IMPLEMENTING NUTRIENT RECOVERY FROM BIOMASS GASIFICATION FACILITY

Date of publication : 30 June, 2020

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Partners:

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List of abbreviations

FB	Fluidized bed
Na_2SO_4	Sodium sulfate
K_2SO_4	Potassium sulfate
SiO_2	Silicon dioxide
Al_2O_3	Aluminium oxide
Pnac	P fraction soluble in neutral ammonium citrate
NAC	Neutral ammonium citrate

1. Introduction

Soil-Concept has been an important industry partner for the recycling of sewage sludge and green waste in Luxembourg since 1996. In close co-operation with the intercommunal syndicates SIDEN, SIDERO and SIACH and on behalf of many municipalities, Soil-Concept has been working successfully in the field of waste recycling for more than 20 years.

At the depot in Fridhaff, Soil Concept has eight stationary red silos, a composting plant, two screening plants and a mobile shredder plant for green waste and green waste-sludge mixtures. Furthermore, three large wheel loaders are in the machine park.

The company has about 12 employees and provides its services mainly for public, commercial and private customers.

The ever tightening of the fertilizer ordinance and the designation of nature reserves have made it more difficult to spread the sewage sludge compost. In order to be able to continue to use sewage sludge, a new poly-generation plant was built. Here, sewage sludge and sewage sludge compost is to be thermally recycled. The energy generated can be converted into electricity or used in the form of heat at the depot via a heat pipe.

Another positive aspect of gasification is the utilization of ashes. The bed ash can be used as fertilizer and the fly ash as a cement substitute. In ReNu2Farm, the AshDec®-process applied by the project partner Outotec should be transferred to the gasification plant. The results can be found in this project report.

Outotec is a Finnish company headed in Espoo (FI) which provides technologies and services in the metals and mining industry. It offers solutions for the whole value-chain from the ore to the metal, ranging from pre-feasibility studies to complete plants with life-cycle services. With over a century of experience of technology development at inhouse R&D centers, an extensive range of solutions for processing all types of ores and concentrates to refined metals have been developed. Besides the strong focus on metallurgical processes, Outotec also offers solutions for the rock phosphate industry and for sewage sludge ash phosphorous recovery using its metallurgical know-how.

Outotec has developed the AshDec®-process to produce a calcined phosphate fertilizer from sewage sludge ash by thermal treatment. The goal is to remove the heavy metals from the feed material and to convert the present insoluble phosphate species created in the incineration step to highly plant-available calcium (Ca)-sodium (Na) / potassium (K) phosphates. In the process, the sludge is mixed with Na / K containing species and dried sewage sludge as a reduction additive, and thermally treated at high temperatures in a rotary kiln. The heavy metals are vaporized under reducing conditions to the gas phase and are condensed after cooling of the off-gas in the filter system to be disposed with the filter dust.

The primary goal of the investigation is to adapt the present process to the fluidized bed technology and to produce a phosphate fertilizer from sewage sludge in one process step. Soil-Concept (LU) installed a gasifying plant on their site on a demo plant scale at Diekirch, LU, for fertilizer production and using the heat from the process as district heating for the surrounding industrial area.

The target was to find suitable process conditions to operate the gasifier to achieve a fertilizer similar to the AshDec® product. For this purpose, small scale tests were performed at the Frankfurt Research Center of Outotec in a 50 mm fluidized bed reactor. After a parameter window would be identified, the demo plant would be operated accordingly to produce fertilizer samples which are tested by the project partners in pot and field trials.

2. 50 mm Fluidized Bed (FB) Reactor tests (Outotec)

2.1. Raw material characterization

2.1.1. Moisture and particle size distribution

In Table 1 raw material samples received by Outotec from Soil-Concept are listed. Both samples are sewage sludge/green cutting mixtures with a ratio of 50:50 wt.-%. They were dried to a moisture < 1 % and cut to a particle size < 1 mm to allow steady dosing in the tests.

Table 1. *Raw materials used in the 50 mm FB reactor tests.*

Material receiving no.	Date received	Particle size distribution as received	Moisture as received	Ash content
17/18	11.02.2018	d_{20}: 2.4 mm[1] d_{50}: 8.1 mm d_{80}: 15.1 mm	41.5 %	45.1 %
92/18	03.05.2018	10 to 40 mm	41.1%	41.1 %

2.1.2. Muffle furnace tests

The raw material was treated in a muffle furnace to observe the tendency for sintering at elevated temperatures. As can be seen in Figure 1, loose agglomerates are formed above 900 °C, however, on application of gentle mechanical force, they fall apart.

[1] *Mass-median-diameter of particles*

Figure 1. *Sample after heat treatment in the muffle furnace at different temperatures*

2.1.3. Additional material

Quartz sand, alumina and ash were used as auxiliary bed in the fluidized bed reactor. In the beginning, quartz sand with a particle size > 315 µm was used and the product was screened as the fine fraction. As it revealed that the fluidization was not sufficient, it was decided to take the fraction < 125 µm of the sand as auxiliary bed and screen the product at 125 µm from the reactor discharge as the coarse fraction. For some tests, pure ash produced from the feed material in the muffle furnace was used as start-up bed.

Similar to the AshDec®-process, sodium sulphate (Na_2SO_4) and potassium sulphate (K_2SO_4) were used as additives in the tests.

2.2. Test set-up and procedure

A quartz glass reactor is placed in an electrical heated oven (Figure 2) and an auxiliary bed material is inserted in the reactor. A gas mixture is supplied underneath a sinter plate inside the reactor which acts as a gas distributor and fluidizes the auxiliary bed. The bed temperature is measured with a submerged thermocouple. Once the auxiliary bed has reached the target temperature, a constant mass flow of sample material is dosed into the auxiliary bed by a pneumatical conveying system. By setting the mass flow rate of the feed material and the volumetric flow rate of air and nitrogen, oxidizing (combustion) or reducing (gasification) conditions can be adjusted. The off-gas is analyzed for the gas composition. After the intended retention time has elapsed, the reactor is pulled out of the oven and its walls are cooled with an air jet from the outside. Once cooled to room temperature, the reactor content is discharged. The reactor content is weighed and screened to separate the product material from the auxiliary bed. A sample is taken from the product material for analyses.

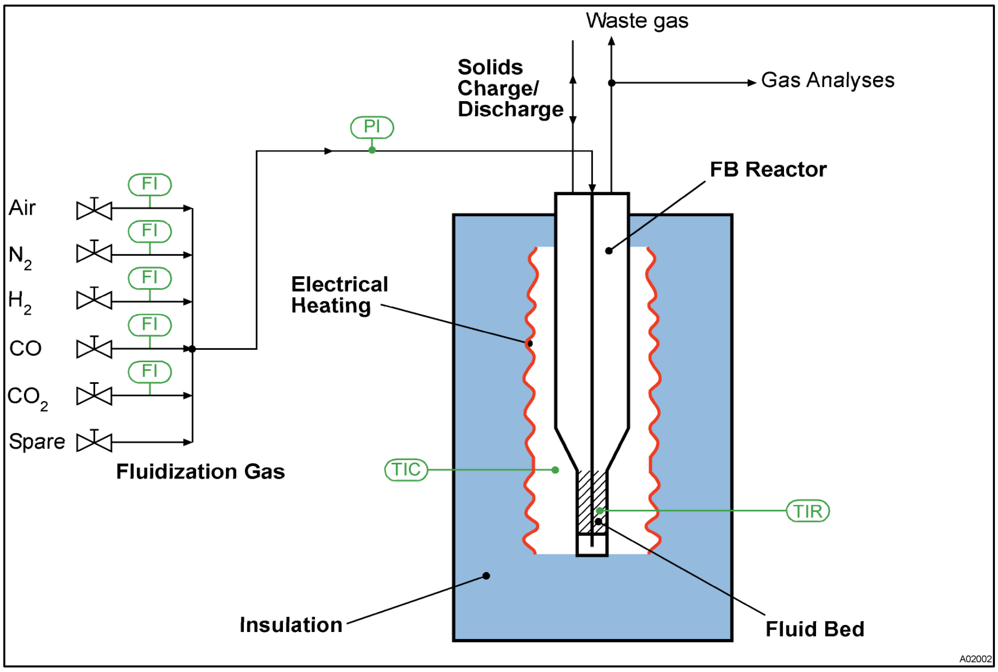


Figure 2. *Diagrammatic representation of the 50 mm Fluidized Bed reactor set-up*

2.3. Test parameters

In Table 2, the test conditions are given. Similar to the AshDec®-process, Na_2SO_4 and K_2SO_4 were used as additives. During continuous dosing of the feed material, a proportional amount of additives was manually dosed to the reactor.

Table 2. *Test parameter range and additional materials.*

Parameter	Conditions required
Temperature range	850 - 950 °C
Combustion gas ratio	0.4 / 1.1 (reducing / oxidizing atmosphere)
Additives	Na_2SO_4, K_2SO_4
Retention time	60 min
Feed amount	200 g continuously
Auxiliary bed material	80 g at start: Quartz sand, Alumina, Ash

In Table 3, the parameter settings for each test are listed. Not all tests were evaluated when agglomerates were formed which completely stopped fluidization.

Table 3. *Test parameters for 50 mm FB reactor tests.*

Test No.	Feed material	Temperature °C	Comb. Gas ratio	Aux. bed	Additive	Mixture ratio
1	17/18	900	1.1	SiO_2 > 315 µm	-	-
3.1	17/18	900	1.1	SiO_2 > 315 µm	-	-
3.2	17/18	1000	1.1	SiO_2 > 315 µm	-	-
2	17/18	900	0.4	SiO_2 > 315 µm	-	-
2.1	17/18	900	0.4	SiO_2 > 315 µm	-	-
1.1	17/18	900	1.1	SiO_2 < 125 µm	-	-
3.3	17/18	950	1.1	SiO_2 < 125 µm	-	-
4	17/18	950	0.4	SiO_2 < 125 µm	-	-
2.2	17/18	900	0.4	SiO_2 < 125 µm	-	-
5	17/18	900	0.4	SiO_2 < 125 µm	Na_2SO_4	1:15
5.1	17/18	850	0.4	SiO_2 < 125 µm	Na_2SO_4	1:5
5.2	17/18	800	0.4	SiO_2 < 125 µm	Na_2SO_4	1:5
10	17/18	800	1.1	SiO_2 < 125 µm	-	-
1B	17/18	950	1.1	SiO_2 < 125 µm	K_2SO_4	1:11
2B	17/18	950	0.4	SiO_2 < 125 µm	K_2SO_4	1:11
3B	17/18	1000	1.1	SiO_2 < 125 µm	K_2SO_4	1:11
4B	17/18	1000	0.4	SiO_2 < 125 µm	K_2SO_4	1:11
5B	17/18	800	0.4	SiO_2 < 125 µm	K_2SO_4/Na_2SO_4 3:1	1:11
6B	17/18	850	0.4	SiO_2 < 125 µm	K_2SO_4/Na_2SO_4 3:1	1:11
1C	92/18	950	0.4	Alumina < 125 µm	Na_2SO_4	1:11
2C	92/18	1000	0.4	Alumina < 125 µm	K_2SO_4	1:11
3C	92/18	950	0.4	Ash	Na_2SO_4	1:11
4C	92/18	1000	0.4	Ash	K_2SO_4	1:11
5C	92/18	950	0.4	SiO2 < 125 µm	Na_2SO_4	1:11
6C	92/18	1000	0.4	SiO_2 < 125 µm	K_2SO_4	1:11

2.4. Results

Figure 3 shows a picture of the reactor discharge after cooling. The formation of agglomerates was observed in all tests with additive dosing. These agglomerates were very stable and had to be crushed to get samples for analyses. It is obvious that also a part of the auxiliary bed (Silicon dioxide (SiO_2), Aluminium oxide (Al_2O_3)) has been entrapped in the agglomerate and thus diluted the sample.

The screened samples were homogenized and analyzed at BAM (Federal Institute for Materials Research and Testing) with the ICP-OES using aqua regia digestion; silicon was not completely dissolved and is not considered in the elemental analysis.

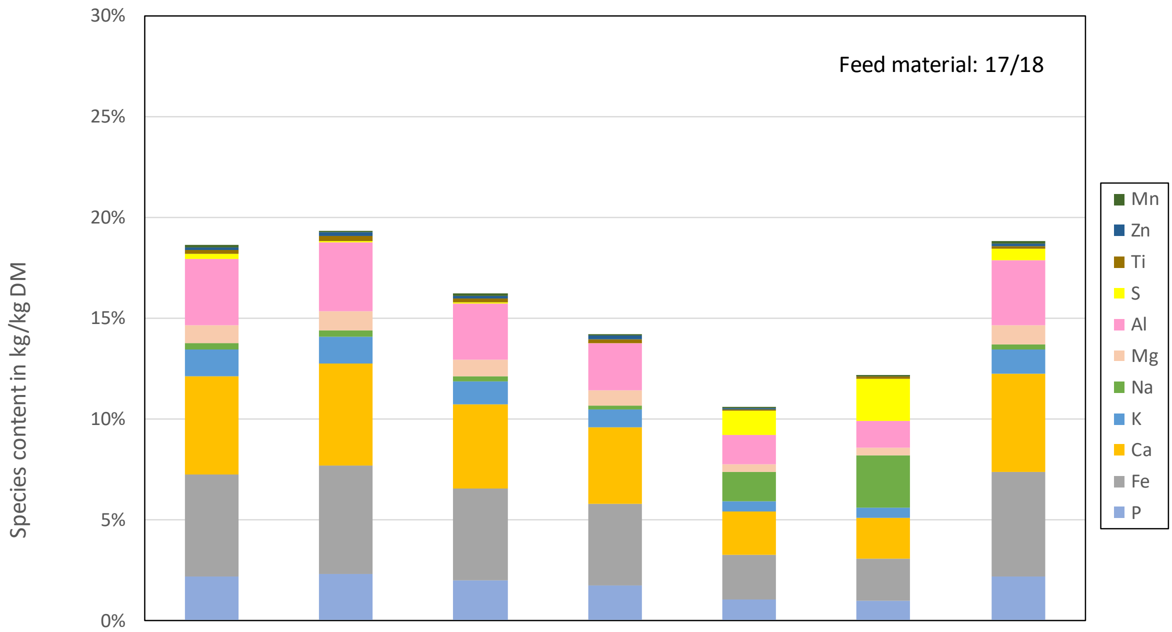
Figure 3. *Image of reactor discharge after test.*

2.5. Main elements

For the following diagrams, it must be considered that the elements carbon (C) and silicon (Si) are not displayed (Si not completely dissolved, C not measured). In the feed materials, C is a major component, which is combusted or gasified which leads to an increasing concentration of elements forming incombustible species in the remaining ash. As the target is to produce a phosphorus (P) fertilizer, the focus is on the P content, which is already comparatively low in the feed material due to mixture with green cuttings. As P containing species are incombustible and are not vaporized at the applied temperatures, the P concentration in the ash is higher than in the feed material. However, there are two dilution effects:

- Dilution with auxiliary bed material: If agglomerates are formed, they collect auxiliary bed material by sintering which cannot be separated by sieving.
- Dilution with additives: The dosing of additives has a dilution effect on the sample as well.

Figure 4 shows the elemental composition of the samples of test 1-10. At temperatures < 900°C without additive dosing (Tests 1.1, 2.2 and 10) the composition is quite similar. Notable is a comparatively low P content which is attributed to the mixture of sewage sludge with green cuttings, which does not contain considerable amounts of P. At temperatures of 950 °C without additives (Test 3.3 and 4) the content of all elements is reduced, which is a result of the dilution of the sample with auxiliary bed, which was collected in the formed agglomerates. This behavior is even more pronounced when dosing Na_2SO_4, as here massive agglomerates are formed. It is also visible that the dosing increased the amount of sulfur (S) and sodium (Na) in the sample.



Additive	-	-	-	-	Na2SO4	Na2SO4	-
Combustion air ratio	1.1	0.4	1.1	0.4	0.4	0.4	1.1
Temperature, °C	900	900	950	950	850	800	800
Aux. bed	SiO2	SiO2	SiO2	SiO2	SiO2	SiO2	SiO2
Test No.	1.1	2.2	3.3	4	5.1	5.2	10

Figure 4. *Main elemental composition of reactor discharge samples with additive Na_2SO_4 (Tests 1 – 10).*

Figure 5 shows the elemental composition of the samples with K_2SO_4 and K_2SO_4 / Na_2SO_4 additive dosing. In these tests, the bed temperature was adjusted to higher values as the melting point of K_2SO_4 (1069 °C) is higher compared to Na_2SO_4 (888 °C). As the melting point was not reached in the bed, the formation of agglomerates was less pronounced like in the experiments with pure Na_2SO_4 dosing. A comparison with the feed material shows a total percentual increase of the measured elements as the organic part (not measured) is combusted/gasified while the potassium (K) content is raised due the additive dosing. However, due to the dilution with the additive, the effect of concentrating P in the ash is counteracted.

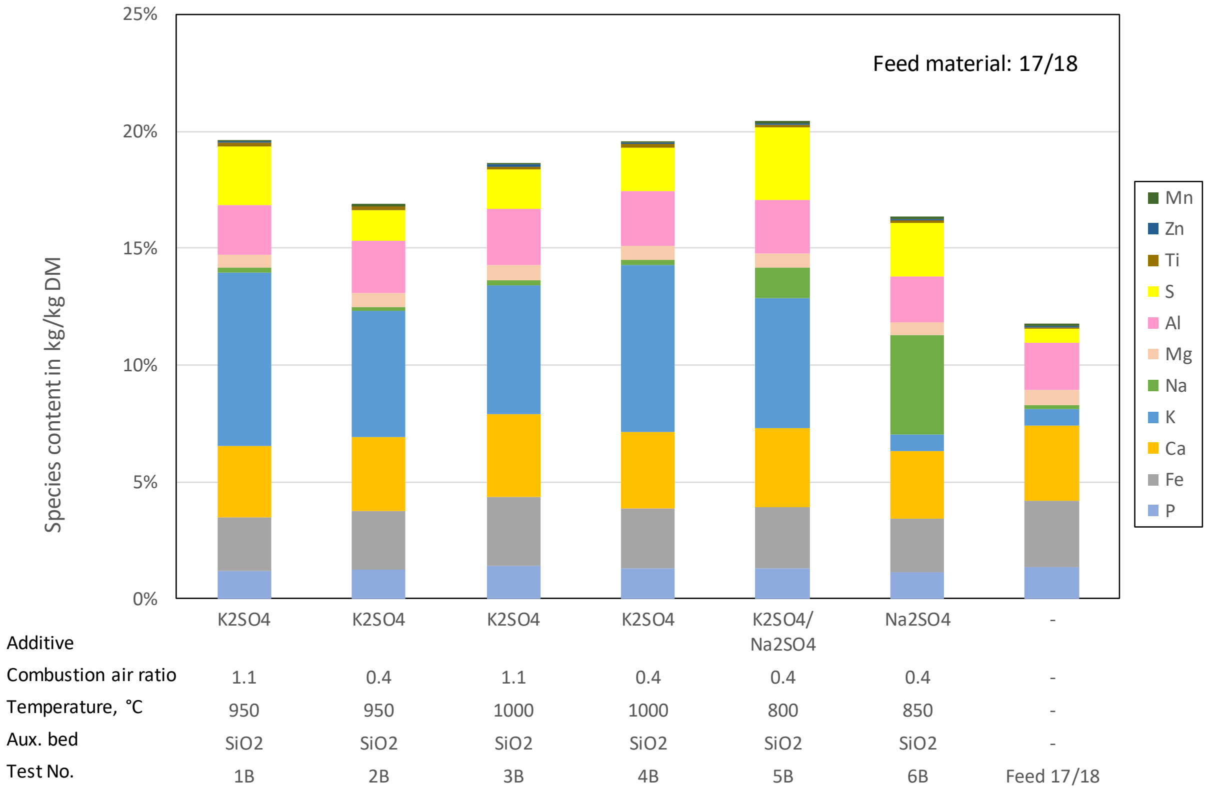


Figure 5. *Main element composition of reactor discharge samples with additives K_2SO_4, K_2SO_4 / Na_2SO_4 mixture (Tests 1B – 6B, Feed material 17/18).*

Figure 6 shows the main elemental composition of the samples with varying auxiliary bed materials. This variation was done to observe the effect on the plant P availability, as it was uncertain if the auxiliary bed consumed a part of the additive which would then be unavailable for the desired reactions to increase the plant P availability. Besides quartz sand, alumina and ash from the feed material produced in a muffle furnace was used. The feed material was 92/18.

It can be clearly seen for the samples 1C and 2C, that the bed material Al_2O_3 has been carried over to the sample due to agglomeration, increasing the amount of Al. For tests 3C and 4C, ash which produced in the muffle furnace was used as start bed, thus no dilution with bed material occurred. Hence, the higher P concentrations were observed in tests 1C and 2C. Tests 5C and 6C were conducted using SiO_2 as auxiliary bed. As in the previous tests, the dilution with Si is apparent in the reduction of the concentrations of all other displayed elements, more pronounced for tests 5C with Na_2SO_4 as additive. As additives were dosed in all tests, the dilution effect must be considered as well.

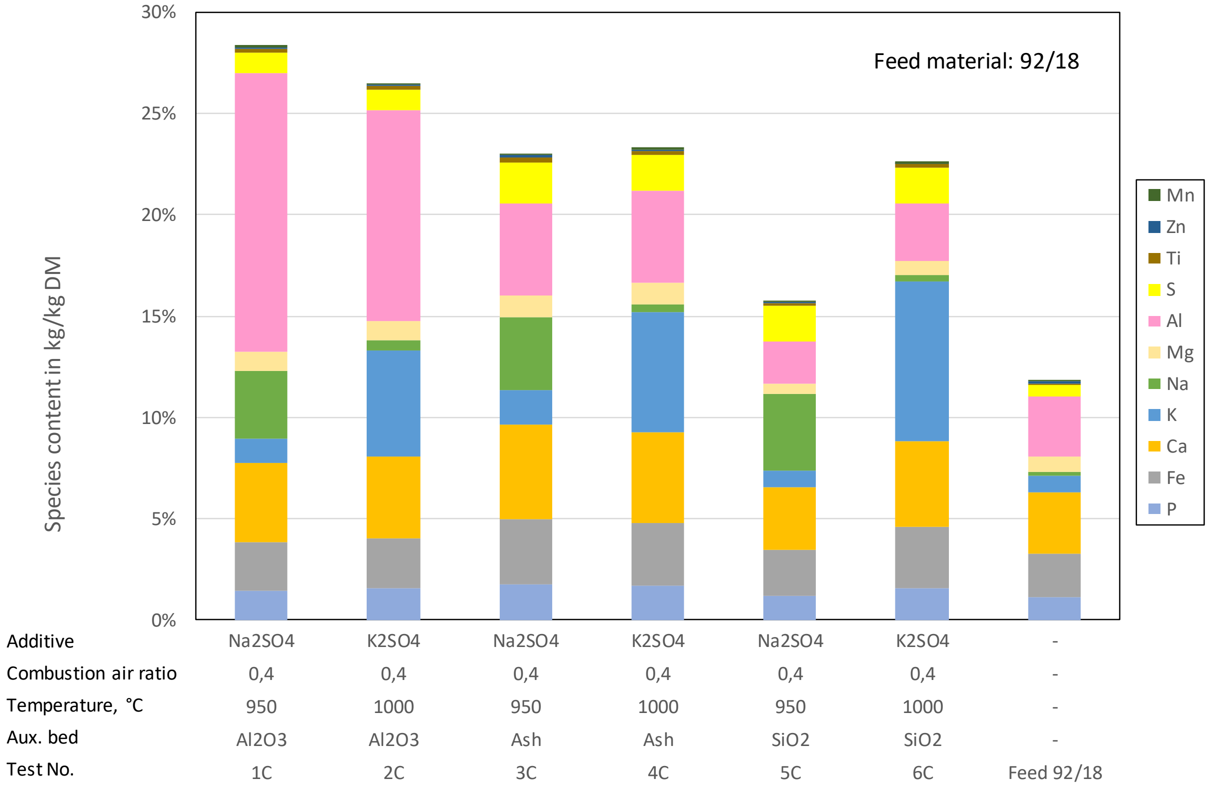


Figure 6. *Main element composition of reactor discharge samples with additives K_2SO_4 and Na_2SO_4 (Tests 1C – 6B, Feed material 92/18).*

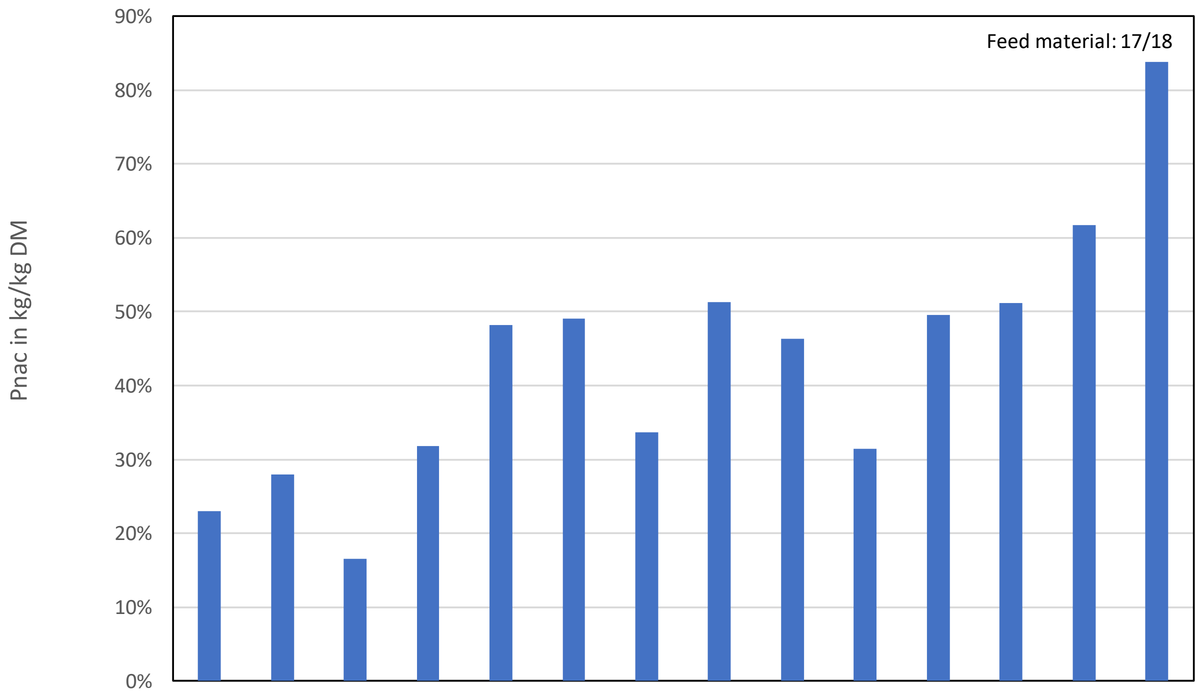
2.5.1. Plant P-availability

The plant P availability was assessed by determining the amount of P dissolved in neutral ammonium citrate (NAC) (Pnac) solution relative to the total P content in the sample (aqua regia digestion). Figure shows the Pnac values of test with feed material 17/18. It is clearly visible, that the Pnac values are poor without additive dosing (Tests 1.1 … 4; 10), meaning that only about 30 % of the total phosphate can be used by the plants as a nutrient. The untreated feed material has a plant P availability of about 90 %, which is a value that the AshDec®-process using a rotary kiln would typically provide. The dosing of the additives

Na_2SO_4 and K_2SO_4 resulted in an increase of P_{nac}, but the target range of >90% was never achieved, the best result being about 60 % in test 6B. One explanation is the inhomogeneous distribution of reactants due to the formation of agglomerates. As these agglomerates are not destroyed during the test, a proper mixing of the reactants is inhibited.

Another reason for the poor Pnac values could be the auxiliary bed, which could consume a part of the additives in competition to the desired reactions to form sodium or potassium silicates. To rule this out, further experiments with different auxiliary/start bed material were conducted. The results of these tests are shown in Figure 8. Besides quartz sand, also Al_2O_3 and ash from the feed material was used as auxiliary bed. It is obvious that the auxiliary bed material had no influence on the plant P availability.

It was therefore concluded that the inhomogeneous mixture is the main reason for poor plant P availability. On the one hand, melting of the additives seems to be necessary to allow the desired reactions to occur, and on the other hand, the melt phase leads to massive agglomeration which disturbs the process. This questions if the fluidized bed technology is feasible for this process at all, as melting phases should always be avoided because they soon lead to blockages, which then requires a shut-down of the plant for cleaning.



Additive	-	-	-	-	Na2SO4	Na2SO4	-	K2SO4	K2SO4	K2SO4	K2SO4	K2SO4/ Na2SO4	Na2SO4	-
Combustion air ratio	1.1	0.4	1.1	0.4	0.4	0.4	1.1	1.1	0.4	1.1	0.4	0.4	0.4	-
Temperature, °C	900	900	950	950	850	800	800	950	950	1000	1000	800	850	-
Aux. bed	SiO2	SiO2	SiO2	SiO2	SiO2	SiO2	SiO2	SiO2	SiO2	SiO2	SiO2	SiO2	SiO2	-
Test No.	1.1	2.2	3.3	4	5.1	5.2	10	1B	2B	3B	4B	5B	6B	Feed

Figure 7. *Plant P availability of reactor discharge samples and feed material 17/18, measured as P fraction soluble in NAC.*

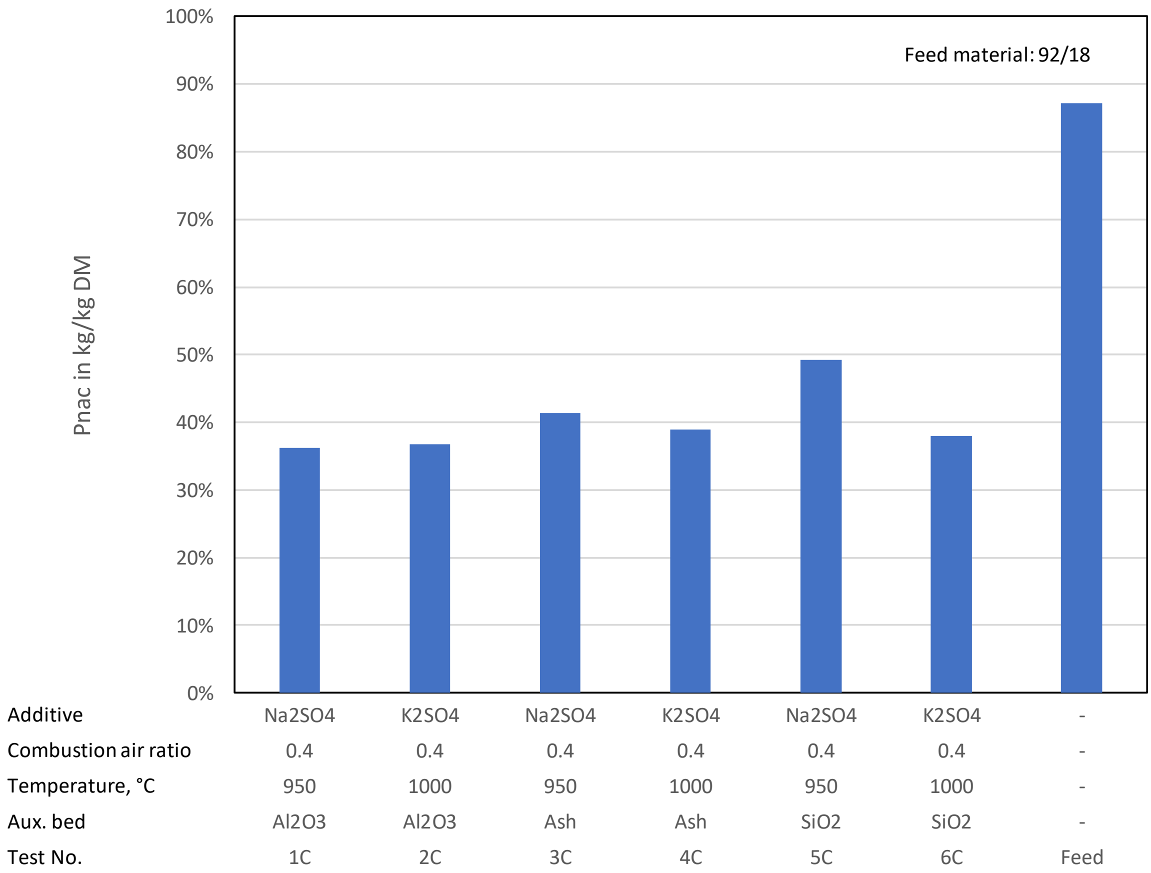


Figure 8. *Plant P availability of reactor discharge samples and feed material 92/18, measured as P fraction soluble in NAC*

2.5.2. Heavy metals

Another target of the treatment of sewage sludge is to reduce the amount of heavy metals in the product. This is done by transforming the heavy metal elements in gaseous state, which after leaving the reactor are condensed in the filter section and are discharged with the filter dust. The additives shall facilitate the release of heavy metals which are dissolved in the matrix of the ash minerals. The following diagrams display the element concentration related to the P content to avoid displaying the dilution effect from the additive / auxiliary bed and the concentration effect by gasification/combustion of combustible species.

Figure 9 and 10 show the concentration of Zinc (Zn) in the product compared with the feed material 17/18. It appears that reducing conditions without additive do not have a positive effect on the volatilization of Zn. The application of a reducing atmosphere in combination with an additive at high temperatures show the highest reduction of Zn in the product. The best result was a reduction compared to the feed material of -54 % with K_2SO_4 at 950 °C and reducing conditions. However, the large deviations of the results can be ascribed to the poor mixture of additives in the bed.

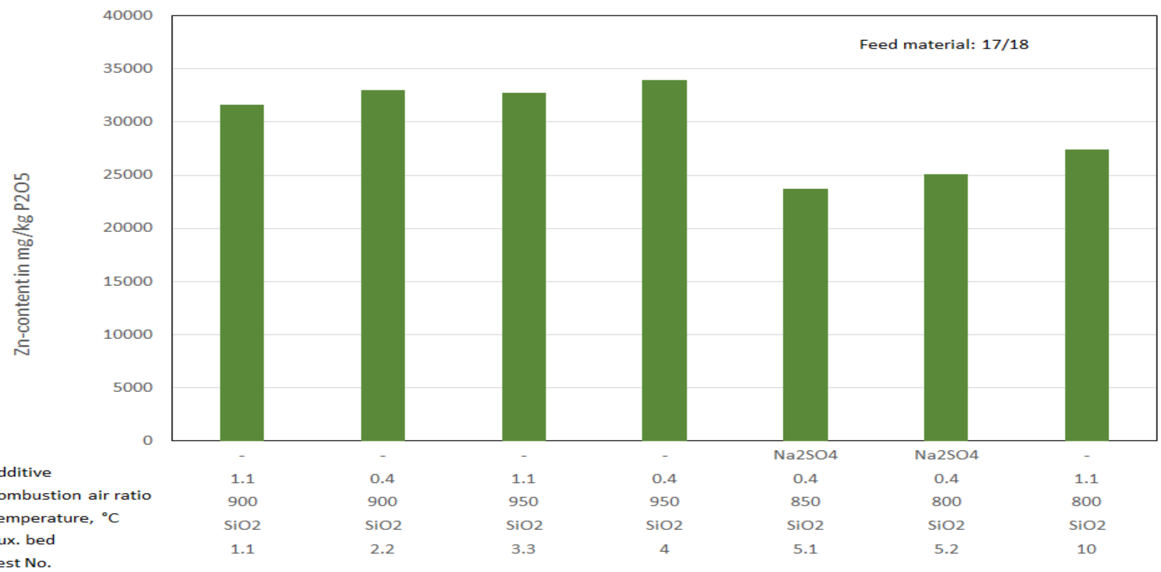


Figure 9. *Zn concentration relative to the P content of reactor discharge samples, first test series*

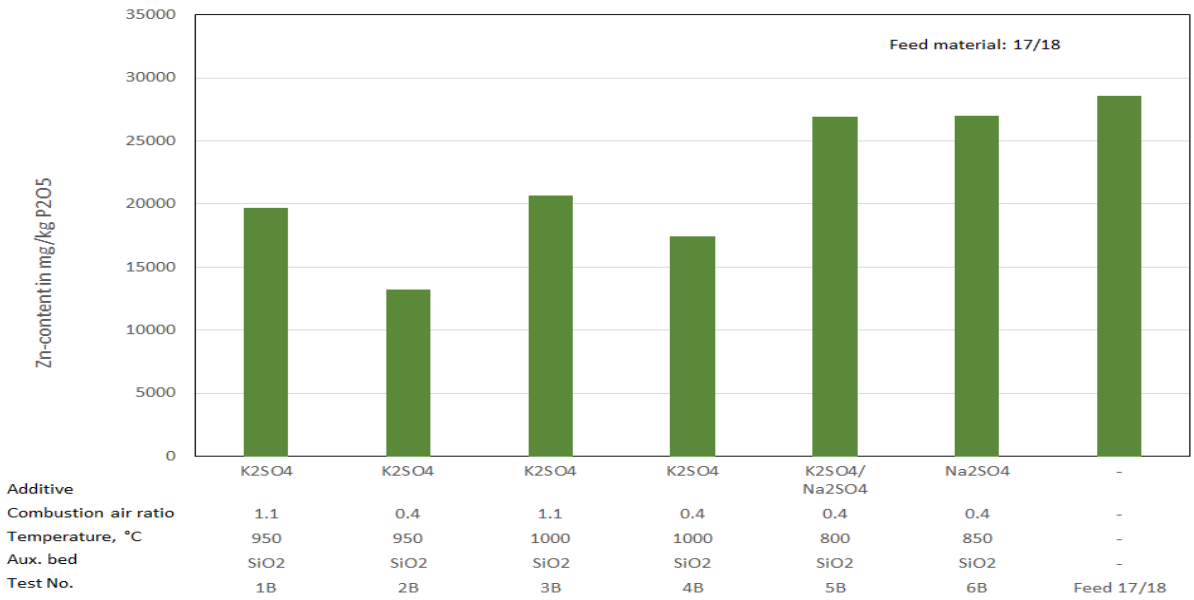


Figure 10. *Zn concentration relative to the P content of reactor discharge samples and feed material 17/18, test series B.*

A similar outcome is shown in Figure 11 with the auxiliary bed variation. Using K_2SO_4 at 1000 °C gives higher reduction in Zn than Na_2SO_4 at 950 °C. There seems to be an influence of the auxiliary bed material on Zn reduction, however, the clarification of a possible relationship would require further tests. In the best case, the Zn reduction was -62 % with a quartz sand bed and dosing K_2SO_4 at 1000 °C under reducing conditions.

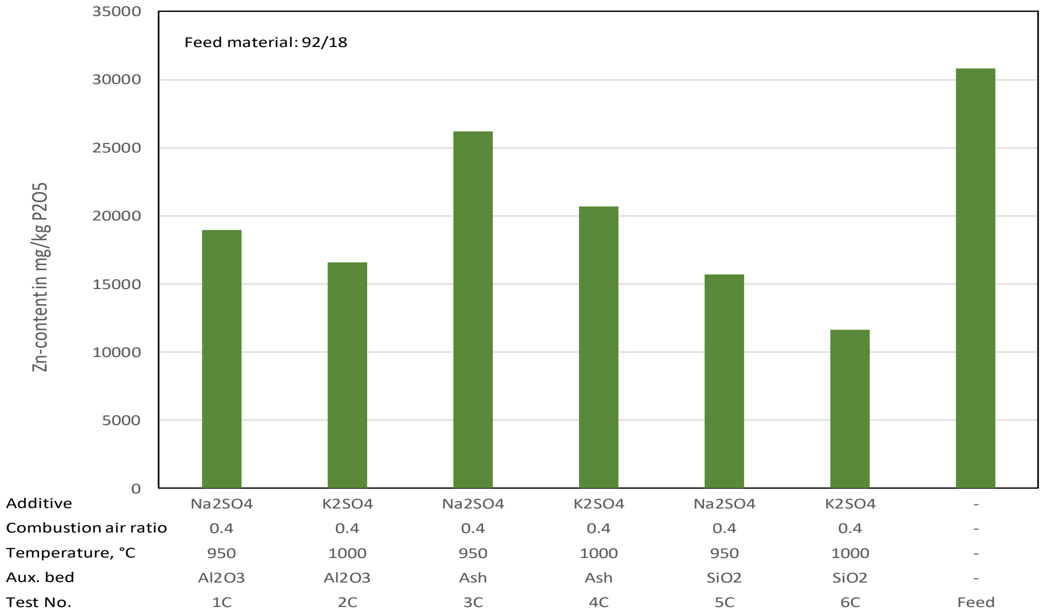


***Figure 11.** Zn concentration relative to the P content of reactor discharge samples and feed material 92/18, test series C.*

Figures 12 to 14 show the cadmium (Cd) content of the product samples relative to the P amount. Here, a clear dependency on the prevailing gas atmosphere is on the Cd reduction is apparent. Even without additives, a significant reduction in Cd can be observed under reducing conditions. This is a result of the reduction of cadmium oxide (CdO) to metallic Cd with a boiling point of 765 °C, which means that the metallic Cd is completely vaporized to the gas phase at temperatures above the boiling point.

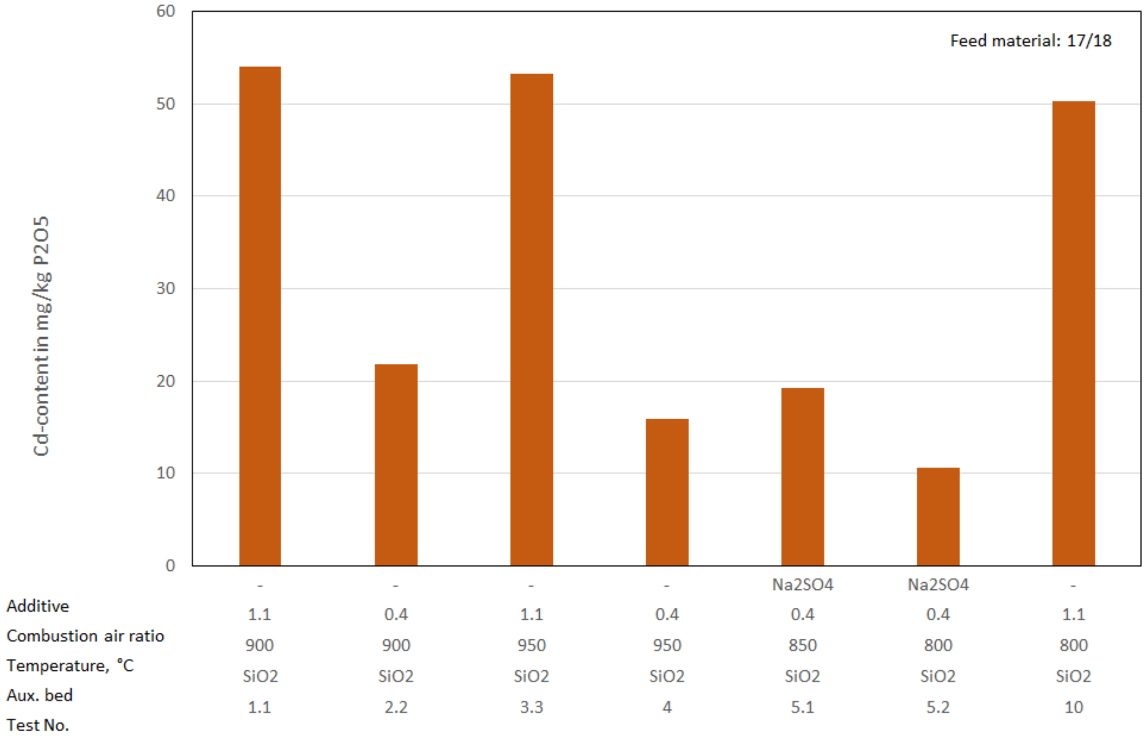


Figure 12. *Cd concentration relative to the P content of reactor discharge samples, first test series.*

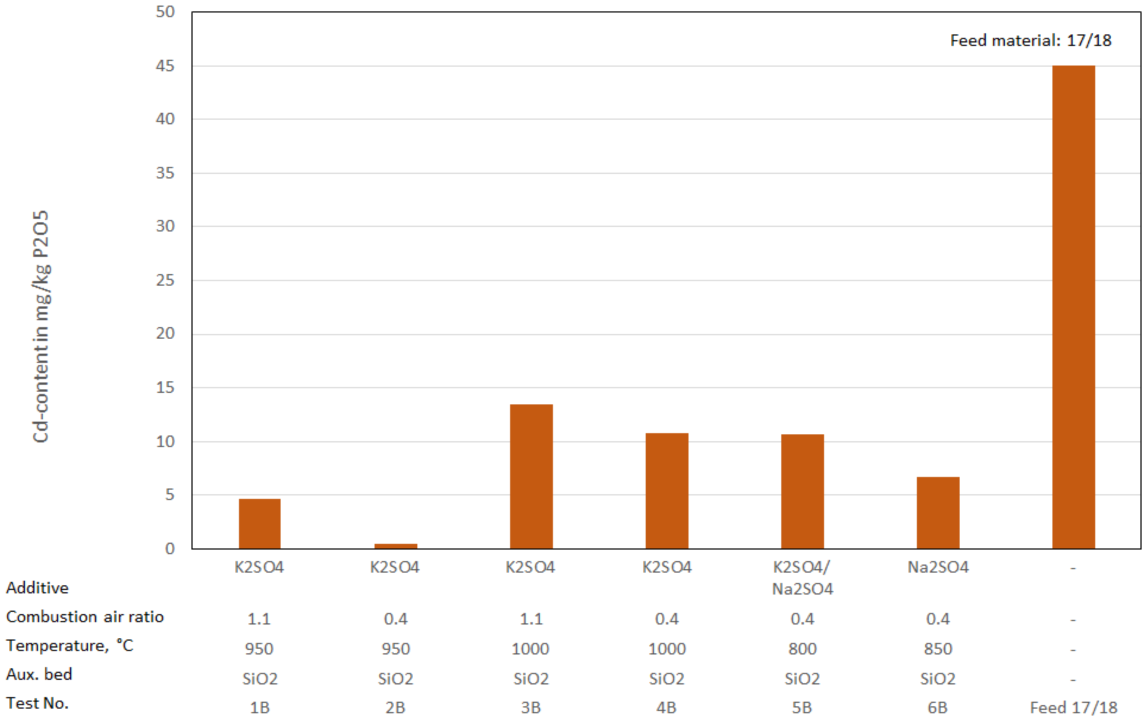


Figure 13. *Cd concentration relative to the P content of reactor discharge samples and feed material 17/18, test series B.*

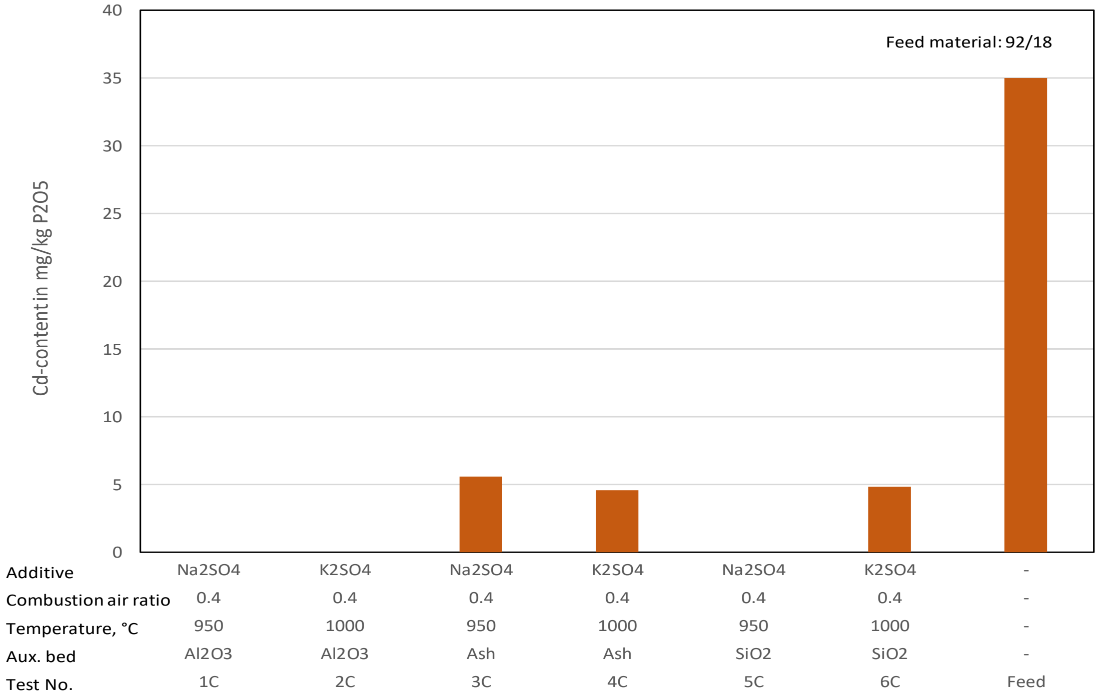


Figure 14. *Cd concentration relative to the P content of reactor discharge samples and feed material 92/18, test series C. Missing values: Measurements below detection range.*

2.6. Conclusions

Based on the results of the tests, following conclusions can be drawn:

- It cannot be recommended to use the same additives applied in the AshDec®-process in a fluidized bed furnace. The formation of massive agglomerates disturb the operation and the achieved plant P availability is far below that of the original AshDec®-process.
- The results indicate that a melt phase is necessary to enable the solid phase reactions by sufficient mixture of the reactants, however this is opposed to the application of a fluidized bed in general as particles were found to be sticking together in the presence of a melt phase to form agglomerates.
- The content of heavy metals in the product can be significantly reduced by evaporation at high temperatures. As metallic species have a lower melting point compared to its oxides, the tests applying reducing atmosphere had a higher heavy

metal removal rate than under oxidizing conditions. For Cd, temperatures of as low as 800 °C result in a significant reduction, while for Zn higher temperatures have to be applied.

- It is recommended to continue with the fertilizer production in the fluidized bed gasifier at Soil-Concept without the tested additives to avoid the build-up of agglomerates which would make continuous operation impossible. Temperatures should be high enough to volatilize heavy metals, but still maintain an acceptable level of plant availability (e.g. 75 % according to fertilizer regulation) of P and to prevent the formation of agglomerates.
- If a satisfying fertilizer performance or composition cannot be achieved this way, a second process step with an additional aggregate (rotary kiln), where the AshDec®-process can be performed separately, is recommended.
- The amount of sewage sludge in the feed mixture should be increased to enhance the P content in the product. With the given ratio of 50 % sewage sludge/ 50 % green cuttings, the P content is too low to sell the product as a P-fertilizer.

3. Production of the Ash at Soil-Concept

As a project partner of Renu2Farm, the following goals were set for Soil-Concept during the project:

Target 1: Adaptation of the AshDec®-process on the gasifier of Soil-Concept could not be fulfilled because of caking during the tests at Outotec.

Target 2: After the transfer of the AshDec®-process to the gasifier, it did not bring the desired successful gasification of sewage sludge with green cuttings compost without additive.

Target 3: Due to the increase of the sewage sludge fraction, very dry material is required for the maintenance of the gasification, as the sewage sludge is very wet. To ensure this, pellets are produced from pure sewage sludge. Here, high drying and the fluidized bed can be achieved.

3.1. The fluidized bed gasifier

At Soil-Concept, sewage sludge compost is converted into thermal and electrical energy by means of a stationary atmospheric fluidized bed gasifier (Figure 15). The gasifier is operated with pre-heated air and super-heated steam to produce a low Btu synthesis gas. The gross capacity (fuel input) of the gasifier is 2 MW thermal. Fluidized bed gasification results in good heat transfer within the reactor, as fluid material (i.e. solid particles) and fluid medium (i.e. gas or liquid) come into close contact. The high heat capacity of the bed inventory results in a relatively homogeneous temperature field within the reactor and keeps the pollutant content in the gasification process low. In sewage sludge compost, however, the synthesis gases must be filtered, as 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 (CHP) 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-value after gasification of pure sewage sludge is 6 - 7 % of a total value of 9 - 10%. The concentration of heavy metals also decreases significantly, usually by 50 %. The fly ash from the process goes to the cement industry due to its high heavy metal concentration. The sewage sludge compost has an ash content of 19 % at a temperature of 815 °C. The calorific value is stated as 12 200 kJ kg^{-1}.

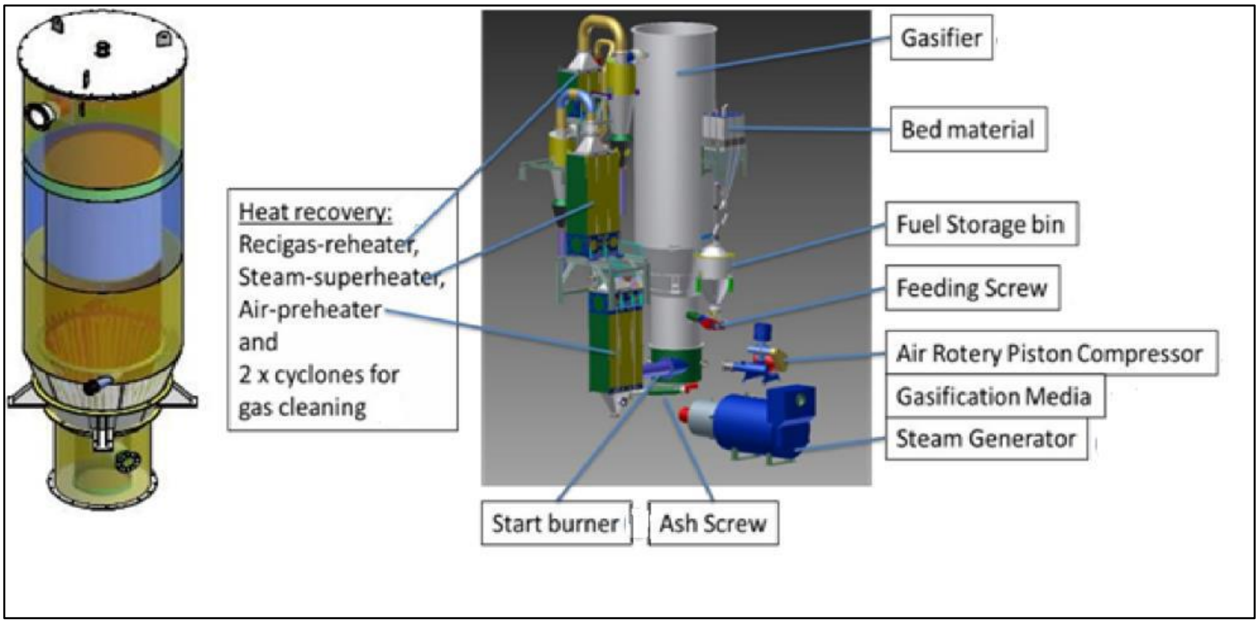


Figure 15. *Overview of the gasification components at Soil Concept*

Figure 16 shows the carburettor in the interior view. The gasification takes place here. The right part shows the ash discharge. The latter is important for an optimal unloading of the gasifier from the bed ash and an optimal maintenance and cleaning of the gasifier. Also to keep the final product ash and the gasification running smoothly, a regular inspection is necessary.

Figure 16. *Gasifier interior view (left) and ash discharge (right)*

3.2. The input material for the first tests

For the first test, sewage sludge compost (Figure 17) was used, and here too, Outotec had already dispensed with an additive on its advice. The composition is 40 % green waste and 60 % sewage sludge. This is stored for about 3 weeks in a red silo for hygienization and drying. The red silos are also equipped with a ventilation system for faster drying. In principle, the dry content increases, i.e. the humidity decreases. This has the advantage that the sewage sludge compost can be fed into the gasifier without any complex direct drying.

Figure 17. *Sewage sludge compost*

3.3. The conversion of ash production

The ash production was not carried out with additive on Outotec's recommendation, as it could have led to an increased caking in the reactor and thus, cause a considerable damage to the plant. In order to still achieve a high level of P available to the plants, pure sewage sludge should be used. The problem with using sewage sludge direct from the sewage treatment plant is that it is too moist. Therefore a pre-drying has to take place. In order to achieve a very high drying rate and a good dosage, granulated sludge pellets are produced (Figure 18).

Figure 18. *Production of the pellets and preparation for induction into the gasifier*

Production of the pellets in steps briefly explained:

- Pipe material is passed on via the push floor
- Drying of the sewage sludge to a residual moisture of up to 10 %.
- Material comminution (if necessary in a hammer mill)
- Conditioner (mixing of water and starch) and binder
- Maturation of the mixture and transfer to the die press
- Sieving of fine material
- Storage in silo

The increased energy requirement for the production of pellets is unprofitable in the long term. The heat and electricity energy released during gasification is required for the production of pellets. Sewage sludge pellets were used to obtain the highest possible amount of plant-available P in the ash.

3.4. The production of ashes

Different batches were used to produce the ashes. At first, the gasifier is brought to a temperature of around 950 °C. The heating is done with liquid gas. Later, the plant can also be kept at temperature with wood pellets. In the next step, an attempt is made to heat up the compost by introducing it and transferring it to the gasification process. Similar to the wood gasification, a so-called combustible gas is produced. The composition always depends on the starting material and varies depending on the quality of the input material. Since the quality of the compost depends strongly on the quality of the sewage sludge and the green waste, adjustments must be made again and again. This means checking the quality to see whether the compost is suitable as a fuel. It is of no use if ash is produced, but the process must be kept alive by excessive gas consumption. For this reason, energy-efficient gasification and ash production is also in focus here. Quality control plays an important role. The lower the water content of the compost, the higher the calorific value.

In addition, preparation of the sand bed of the gasifier must also be adapted. Ash can also be used as a starting bed for the gasifier, so there is less sand in the end product and it does not have to be filtered out as is the case below.

Figure 19 shows the manual processing, where a screening with different matrices is carried out. The aim is to reduce the sand content.

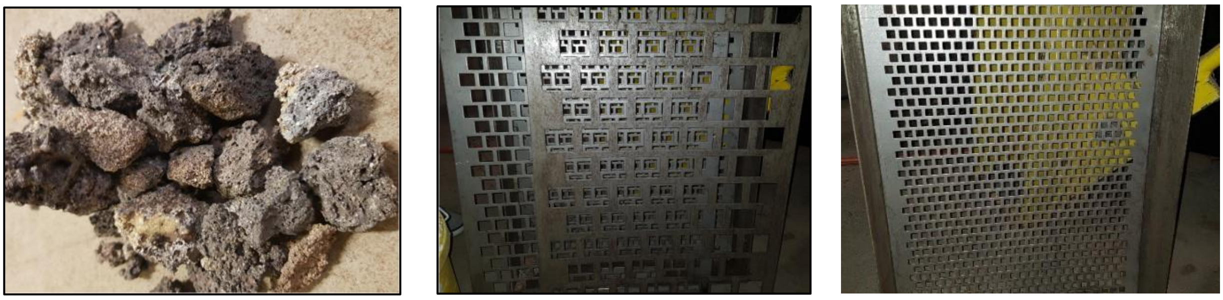


Figure 19. *Filter matrices and parts of the caked ash*

To further sieve the ashes, different sieving stages are necessary. This reduces the proportion of coarse sand grains and also the overall proportion of sand in the end product (Figure 20).

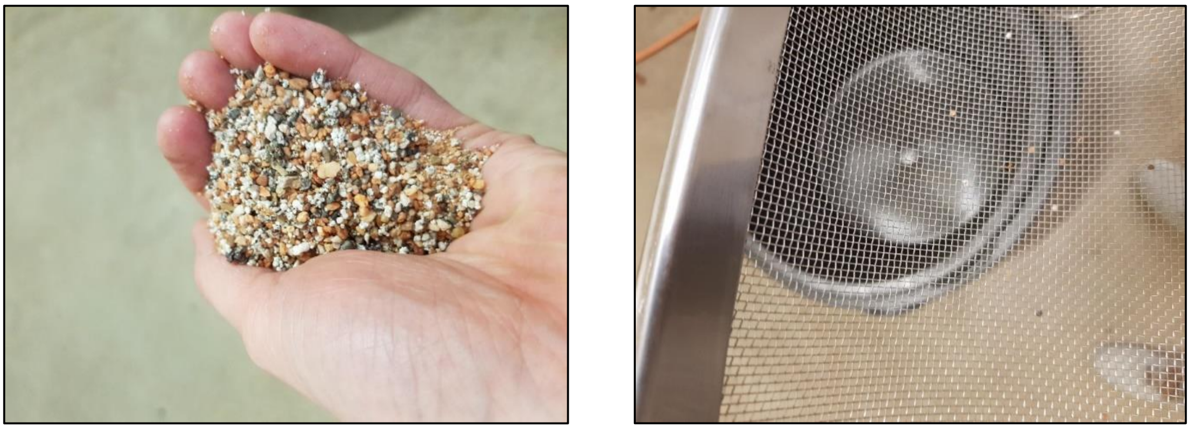


Figure 20. *Ash screening to 5 mm size with high sand content*

It is easy to see in Figure 21 that the overall picture of the ashes becomes more homogeneous through the sieving process. Coarse black grains are filtered out and the product looks more like ash.

Figure 21. *Ash Screening to 0.63 mm size*

The screening to 0.16 mm is shown in the Figure 22. It is clear that a high homogeneous proportion is achieved. Nevertheless, the sand portion is high, which is why ash was used for the starting board of the gasification reactor.

Figure 22. *Ash Screening to 0.16 size*

Figure 23 shows what happens when an ash tray is used. Sieving of the ashes is not necessary, only a crushing has been carried out, so that an optimal spreading on the fields can be guaranteed.

***Figure 23**. Sewage sludge ash Screening to 1 cm size and without sand*

In terms of process engineering, the size is achieved by an optimal operating mode of the gasifier. Here the circulation speed determines how large the ash particles can be ground. If they remain in the reactor too long, they become larger. Therefore, a cyclical ash discharge is important to avoid caking or the particles becoming too large. The optimal result can be seen in Figure 22. It should be said again that no additive was used, but a normal gasification took place. The final product is almost sand free.

3.5. Results

The following figures show the different process engineering production methods of the ash. Further details are explained below:

- blue: represents the limit according to the German fertilizer ordinance as reference value
- orange: the sewage sludge compost mg/kg dry mass without gasification
- grey: sewage sludge compost with additive 950 °C mg/kg dry mass

- light blue: sewage sludge compost without additive 950 °C mg/kg dry mass
- yellow: adapted gasification with sewage sludge pellets sewage sludge pellets without additive 950 °C mg/kg dry mass:

For arsenic (As) (Figure 24), the limit values are met in all four tests. Especially with additive (light blue) a significant reduction is noticeable. This is followed by gasification with sewage sludge compost. Pure non-gasified sewage sludge compost to approx. 7 mg/kg dry mass. The pure sewage sludge in the form of pellets reaches 10 mg/kg dry mass after gasification. It should also be mentioned here that with pure sewage sludge, the purely vegetable available phosphorus is also higher than with pure compost or gasified compost without additives. The proportion of sewage sludge compost with additive is best for plant-available phosphorus in relation to the heavy metal As.

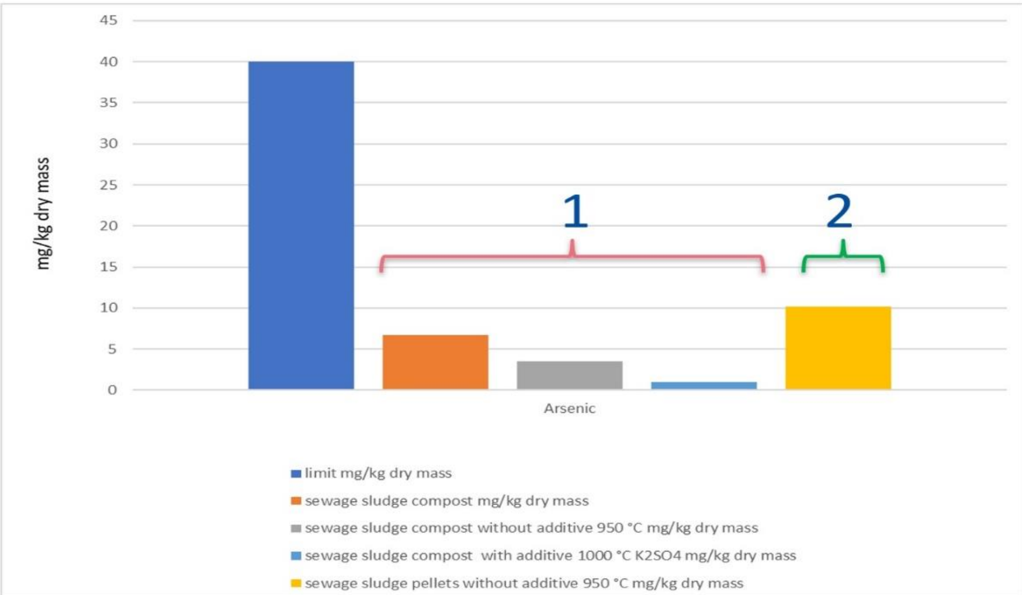


Figure 24. *Compliance with the limit values for pollutants in accordance with the German Fertiliser Ordinance (As) (1. Test at Outotec with sewage sludge compost ; 2. Test at Soil-Concept with sewage sludge)*

For lead (Pb) (Figure 25), the limits are met in all four experiments. Especially with additive (light blue) a significant reduction is noticeable. This is followed by gasification with sewage sludge compost. Pure non-gasified sewage sludge compost to approx. 39 mg/kg dry mass. The pure sewage sludge in the form of pellets reaches 70 mg/kg dry mass after gasification. It should also be mentioned here that pure sewage sludge also has a higher level of plant-available P than pure compost or gasified compost without additives. The proportion of sewage sludge compost with additive is best for plant-available P in relation to the heavy metal Pb.

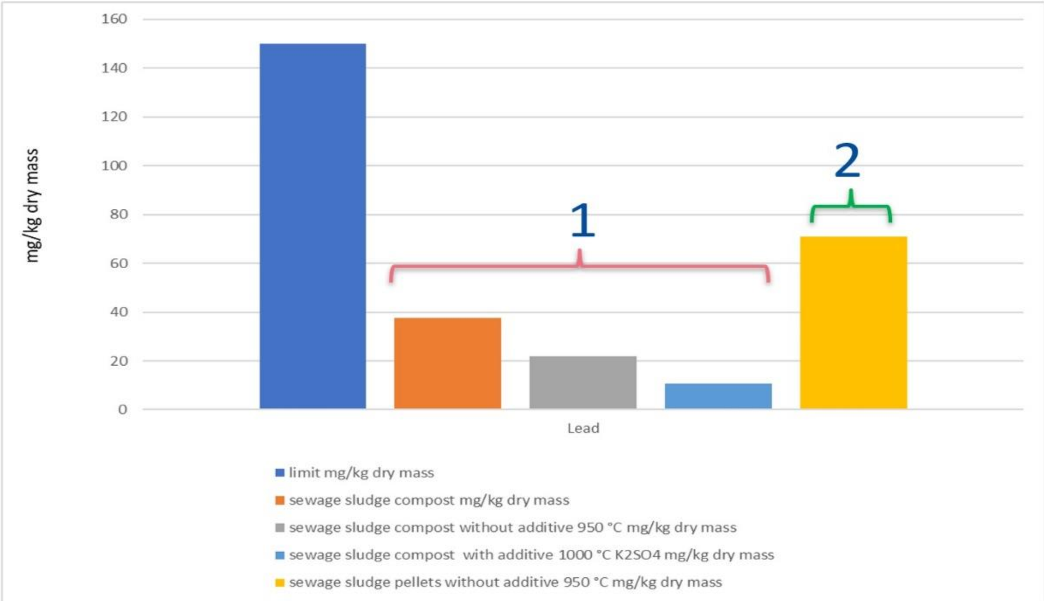


Figure 25. *Compliance with the limit values for pollutants in accordance with the German Fertiliser Ordinance (Pb) (1. Test at Outotec with sewage sludge compost ; 2. Test at Soil-Concept with sewage sludge)*

For Cd (Figure 26), the limit values are met in all four tests. Especially with additive (yellow) a significant reduction is noticeable. Then gasification with sewage sludge compost and additive (light blue. Followed by sewage sludge compost without additive (grey). The pure non-gasified sewage sludge compost (orange), which almost approaches the limit of 1.5 mg/kg dry mass of the German fertilizer ordinance, should be viewed critically. This lies at 1.4 mg/kg dry mass. This lies at 1.4 mg/kg dry mass.

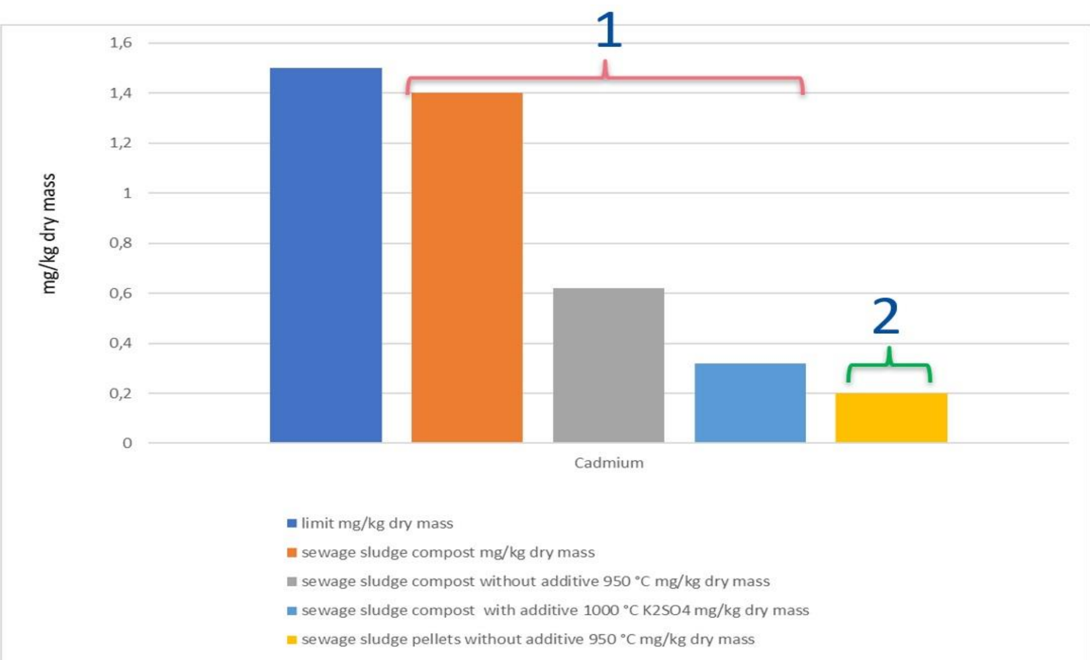


Figure 26. *Compliance with the limit values for pollutants in accordance with the German Fertiliser Ordinance (Cd) (1. Test at Outotec with sewage sludge compost ; 2. Test at Soil-Concept with sewage sludge)*

For Zn (Figure 27), the limit values in all two of the four tests are kept within the specified limits. The pure sewage sludge compost and the sewage sludge compost gasified with additive can comply with the limit values. The sewage sludge compost gasified without additive cannot meet the limit values. There is a clear excess in the gasification of pure sewage sludge pellets. They are twice the limit value actually specified.

Figure 27. *Compliance with the limit values for pollutants in accordance with the German Fertiliser Ordinance (Zn) (1. Test at Outotec with sewage sludge compost ; 2. Test at Soil-Concept with sewage sludge)*

Table 4 shows an overview of the last four figures. The four heavy metals As, Pb, Cd and Zn on the left side of the table. In the second column we find the maximum values according to the German Fertiliser Ordinance. It indicates how much heavy metals in mg kg^{-1} dry mass may be contained in the ash. The previous values were already described in the previous figures.

Table 4. *Compliance with the limit values for pollutants in accordance with the German Fertiliser Ordinance (* labelling obligation)*

Element	Limit mg/kg dry mass	Sewage sludge compost mg/kg dry mass	Sewage sludge compost without additive 950 °C mg/kg dry mass	Sewage sludge compost with additive 1000 °C mg/kg dry mass	Sewage sludge pellets without additive 955 °C
As	40	6.7	3.5	1	10
Pb	150	38	22	11	71
Cd	1.5	1.4	0.62	0.32	< 0.2
	50 mg/kg P_2O_5	45 mg/kg P_2O_5	16 mg/kg P_2O_5	10 mg/kg P_2O_5	12 mg/kg P_2O_5
Zn	1000*	876	1320	523	2100

Figure 28 shows a distribution of the different Pnac values related to the process engineering mode of operation during the gasification of sewage sludge compost (blue) or sewage sludge pellets (orange). Below the graphic representation, we have in the first row, the temperature distribution during the experiment. On the second level, the lambda value is the numerical value, i.e. the amount of air used for combustion or gasification. In the air-reduced range, 0.4 means that less air was provided than would be required for optimum combustion, and lambda must be equal to one. In this case, it is less than one and thus one speaks of a gasification. If the value is above one, this indicates that the combustion is running in the optimal range. On the second level, however, additives such as K_2SO_4 or Na_2SO_4 are also mentioned. These additives were used by Outotec to test the sewage sludge compost. The Pnac value increases by up to 60 percent with these values (from left bar 5 to 8), while the bars from 1 to 4 show values around 30 and even below 20 %. The orange bar on the far right shows the adjustment made at Soil-Concept with pure sludge in the form of pellets in the gasifier. It lies between the use of additives in sewage sludge gasification and sewage sludge gasification without additives. However, the value is lower than the usual processes achieved by AshDec but without additive and additional costs.

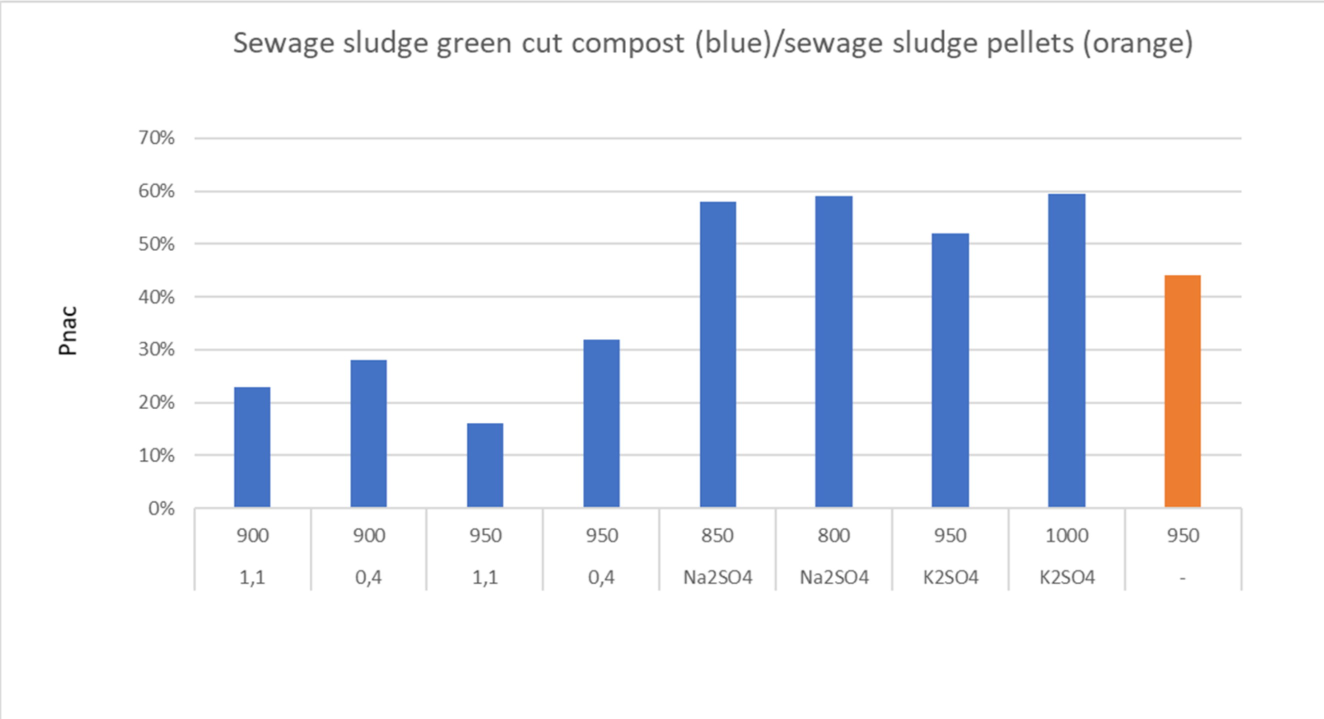


Figure 28. *Compliance with the limit values for pollutants in accordance with the German Fertiliser Ordinance (Arsenic) (1. Test at Outotec with sewage sludge compost ; 2. Test at Soil-Concept with sewage sludge)*

3.6. Results

In conclusion, it can be said that:

- the percentage of sewage sludge has been increased to 100 % and Pnac percentage to 43 %.
- the plant availability of the product's P, measured as Pnac, is higher than that of sewage sludge green cut compost but not as high as that of the conventional AshDec®-process.
- clumping in the bed occurs sporadically, but could be regulated by adjusting the reactor during aeration.
- the reducing atmosphere leads to an effective reduction of heavy metals in the product when the sewage sludge content increases. In principle, such ashes would be suitable for combination with a K fertilizer.