotec Sludge Incineration Plant. Company website. Available from: https://www.outotec.com/products/energy-production/sludge-incineration-plant/

Pace, M., Miller, B. and Farrell-Poe, K., 1995. The composting process. Available from: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1047&context=extension_histall

Patil, A., Kulkarni, A. and Patil, B., 2014. Waste to Energy by Incineration. *Journal of Computing Technologies* 3 (6), 2278-3814.

Polat, E., Karaca, M., Demir, H. and Onus, A.N., 2004. Use of natural zeolite (clinoptilolite) in agriculture. *Journal of Fruit and Ornamental Plant Research* 12(1), 183-189.

Popovic, O., Gioelli, F., Dinuccio, E., Rollè, L. and Balsari, P., 2017. Centrifugation of Digestate: The Effect of Chitosan on Separation Efficiency. *Sustainability* 9(12), 2302. https://doi.org/10.3390/su9122302

P-REX, 2015a. Ashdec®: Thermo-chemical ash treatment – Factsheet.

P-REX, 2015b. Struvia™: Struvite crystallisation in sludge liquor - Technical Factsheet.

P-REX, 2015c. Deliverable D4.1. Technical comparison on the design, operation and performances of ash processes.

Ptasinski, K.J., 2008. Thermodynamic efficiency of biomass gasification and biofuels conversion. *Biofuels, Bioproducts and Biorefining* 2(3), 239-253. https://doi.org/10.1002/bbb.65

Puccini, M., Stefanelli, E., Hiltz, M., Seggiani, M. and Vitolo, S., 2017. Activated carbon from hydrochar produced by hydrothermal carbonization of wastes. *Chemical Engineering Transactions* 57, 169-174. DOI: 10.3303/CET1757029

Pulz, O. and Gross, W., 2004. Valuable products from biotechnology of microalgae. *Applied Microbiology and Biotechnology* 65(6), 635-648. https://doi.org/10.1007/s00253-004-1647-x

Quan, X., Wang, F., Zhao, Q., Zhao, T. and Xiang, J., 2009. Air stripping of ammonia in a water-sparged aerocyclone reactor. *Journal of Hazardous Materials* 170(2-3), 983-988. https://doi.org/10.1016/j.jhazmat.2009.05.083

SABANA, n.d. Project website. Available from: http://www.eu-sabana.eu/

Schröder, J.J., De Visser, W., Assinck, F.B.T., Velthof, G.L., Van Geel, W. and Van Dijk, W., 2014. Nitrogen Fertilizer Replacement Value of the Liquid Fraction of Separated Livestock Slurries Applied to Potatoes and Silage Maize. *Communications in Soil Science and Plant Analysis* 45, 73-85. https://doi.org/10.1080/00103624.2013.848881

Sengupta, S., Nawaz, T. and Beaudry, J., 2015. Nitrogen and Phosphorus Recovery from Wastewater. *Current Pollution Reports* 1(3), 155-166. https://doi.org/10.1007/s40726-015-0013-1

Sharma, H., 2017. Life-Cycle Assessment of different technologies to process sewage sludge. Master thesis, Delft Univeristy of Technology, Delft, the Netherlands, pp. 123.

Sigurnjak, I., 2017. Animal manure derivatives as alternatives for synthetic nitrogen fertilizers. PhD thesis, Faculty of Bioscience Engineering, Ghent University, Ghent, Belgium, pp. 165.

Sigurnjak, I., Vaneeckhaute, C., Michels, E., Ryckaert, B., Ghekiere, G., Tack, F.M.G. and Meers, E., 2017b. Fertilizer performance of liquid fraction of digestate as synthetic nitrogen substitute in silage maize cultivation for three consecutive years. *Science of The Total Environment* 599, 1885-1894. https://doi.org/10.1016/j.scitotenv.2017.05.120

Sigurnjak, I., Brienza, C., Snauwaert, E., De Dobbelaere, A., De Mey, J., Vaneeckhaute, C., Michels, E., Schoumans, O., Adani, F. and Meers, E., 2019. Production and performance of bio-based mineral fertilizers from agricultural waste using ammonia (stripping-)scrubbing technology. *Waste Management* 89, 265-274. https://doi.org/10.1016/j.wasman.2019.03.043

Sivakumar, G., Xu, J., Thompson, R.W., Yang, Y., Randol-Smith, P. and Weathers, P.J., 2012. Integrated green algal technology for bioremediation and biofuel. *Bioresource Technology* 107, 1-9. https://doi.org/10.1016/j.biortech.2011.12.091

Smet, E., Debruyne, J., Deckx, J. and Deboosere, S., 2003. Manure treatment according to the Trevi-concept. *Communications in agricultural and applied biological sciences*, *68* (2; PART A), 125-132

Soil-Concept, n.d. Company website. Available at: https://www.soil-concept.lu/

Stenmarck, Â., Jensen, C., Quested, T., Moates, G., Buksti, M., Cseh, B., Juul, S., Parry, A., Politano, A., Redlingshofer, B. and Scherhaufer, S., 2016. Estimates of European food waste levels. IVL Swedish Environmental Research Institute. Available from: https://library.wur.nl/WebQuery/wurpubs/501451

Stiles, W.A., Styles, D., Chapman, S.P., Esteves, S., Bywater, A., Melville, L., Silkina, A., Lupatsch, I., Grünewald, C.F., Lovitt, R. and Chaloner, T., 2018. Using microalgae in the circular economy to valorise anaerobic digestate: challenges and opportunities. *Bioresource Technology* 267, 732-742. https://doi.org/10.1016/j.biortech.2018.07.100

Sydney, E.B., Larroche, C., Novak, A.C., Nouaille, R., Sarma, S.J., Brar, S.K., Letti, L.A.J., Soccol, V.T. and Soccol, C.R., 2014. Economic process to produce biohydrogen and volatile fatty acids by a mixed culture using vinasse from sugarcane ethanol industry as nutrient source. *Bioresource Technology* 159, pp.380-386. https://doi.org/10.1016/j.biortech.2014.02.042

Systemic project, 2018a. Systemic Factsheets. Available from: https://systemicproject.eu/wp-content/uploads/2018/07/D1.6_Update_Factsheets_Demo_Plants.pdf

Systemic project, 2018b. Product factsheets. Available from: https://systemicproject.eu/downloads/ #toggle-id-3

Tambone, F., Genevini, P., D'Imporzano, G. and Adani, F., 2009. Assessing amendment properties of digestate by studying the organic matter composition and the degree of biological stability during the anaerobic digestion of the organic fraction of MSW. *Bioresource Technology*, *100*(12), 3140-3142. https://doi.org/10.1016/j.biortech.2009.02.012

Tampio, E., Salo, T. and Rintala, J., 2016. Agronomic characteristics of five different urban waste digestates. *Journal of Environmental Management* 169, 293-302. https://doi.org/10.1016/ j.jenvman.2016.01.001

Tchobanoglous, G. and Burton, F.L., 1991. Wastewater engineering treatment, disposal and reuse. McGraw-Hill, Inc.

Terra Humana, n.d. 3RAgrocarbon. Company website. Available from: https://www.3ragrocarbon.com/

Thomsen, T.P., Ravenni, G., Holm, J.K., Ahrenfeldt, J., Hauggaard-Nielsen, H. and Henriksen, U.B., 2015. Screening of various low-grade biomass materials for low temperature gasification: method development and application. *Biomass and Bioenergy* 79, 128-144. https://doi.org/10.1016/ j.biombioe.2014.12.019

Tian, W., Wen, X., and Qian, Y., 2004. Using a zeolite medium biofilter to remove organic pollutant and ammonia simultaneously. *Journal of Environmental Sciences,* 16(1), 90-93.

Tiquia, S.M., Tam, N.F.Y. and Hodgkiss, I.J., 1996. Microbial activities during composting of spent pig-manure sawdust litter at different moisture contents. *Bioresource Technology* 55(3), 201-206. https://doi.org/10.1016/0960-8524(95)00195-6

Tronina, P. and Bubel, F., 2008. Food industry waste composting in a rotational reactor. *Polish Journal of Chemical Technology* 10(2), 37-42. doi:10.2478/v10026-008-0026-2

Tyagi, V.K. and Lo, S.L., 2016. Energy and Resource Recovery From Sludge: Full-Scale Experiences. In *Environmental Materials and Waste,* 221-244. https://doi.org/10.1016/B978-0-12-803837-6.00010-X

Udovic, M. and McBride, M. B., 2012. Influence of compost addition on lead and arsenic bioavailability in reclaimed orchard soil assessed using Porcellio scaber bioaccumulation test. *Journal of Hazardous Materials* 205, 144-149. https://doi.org/10.1016/j.jhazmat.2011.12.049

Vaneeckhaute, C., Meers, E., Michels, E., Christiaens, P. and Tack, F.M.G., 2012. Fate of macronutrients in water treatment of digestate using vibrating reversed osmosis. *Water, Air, & Soil Pollution* 223(4), 1593-1603. https://doi.org/10.1007/s11270-011-0967-6

Vaneeckhaute, C., Meers, E., Michels, E., Ghekiere, G., Accoe, F., and Tack, F.M.G., 2013. Closing the nutrient cycle by using bio-digestion waste derivatives as synthetic fertilizer substitutes: A field experiment. *Biomass and Bioenergy* 55, pp.175-189.

VCM, n.d. Biological treatment. Company website. Available from: https://www.vcm-mestverwerking.be/en/ manureprocessing/10605/biological-treatment

Velthof, G., 2011. Synthese van het onderzoek in het kader van de Pilot Mineralenconcentraten Alterra Report 2211. Wageningen, the Netherlands.

Velthof, G.L., 2015. Mineral concentrate from processed manure as fertiliser. Alterra Wageningen UR, pp. 1-16.

Vermeulen Construct, n.d. VEDOWS. Company website. Available from: https://www.vermeulenconstruct.be/en/animal-stall-equipment/vedows/

VLACO, 2012. Karakterisatie eindproducten van biologische verwerking. Juni 2012.

Wang, T., Zhai, Y., Zhu, Y., Li, C. and Zeng, G., 2018. A review of the hydrothermal carbonization of biomass waste for hydrochar formation: Process conditions, fundamentals, and physicochemical properties. *Renewable and Sustainable Energy Reviews* 90, 223-247. https://doi.org/10.1016/j.rser.2018.03.071

Wu, L.J., Kobayashi, T., Kuramochi, H., Li, Y.Y. and Xu, K.Q., 2016. Improved biogas production from food waste by co-digestion with de-oiled grease trap waste. *Bioresource Technology* 201, 237-244. https://doi.org/10.1016/j.biortech.2015.11.061

Yoon, S.H., 2006. Classification of membranes according to pore size. *Membrane Bioreactor Processes: Principles and Applications*.

Zhu, N., 2006. Composting of high moisture content swine manure with corncob in a pilot-scale aerated static bin system. *Bioresource Technology* 97(15), 1870-1875. https://doi.org/10.1016/j.biortech.2005.08.011