Technology related results of the case study Braunschweig (DE)

Non-official deliverable

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1. Description of the demo site

The wastewater treatment plant Steinhof, near Braunschweig, has a long tradition of water and nutrient reuse. Already at the end of the 19th century, fields were irrigated with sewage. From 1954 on, the wastewater was mechanically clarified and reused for irrigation. Finally, in 1979, the wastewater treatment plant (WWTP) was built and comprised a conventional activated sludge treatment system and a digestion stage. Until 2016, in summer, the digestate was directly reused in agriculture, while in winter, the digestate was dewatered and stored until the summer season. However, due to the new legislation in Germany, since 2017 only 60% of the digestate can be applied on the fields. The reasons are restricted periods for fertilising with digested sewage sludge and the limitation of the nitrogen load to the agricultural fields. Thus, the other 40% of the digestate were dewatered and incinerated.

In 2019, a new circular economy concept was implemented. Here, energy recovery technologies are combined with nutrient recovery technologies. Therefore, the sludge management concept was adapted to increase the nutrient recovery rate and simultaneously, as a synergetic effect, the biogas recovery rate increased. Hence, circular economy solution comprises a thermal hydrolysis process between two digestion stages and a full-scale nutrient recovery plant consisting of a struvite production unit to recover phosphorus and an ammonium sulphate solution production unit to recover nitrogen.

The secondary fertilisers will be reused by the local farmers and the produced energy in the form of biogas and heat is reused by the plant itself.

2. Motivation of implementing circular economy solutions in the water sector

The original WWTP was designed for 275’000 population equivalents. However, the actual load refers to 380’000 population equivalents. In order to guarantee a clean effluent of the WWTP complying with legal thresholds, a circular economy approach was implemented not only to remove nutrients from the wastewater, but also to recover them in combination with an enhanced energy recovery system. In detail, phosphorus and nitrogen are recovered via the production of struvite and ammonium sulphate and the biogas production rate is enhanced due to a thermal pressure hydrolysis.

The benefits of the thermal pressure hydrolysis are:

- ✓ **Subsequent anaerobic digestion: increase in methane yield up to 25% due to THP**

The THP breaks down complex organic carbon compounds such as microbial cells into soluble compounds. In a subsequent anaerobic digester, microorganisms degrade those soluble compounds resulting in an increase in the methane yield of about 15% – 25% compared to anaerobic digestion without THP (DWA 2014).

- ✓ **Reduction of the sludge disposal volume and correspondingly their disposal costs**

Due to the higher degradation rate in a subsequent anaerobic digester to the THP, the volume of the digestate decreases correspondingly. Furthermore, according to Neyens and Baeyens (2003), the dewaterability is enhanced after THP. Hence, the volume of

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the dewatered sludge can be reduced reaching a dry matter content of 30% and more due to the better dewaterability and the higher degradation rate during anaerobic digestion (Metcalf et al. 2013, Neyens and Baeyens 2003). Thus, the disposal costs for the dewatered sludge decrease, too. Phothilangka et al. (2008) saved 25% of their disposal costs.

- ✓ **THP enables the operation of the downstream digestion at higher dry solids (DS) contents and with higher organic loading rates**

THP leads to a lower viscosity (Higgins et al. 2017) enabling the operation of the downstream digestion process at higher DS contents still achieving favourable mixing conditions. Furthermore, the enhanced biodegradability leads to higher digestion rates and thus, to lower required hydraulic retention times allowing for the operation at higher organic loading rates (Pilli et al. 2015).

- ✓ **Release of ammonium and phosphate for a subsequent nutrient recovery**

The disintegration process in the THP enhances the performance of the anaerobic digestion process also resulting in a higher ammonium and phosphate release into the liquid phase. Due to the accumulation of ammonium and phosphate, the resulting liquor is very suitable for a subsequent nutrient recovery such as ammonium stripping or struvite production.

- ✓ **Sterilized sludge after high temperature THP**

Due to high temperatures between 130 °C and 180 °C and the rapid decompression from 6 bar to 0.2 bar, microbial cell walls are destroyed (Pilli et al. 2015) and thus, pathogenic organisms, too.

Further reasons for the implementation of a struvite production unit are:

- ✓ **Reduction of the phosphate return load of a WWTP**

The WWTP profits from the reduced phosphate return load. Thus, a part of iron or aluminium salts often used for a conventional chemical removal might be saved due to the lower return load.

- ✓ **Prevention of clogging events in pipes**

Depending on the chemical composition of the wastewater and the pH conditions, struvite can precipitate in undesired parts in the wastewater treatment plant e.g. in pipes leading to scaling and clogging. Due to a controlled removal of the phosphate from the liquor, those processes will be diminished or even avoided in the subsequent plant parts.

Further arguments to implement an ammonium sulphate production unit via air stripping and gas scrubbing are:

- ✓ **Robust process**

In contrast to the microbial nitrogen removal via nitrification and denitrification, the nitrogen removal via stripping and scrubbing does not rely on microorganisms and thus, the process is very robust.

- ✓ **Reduction of formation of N_2O in the activated sludge process of the WWTP**

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Reducing the nitrogen return load to the mainline will stabilize the nitrogen removal and helps to prevent overloads of the treatment capacity. As high nitrogen loads and high fluctuations often lead to higher emissions of N_2O from the activated sludge process, air stripping will also lead to a decrease in emissions of this potent greenhouse gas.

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3. Actions and CS objectives

Table 1 Actions and objectives of the case study in Braunschweig

Case Study number & name	Subtasks	Technology baseline	NextGen intervention in circular economy for water sector	TRL	Capacity	Quantifiable target
#1 Braun-schweig (DE) Location: WWTP Steinhof	**Sub-Task 1.3.2** Internal heat usage and heat management for two stage digestion system &thermal pressure hydrolysis (TPH)	Three one-satge digesters; heat reuse from CHPs for tempering the digesters and surrounding buildings	Two-stage digestion system with thermal pressure hydrolysis between the stages: higher heat demand due to TPH, reuse of excess heat from TPH and more available heat from CHPs due to increased methane production	Digestion system with TPH: TRL 8 → 9	On average up to 250 m³/h methane production; with TPH increase on average to 300 m³/h (max. 330 m³/h)	Enhanced biogas production due to TPH: Increase in methane production on average by factor of 1.2
	Sub-Task 1.4.7 Full-scale nutrient recovery from wastewater	Irrigation and fertilisation of agricultral fields with WWTP effluent and digestate	Phosphorus recovery for struvite production	TRL 9	Around 250 t/a struvite (dry) ➔ **30 t P/a** ➔ **15 t N/a**	Struvite prodcution: ≥80% recovery from P load to recovery unit
			Ammonia stripping for ammonium sulphate ($(NH_4)_2SO_4$) production	TRL 9	Around 2000 t/a ammonium sulphate solution (wet) • **175 t N/a**	$(NH_4)_2SO_4$ production: ≥85% recovery from N load to recovery unit

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4. Unique selling points

Unique selling points for the implementation of a thermal pressure hydrolysis unit are:

- ✓ Release of soluble organic matter leading to higher degradation during anaerobic digestion → enhancing biogas production and decreasing the organic matter content in the digestate
- ✓ Better dewaterability of digestate → reduction of disposal costs
- ✓ Release of phosphate and ammonium from disintegrated organic compounds

Unique selling points for the production of struvite from process water are:

- ✓ High phosphorus removal and recovery rates related to the influent to the recovery unit of up to 97%
- ✓ Struvite is a high quality product which can be used in agriculture as slow release fertiliser
- ✓ Reduced struvite scaling in pipes and pumps downstream the struvite production unit
- ✓ Significant reduction of the phosphorus return load

Unique selling points for the production of ammonium sulphate via air stripping and gas scrubbing are:

- ✓ High ammonia recovery rates related to the ammonium influent to the recovery unit between 85% and 97%
- ✓ Market-ready product: ammonium sulphate solution as a liquid fertiliser
- ✓ Mature technology and robust process
- ✓ Reduction of N_2O emissions vis reduction of nitrogen return load

5. Principal and main characteristics of the technologies

In the case study Braunschweig, three different technologies were implemented that are interconnected with each other:

- Thermal pressure hydrolysis,
- Struvite production and
- Ammonium sulphate solution production via air stripping and gas scrubbing.

5.1 Thermal pressure hydrolysis

The thermal hydrolysis process (THP) is used as a pre-treatment for anaerobic digestion usually at wastewater treatment plants with a capacity for 100’000 population equivalents and greater. Originally, THP was used to enhance the dewaterability of sludge (Zhen et al. 2017). However, in addition it was shown, that THP improves the solubilisation of the sludge, reduces its viscosity (Bougrier et al. 2006, Higgins et al. 2017, Liu et al. 2019) and increases its biogas yield (Neyens and Baeyens 2003).

Usually excess sludge or mixed sludge consisting of primary and excess sludge are pre-treated via THP and disintegrated at temperatures between 60 °C and 180 °C (Zhou et al. 2021). The THP breaks down complex organic compounds and cell

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structures into more soluble compounds and thus, increases the substrate availability for anaerobic biodegradation.

As an example, the high temperature thermal hydrolysis process is described in detail here (Figure 1, Figure 2). Typical high temperatures are between 140 °C and 180 °C. In addition, the THP is operated at high pressure conditions usually ranging between 5 and 8 bar. For the sludge disintegration, first the sludge is tempered to 85 °C in a preheater for example by using excess heat from the hydrolysate. Then, the sludge passes through three tanks: (1) the pressuriser, (2) the reactor and the (3) economiser. In the pressuriser, the sludge is further heated to 105 °C and the pressure is increased between 5 and 8 bar. In the reactor, the high pressure is maintained, while the temperature is further increased to around 140 °C or more. In the economiser, the pressure is decreased via a rapid decompression to 0.2 bar, forcing the sludge through a small orifice. Due to high mechanical shear forces with this “flash”, the microbial cell walls are destroyed and thus, soluble organic compounds are released.

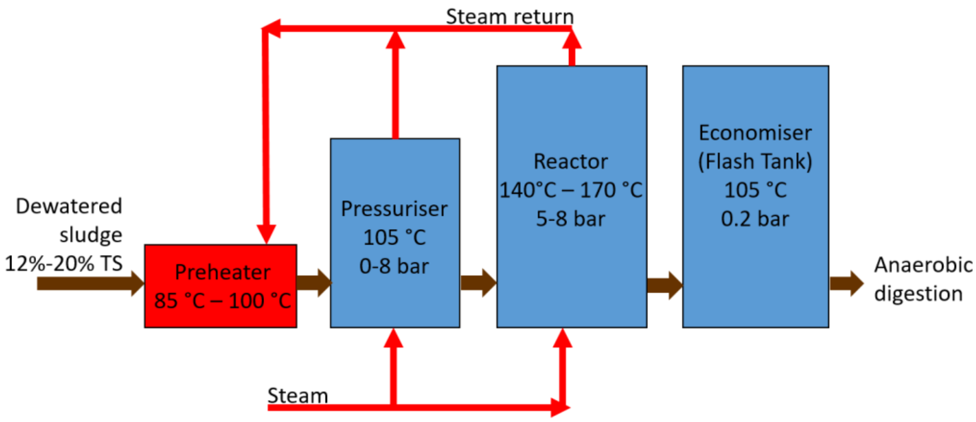

Figure 1 Flow scheme of the thermal pressure hydrolysis unit (Haarslev process)

Figure 2 Pictures of the thermal pressure hydrolysis units (Haarslev process)

5.2 Struvite production unit

In the wastewater sector, struvite is usually used as a name for magnesium ammonium phosphate ($MgNH_4PO_4*6H_2O$), even though it is the name of a mineral family. Struvite is a slow release fertiliser (Kratz et al. 2019) and all three nutrients are plant available as from mineral fertilisers (Watson et al. 2019).

Phosphorus removal and recovery via struvite precipitation is applied at wastewater treatment plants, usually after a pre-treatment such as anaerobic digestion or even a combination of anaerobic digestion with an additional hydrolysis such as a thermal

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pressure hydrolysis or a thermal alkaline hydrolysis in order to increase the dissolved phosphate concentration. It is usually applied at wastewater treatment plant treating the wastewater of 100’000 population equivalents and more.

To enable struvite precipitation, a pH of 7.5 and higher is required. Hence, as a first step towards a higher pH, the CO_2 is stripped via air injection. In a second step, caustics are added such as NaOH, if the CO_2 stripping has not reached the required pH value. To induce struvite precipitation, together with a certain ammonium concentration, a magnesium source is usually added such as $MgCl_2$, MgO or $Mg(OH)_2$. Magnesium forms together with phosphate and ammonium struvite. This takes place in a reaction tank, the so called struvite reactor, which is typically a continuously stirred tank reactor. Crystal growth is promoted by mixing, sufficient retention time and recirculation of formed crystals. As a last step, the struvite in form of larger crystals is separated in a settling tank. Usually, the struvite is dewatered, dried and processed, before it can be applied as a slow-release fertiliser.

Variants of the process: sludge - liquor

If the CO_2 stripping and struvite precipitation take place in the sludge, the separation of the struvite crystals is less efficient and the crystals are usually inhomogeneous due to organic and/or inorganic impurities. However, the controlled struvite precipitation can be a useful measure to prevent pumps or pipes in the sludge line from scaling or even clogging (Desmidt et al. 2015).

If the CO_2 stripping and struvite precipitation take place in the liquor (e.g. after dewatering), the subsequent separation of the struvite is very efficient. However, the higher phosphate concentrations are, the lower the dewatering efficiency of the upstream dewatering unit is (Kuhn et al. 2013). Thus, the dewatering step might require more energy and sometimes even additives such as polymers in order to reach the required liquor quality. In the liquor, the crystals grow usually homogeneous. In NextGen the focus is on struvite production in the liquor, hence, the following sections will focus on this technological solution only.

The flow scheme and the pictures show an example for struvite production in the liquor (Figure 3, Figure 4). After CO_2 stripping, the struvite crystals precipitate in the struvite reactor as already described.

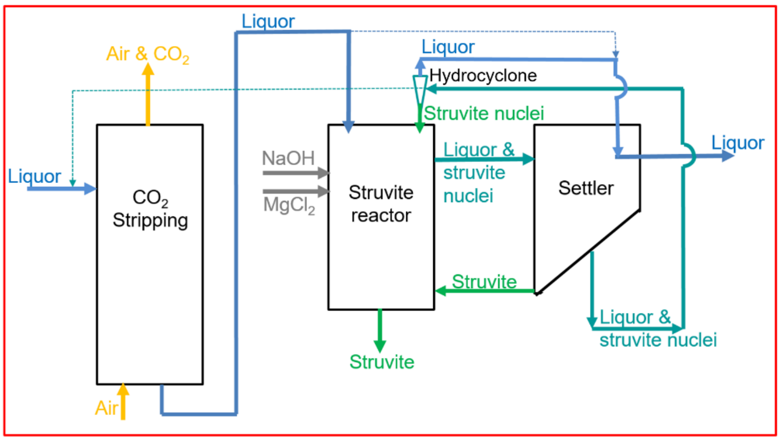

Figure 3 Flow scheme of the struvite production unit (NuReSys process)

Macro crystals settle down ready to leave the struvite reactor and micro crystals (struvite nuclei) are distributed in the liquor and enter the settling reactor. There, they can further grow and settle down. However, if they are still too small for settling, they

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are transported back to the struvite reactor. The hydrocyclone separates the small crystals from the liquor. They serve as struvite nuclei and lead to an improved crystal growth within the struvite reactor. The system of the reactors is very flexible, shown by the dotted lines that indicate an alternative way of operation.

Figure 4 Pictures of the struvite production unit consisting of a CO2 stripping unit, a struvite reactor, a settler and a container to collect the harvested struvite crystals (NuReSys process).

5.3 Ammonium sulphate production via air stripping and gas scrubbing

Nitrogen is one of the main nutrients contained in wastewater. In wastewater treatment, nitrogen is usually removed biologically via nitrification and denitrification. There, the nitrogen is emitted into the air. The process described here relies on chemical reactions and offers the opportunity to recover the nitrogen in the form of ammonium sulphate solution. The process is usually applied in sludge liquor that is rich in ammonium. This process is usually applied at wastewater treatment plants with a capacity of 100 000 population equivalents and greater.

In order to produce ammonium sulphate solution, two columns are used in sequence (Figure 5).The first column is the ammonia stripping unit (Figure 6). Here, the ammonium rich liquor is stripped with air at a temperature between 55 °C and 65 °C and at a pH between 9 and 11.

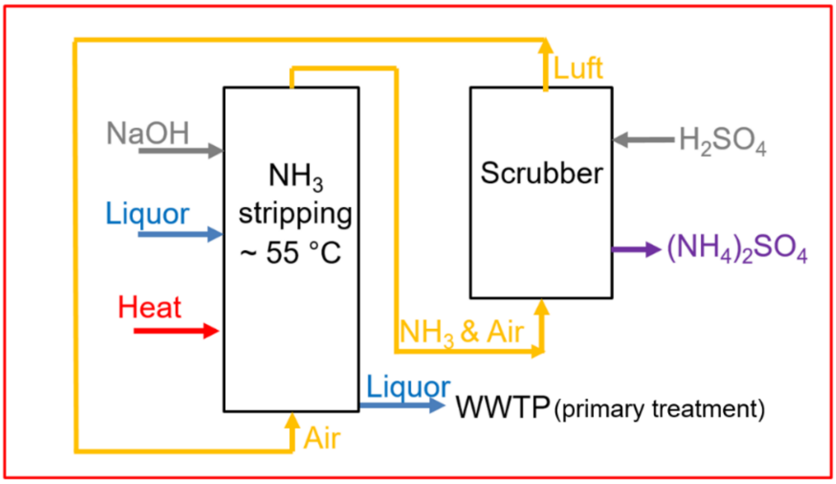

Figure 5 Flow scheme of the ammonium sulphate production unit

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The higher the temperature is and the higher the pH is, the more the equilibrium between ammonium and ammonia shifts to the ammonia side. In order to increase the pH to alkaline conditions, carbon dioxide is stripped from the liquor and sodium hydroxide is added. Under those conditions, ammonium reacts to ammonia and can be stripped out via air stripping. In a subsequent gas scrubber, that is the second column, the obtained ammonia gas reacts with sulphuric acid to ammonium sulphate. Hereby, the ammonia free air can be reused and is injected in the air stripper again. The relation of the air flow compared to the liquor flow is around 500.

Figure 6 Pictures of the ammonium sulphate production units, the storage tank and an ammonium sulphate solution sample

Ammonium sulphate solution is a nitrogen fertiliser. Typical concentrations are 37 – 40% of ammonium sulphate in water. According to Szymańska et al. 2019, the reference fertiliser efficiency describes the effectiveness of the ammonium sulphate produced by such a system compared to that of commercially available ammonium sulphate. Both are in a similar range, the reference fertiliser efficiency of the ammonium sulphate solution is between 89 and 103% of that for commercial ammonium sulphate depending on the plant and soil type.

6. Requirements for the implementation of the technologies and operating conditions

In the case study Braunschweig, three different technologies were implemented that are interconnected with each other:

- thermal pressure hydrolysis,
- struvite production and
- ammonium sulphate solution production via air stripping and gas scrubbing.

6.1 Thermal pressure hydrolysis

Prior to the treatment, the excess sludge is digested in order to reduce its organic matter content and then, it is thickened usually to a dry solids content of up to 18%. In order to disintegrate organic compounds such as microbial cells, the sludge must be heated to a range between 60 °C and 180 °C. At temperatures until 100 °C, the process is operated at normal pressure conditions. At high temperatures between >100 °C and

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180 °C, the THP is maintained at high pressure conditions between 2 and 9 bar. In detail, for the typical temperature range between 140 °C and 180 °C, the pressure is usually operated between 5 and 6 bars (DWA 2014). The hydraulic retention time (HRT) usually ranges between 15 and 60 min.

Table 2 Requirements and operating conditions for the thermal pressure hydrolysis

Parameter	Units	Min	Max	Reference
DS sludge feed	%	**12**	**18**	DWA 2014, Heinze, J. (2022)
Temperature	°C	**60**	**180**	Zhou et al. 2021, DWA 2014; Neyens and Baeyens 2003
High pressure conditions (T > 100°C)	bar	**2**	**10**	Zhou et al. 2021, Pilli et al. 2015, DWA 2014
Hydraulic retention time	min	**15**	**60**	Zhou et al. 2021

6.2 Struvite production

In order to reach high struvite yields, the dissolved phosphate concentration in relation to the total phosphorus content should be as high as possible in the reactor influent. According to Cornel and Schaum (2009) concentrations of 50 mg PO_4-P/L are already economically rewarding. However, higher concentrations are preferred e.g. in Braunschweig, the concentrations in the influent to the reactor range between 250 and 500 mg PO_4-P/L. The total suspended solids (TSS) should be below 600 mg/L. Furthermore, ammonium and magnesium need to be present. Therefore, a molar ratio of Mg:N:P between 1:2:1 and 1:12:1 should be maintained in the reactor.

Table 3 Requirements and operating conditions for the struvite production unit

Parameter	Units	Min	Max	Reference
PO_4-P (influent to reactor)	mg/L	**50** **250**	**-** **500**	Cornel and Schaum (2009) Heinze (2022)
TSS (influent to reactor)	mg/L	**<600**		Heinze (2022)
pH (in reactor)	-	**7.5**	**9**	Heinze (2022), Cornel and Schaum (2009), Shaddel et al. (2019)
Mg:N:P molar ratio (in reactor)	-	**1:12:1**	**1:2:1**	Shaddel et al. (2019)

6.3 Ammonium sulphate production via air stripping and gas scrubbing

In order to reach high ammonia yields, the fraction of ammonium in relation to the total nitrogen content should be as high as possible. Up to now, the process was applied for concentrations between 800 and 4000 mg NH_4-N/L. However, technically a lower

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concentration is also feasible. In this case, it should be investigated, if the process can be still operated economically rewarding. Anaerobic digestion combined with an additional thermal pressure hydrolysis can help to lyse and degrade organic compounds resulting in an increase in ammonium concentrations.

Table 4 Requirements and operating conditions for ammonium sulphate solution production

Parameter	Units	Min	Max	Reference
NH_4-N feed	mg/L	**800**	**4000**	Böhler et al. 2012, Heinze (2022)
TSS feed	mg/L	**-**	**600**	Heinze (2022)
pH	-	**9.5**	**11**	Heinze (2022)
Temperature	°C	**55**	**65**	Heinze (2022)

7. Results obtained

In the case study Braunschweig, the results were obtained for three different technologies that are interconnected with each other:

- thermal pressure hydrolysis,
- struvite production and
- ammonium sulphate production via air stripping and gas scrubbing.

7.1 Thermal pressure hydrolysis

To evaluate the effect of the thermal pressure hydrolysis on the enhancement of the biogas production process, the methane production rate was considered as crucial parameter, because the methane content is crucial for the energy production via the combined heat and power plant.

In 2019, the thermal pressure hydrolysis (TPH) was implemented and put into operation. Before that, the methane production rate usually ranged between 230 m³/h and 280 m³/h with the first 280 days (Figure 7). Due to the effect of the TPH and hence, the better biodegradation of the hydrolysed sludge, the methane production rate increased from 200 m³/h to even 400 m³/h. When the TPH was switched off, the methane production rate decreased to its old ranges. As soon as the TPH was put into operation again, the methane production rate increased again and remained on a higher level between 270 and 330 m³/h. On average, the methane production rate increased by a factor of 1.2 due to the effect of the TPH.

A second benefit of the TPH is the better dewaterability of the digestate. Figure 8 shows the total solids content of the digestate before the implementation of the TPH and after. Without the effect of the TPH and the adjustment of the old polymer, the total solids content ranged between 21% and 23%. Due to the effect of the TPH and after the adjustment of the polymer type and dosage due to the new characteristics of the hydrolysed digestate, the total solids content increased to a range between 24% and 26%. Hence, on average the total solid content increased by a factor of 1.1. This shows a better dewaterability and has a positive effect on the disposal costs of the sludge due to its decrease in volume of 10%.

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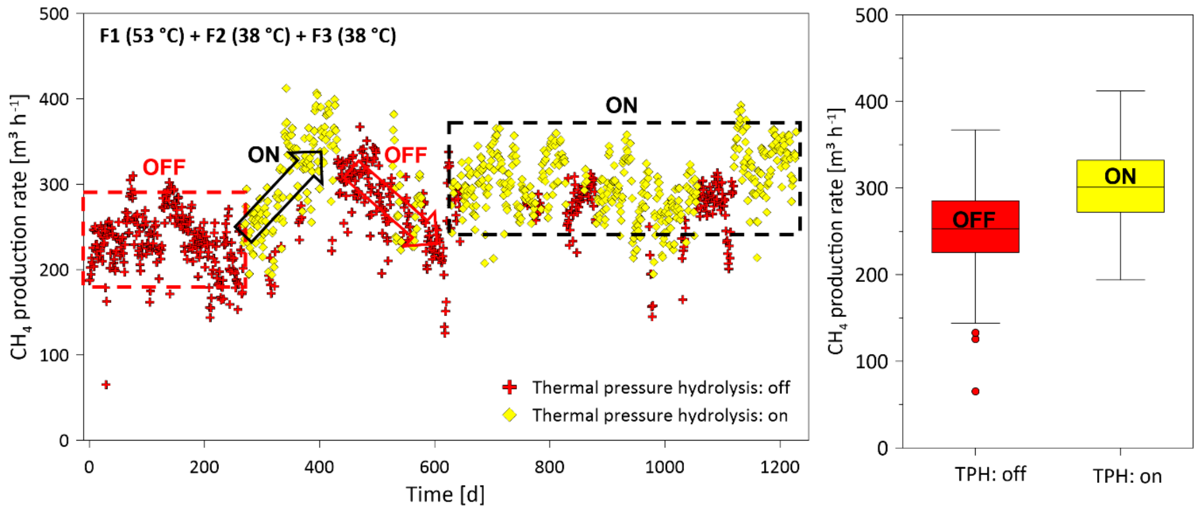

Figure 7 Methane production rate of the two stage digestion system with (ON) and without (OFF) the effect of the thermal pressure hydrolysis

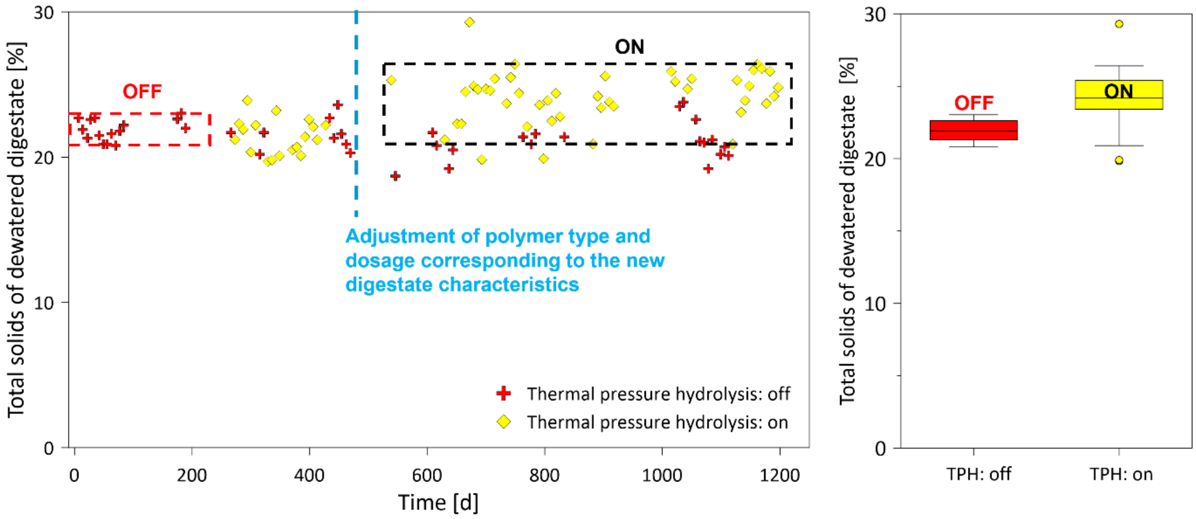

Figure 8 Total solids content of the dewatered digestate with (ON) and without (OFF) the effect of the thermal pressure hydrolysis

The increased methane rate allows the combined heat and power plant (CHP) to produce more heat and electricity compared to the situation before Nextgen. The increased heat production by the CHP and the heat demand of the thermal pressure hydrolysis and digesters are influencing the heat balance. To show the changes between heat demand and supply for different operation modes regarding heat supply of the thermal pressure hydrolysis, three scenarios had been investigated:

a) **a baseline scenario before implementation of the NextGen scheme**
b) **the realised NextGen I. scenario with the thermal pressure hydrolysis using steam from a steam generator using biogas**
c) **a hypothetic NextGen II. scenario with the thermal pressure hydrolysis using steam generated by utilisation of HT (high temperature heat) from the CHP**

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The CHP has a thermal efficiency of around 38%, whereby about 45% of the heat generated by the CHP is low temperature heat (LT) below 100 °C and 55% of the heat generated by the CHP is high temperature heat (HT) above 100 °C. LT heat can be used for various purposes e.g. heating the digester and associated buildings or pre-heating the return load for ammonium recovery, however the generation of steam for a thermal pressure hydrolysis is not possible with LT heat. This is only possible with HT heat, whereby of course HT heat can also be used for LT heating purposes.A further limitation in terms of heat valorisation is the seasonal fluctuating heat demand, which is higher in the winter season and lower in the summer season.

a) baseline before NextGen

Assuming a constant operation of the CHP in the baseline scenario, a constant amount of heat was produced over the whole year, resulting in a heat surplus in summer and a heat deficit in winter (= 106 MWh/year), which needs to be covered by gases from external sources (e.g. natural gas). This is illustrated in Figure 9. The heat surplus in summer (e.g. 1’800 MWh/year) was lost.

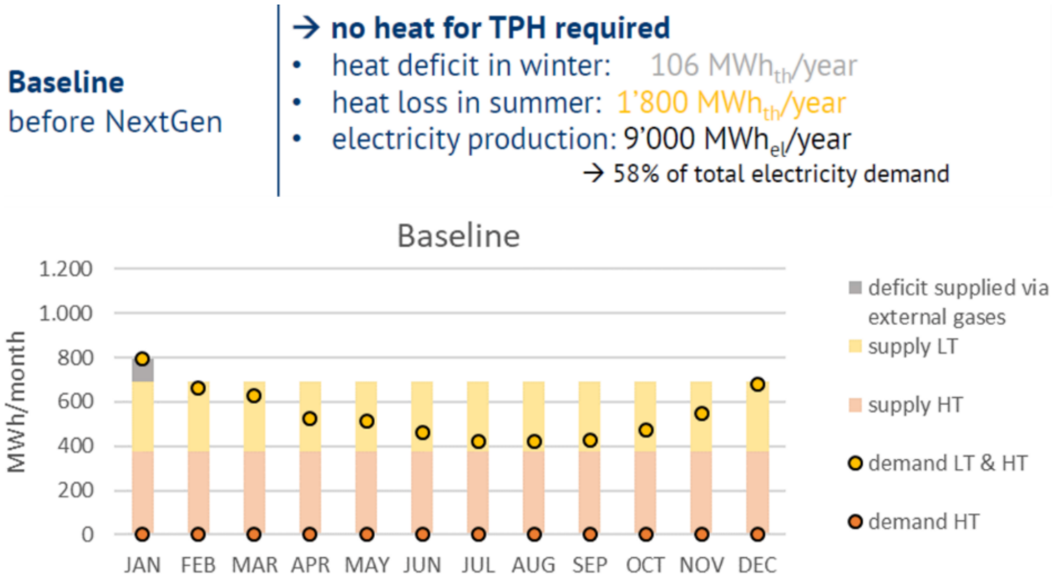

Figure 9 Monthly heat management and annual electricity generation for the baseline scenario

b) NextGen I. – steam generator uses biogas

The NextGen technologies (NextGen I.) have a strong impact on the heat management of the WWTP. The implementation of the thermal pressure hydrolysis using steam created a constant demand of HT heat, whereby the demand of LT heat decreased moderately (additional heat demand of nutrient recovery and reduced heat demand of digesters due to mixing the heated hydrolysed excess sludge with cold primary sludge). In total, the heat demand total system (TPH, digestion & ammonia stripping unit) increased by about 25%, however also the heat supply from the CHP increased by 8% on average due to the higher methane production rate as a result of the hydrolysis treatment. The HT heat for the steam production is realised via a steam evaporator using biogas. The consequential heat balance is shown in Figure 10.

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Compared to the baseline, only 15% of the external gases are needed, whereby the heat loss in summer is increased towards 2’800 MWh/year.

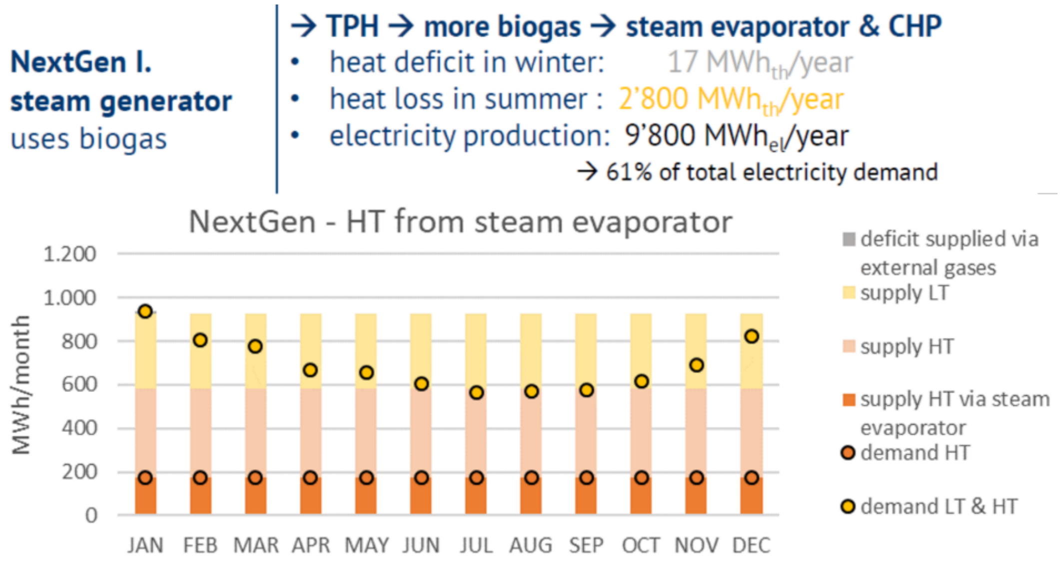

Figure 10 Monthly heat management and annual electricity generation for the NextGen I. scenario

c) NextGen II. - steam generated from HT heat from the CHP

An alternative for this scenario would be to use the present HT heat from the CHP for steam generation (scenario NextGen II.). However, this process requires in addition very expensive heat exchangers and was due to infrastructural boundaries at the WWTP not foreseen. Nevertheless, this scenario is shown in Figure 11. There is an increasing demand heat from external sources in winter of 118 MWh/year, however the electricity production is increased since all biogas is utilised in the CHP. Thereby the own production might cover up 67 % of the total electricity demand of the WWTP compared to 61 % in the scenario NextGen I.

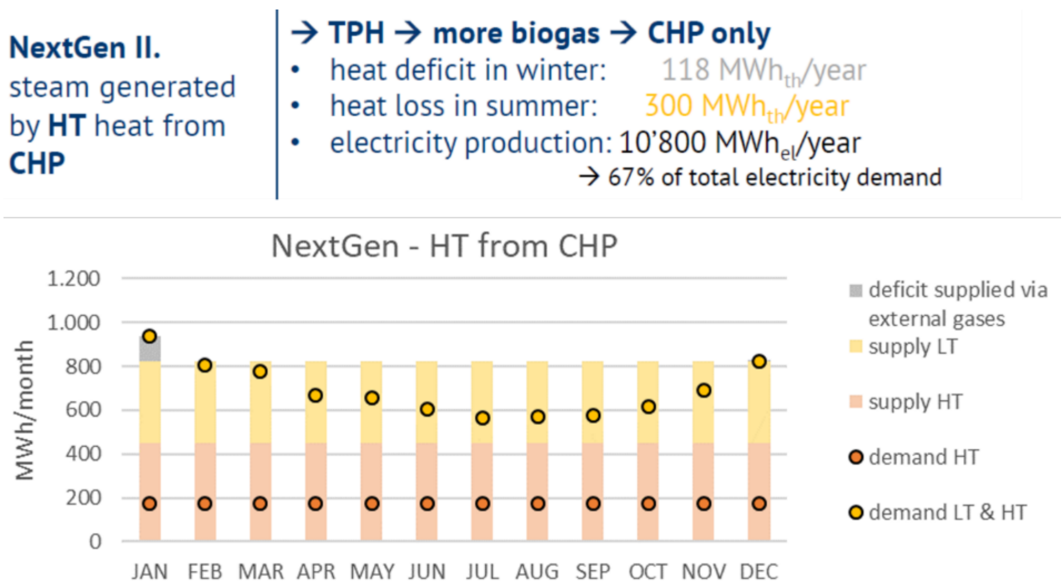

Figure 11 Monthly heat management and annual electricity generation for the NextGen II. scenario

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The NextGen I. scenario was the most economic one due to high CAPEX costs of the scenario NextGen II. The fact that the WWTP uses green gases (deposit and biogas from an agricultural biogas plant) for stream production reduces the carbon footprint of the NetGen scenario compared to the usage of natural gas. However, this might be not always possible, when this system is integrated to another WWTP. More details about the CO_2 footprint of the technologies in Braunschweig are shown in D2.1 of the NextGen project in the corresponding life-cycle-analysis (LCA).

7.2 Struvite production

The struvite production unit was implemented and put into operation in autumn 2019. As Figure 12 shows, within the first year of operation, the phosphorus recovery rates were still below their expected minimum rate of 80%. Also, many downtimes of the plant occurred that are indicated by time periods without any data points. After one year of operation, the recovery rate started to increase and reached sometimes even its expected value at and above 80%.

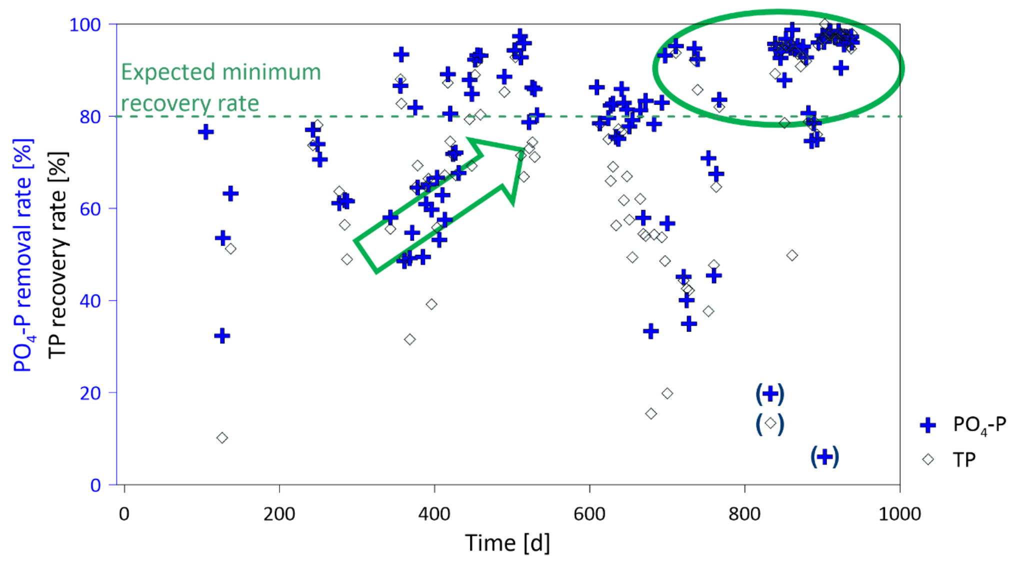

Figure 12 Phosphorus recovery rate referring to the total phosphorus (TP) and phosphate removal rate referring to dissolved phosphate (PO_4-P): The lower recovery rates referring to the total phosphorus compared to the higher removal rates of dissolved phosphate show the wash out of very small struvite crystals.

In summary, it took almost two years of optimisation of the process and the equipment until the process worked as expected and reliable high recovery rates were reached. Figure 12 shows two different rates. One rate refers to the phosphate removal rate and the other rate refers to the total phosphorus recovery rate. The phosphate removal rate indicates the successful precipitation process. Within the first two years, usually the phosphate recovery rate was higher than the total phosphorus recovery rate, indicating that more phosphate precipitated than it was recovered. Hence, very small crystals were washed out of the system and entered the subsequent ammonia recovery unit.

The reasons therefore were the too small size of the struvite crystals and an insufficient separation of the small crystals via the hydrocyclone. Consequently, the retention time of the small crystals in the reactor was too short to allow the crystals to grow bigger. Different measures were investigated to increase the crystal size:

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- The flow rate in the hydrocylone was increased to better separate the fine crystals from the liquor.
- The geometry of the settler was changed and the slope of the declining reactor wall was increased to allow for better settling conditions of the small crystals
- Different $MgCl_2$ dosing rates were tested (Figure 13) to allow for a better crystal growth.
- The retention time of the crystals in the reactor was increased by a delayed harvest of the crystals. However, at the same time, a clogging event of the settler occurred.

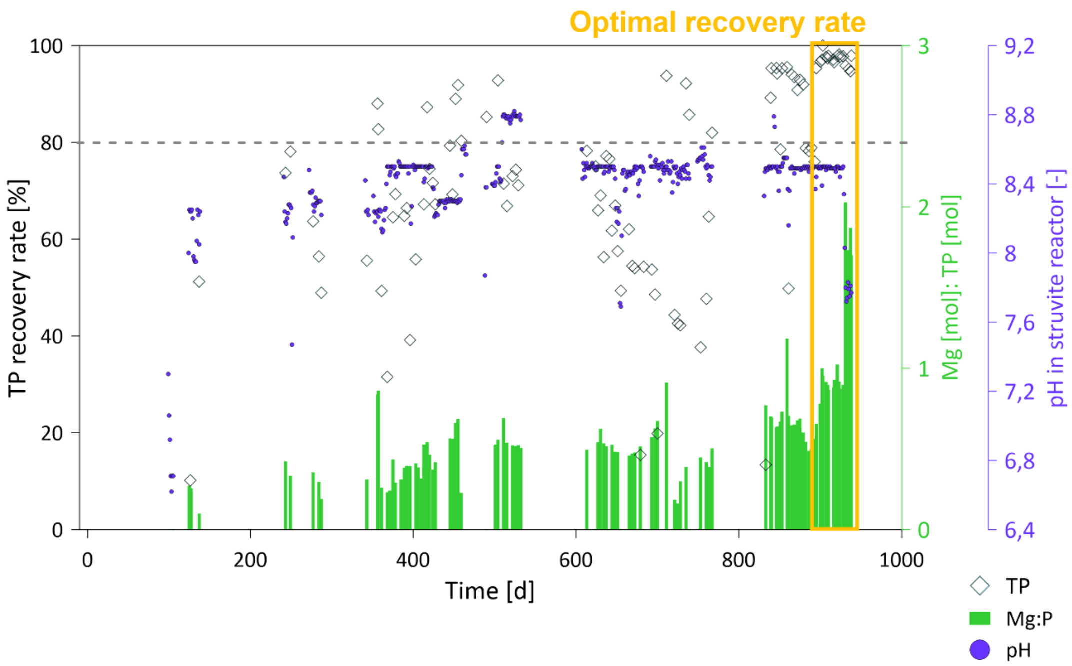

Figure 13 Phosphorus recovery rate referring to the total phosphorus (TP), pH and $MgCl_2$ dosing rate: after 900 days high recovery rates were reached with optimal operating conditions

After 900 days, the mixing conditions in the reactor were further optimised implementing an enlarged stirrer length and using a higher agitation speed. Furthermore, to extend the hydraulic retention time of the crystals, the small harvested crystals were reinjected in the reactor using an external vibrator and in the settler nozzels were exchanged to avoid any clogging. Simultaneously, the $MgCl_2$-dosing was increased shown by the ratio of the magnesium to the total phosphorus (Figure 13). Using a high Mg:P molar ratio of around 2, resulted in a recovery rate above 80% at a lower pH of 7.8. In contrast to the high recovery rates during the days before, the pH was at 8.5 and the Mg:P ratio varied between 0.8 and 1.

As shown in Figure 14, the expected phosphorus recovery rate above 80% was always reached with a molar ratio for Mg:P > 0.8. However, the molar ratio of N:P did not reveal any correlation in its investigated range between 4 and 25. It mainly varied between 8 and 10.

The chemical composition of the produced struvite showed so low contents of Ca, Na, K, Fe, S, Al, B, Mn and Co, that that the labelling only for the main nutrients P, Mg and N is required according to the German fertiliser ordinance (DüMV 2012, Figure 15).

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Furthermore, the P content is higher than 10% and complies with the German fertiliser ordinance (DüMV 2012).

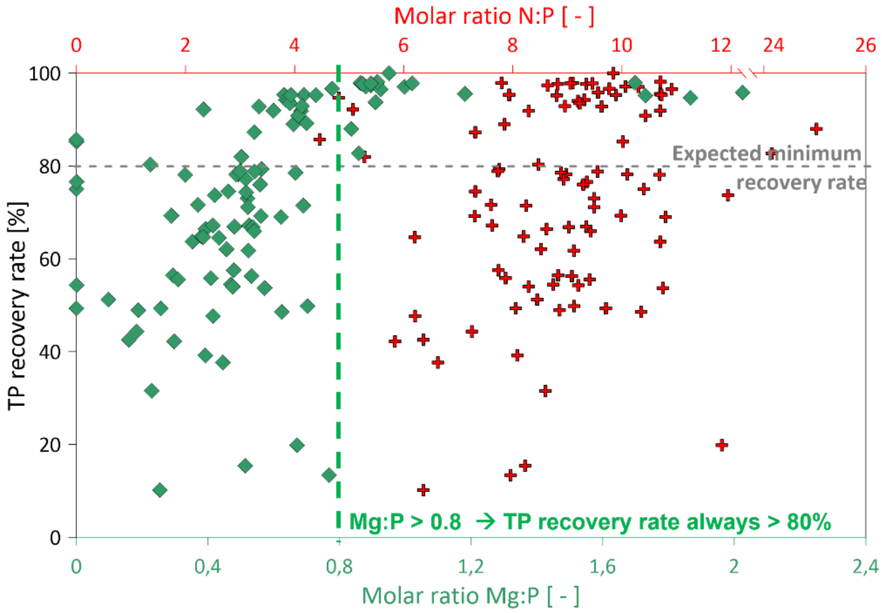

Figure 14 Case study Braunschweig: phosphorus recovery rates depending on the molar ratio of Mg:P: for Mg:P > 0.8 the expected recovery rates are always reached; no correlation observed for N:P

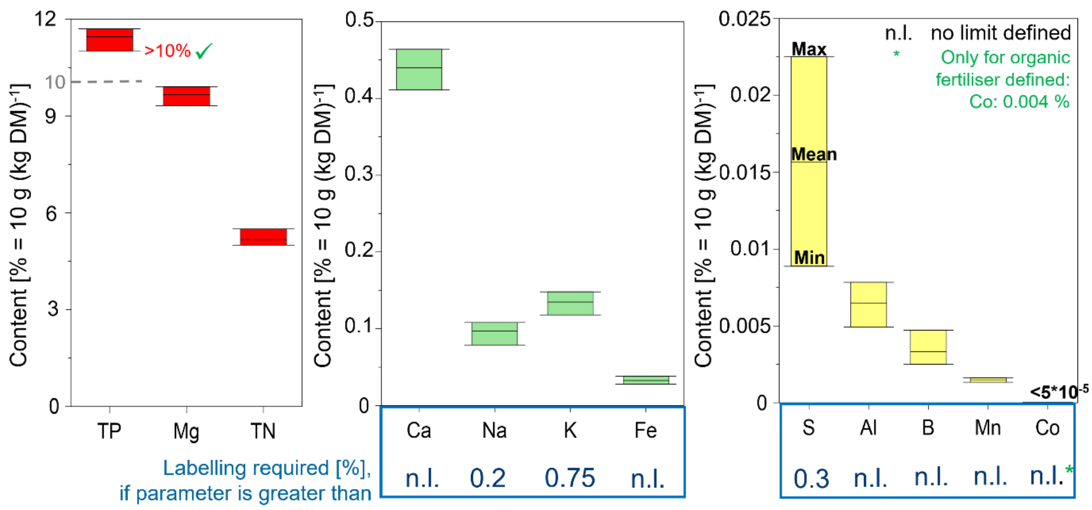

Figure 15 Chemical composition of the produced struvite of n=4 samples: the P content complies with the German fertiliser ordinance (DüMV 2012) and labelling is only required for the main nutrients.

The heavy metals contents are also far below the thresholds of the German fertiliser ordinance (DüMV 2012) and even far below the value, for which a labelling is required (Figure 16). Thus, the produced struvite has a high quality. One further requirement of the German fertiliser ordinance is however a grain size of smaller and equal to 0.63 mm and 0.16 mm for 98% and 90% of the struvite crystals, respectively. Those sizes are much smaller than the grain sizes of the produced struvite ranging roughly between 0.5 and 2 mm. Hence, to promote better such technologies in Germany, the German fertiliser ordinance should include a wider range grain sizes.

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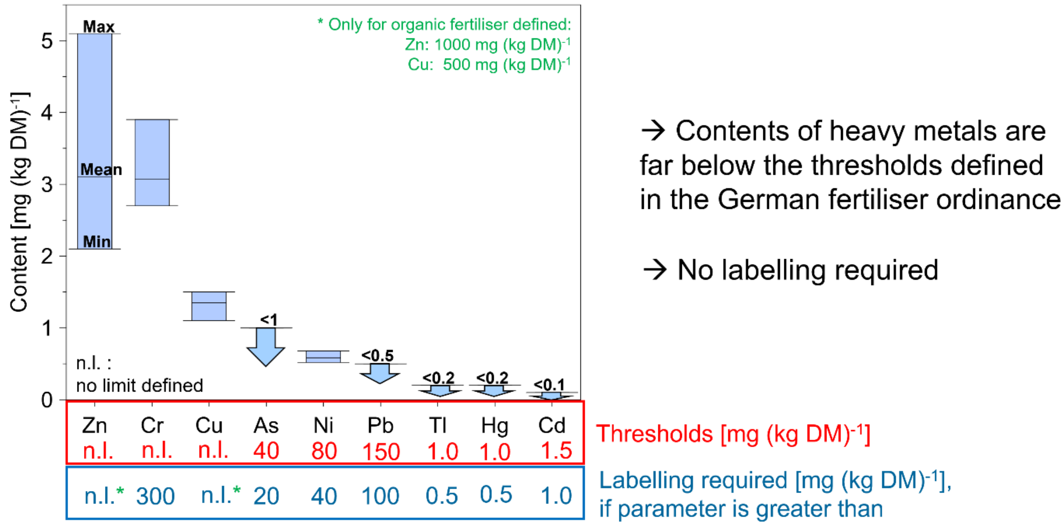

Figure 16 Contents of heavy metals in the produced struvite (n= 4 samples): according to the German fertiliser ordinance (DüMV 2012) no labelling of heavy metals are required, because the actual contents are far below the thresholds of the ordinance indicating a high quality of the product

Since Nov. 30th 2021, the Fertilising Products Regulation also includes struvite that has been recovered from sewage sludge and wastewater (EU 2021/2086). In the case of Braunschweig, however, the struvite will be used in the region, why in NextGen the German fertiliser ordinance was considered. If the Fertilising Products Regulation shall be applied, additional parameters must be determined such as hexavalent chromium, biuret and perchlorate. For Zn, Cu, As, Ni, Pb, Hg, and Cd the thresholds are quite similar to those in the German fertiliser ordinance and their actual content is far below their thresholds.

7.3 Ammonium sulphate production unit via air stripping and gas scrubbing

In 2019, the ammonium sulphate production unit was implemented. As shown in Figure 17, the process is running since almost 1000 days with periods of downtimes due to the optimisation demand of the struvite production process. However, during the periods of operation, the nitrogen recovery rates ranged mainly between 88% and 97% in the expected range above 85%. Two optimal operating conditions were identified for pH 11 with a temperature at 55 °C and for pH 9.5 with a temperature at 65 °C.

Due to the lower pH of 9.5 compared to a pH of 11, around 30% of sodium hydroxide was saved. However, due to the higher temperature of 65 °C compared to 55 °C, the heat demand increased. Because excess heat from the combined heat and power plant is available, the operating condition with the lower pH is beneficial for Braunschweig.

A further decrease in the temperature below 55° C and down to 50°C at the pH of 9.5 resulted in a recovery rate of 79% around day 900 that was considered as too low. Therefore, if a recovery rate of 85% and greater is required, the temperature should be maintained at 55 °C for a pH at 9.5.

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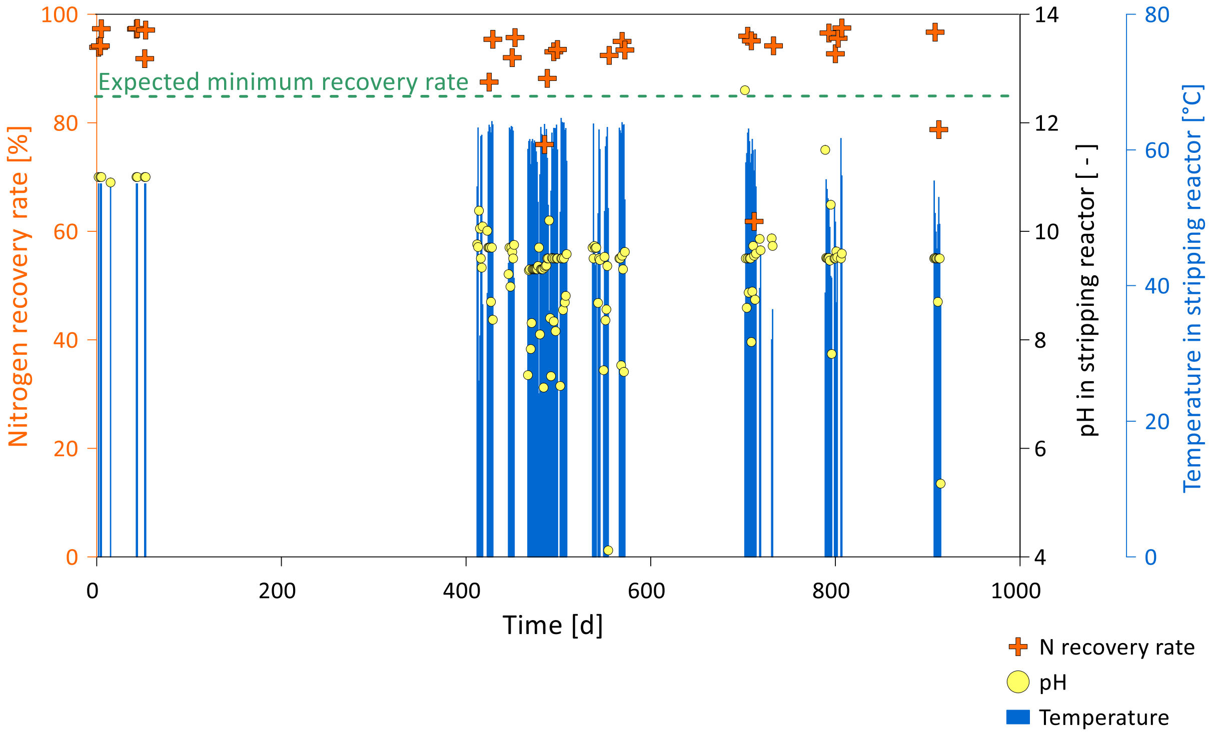

Figure 17 Nitrogen recovery rates reach their expected range at 85% and higher with different operating conditions in pH and temperature

The chemical composition of the ammonium sulphate solution is shown in Figure 18. The nitrogen content is around 9% and complies with the German fertiliser ordinance (DüMV 2012) which requires a content above 5%. Correspondingly, the sulphur content is around 10% and hence above 6% as required by the German ordinance (DüMV 2012).

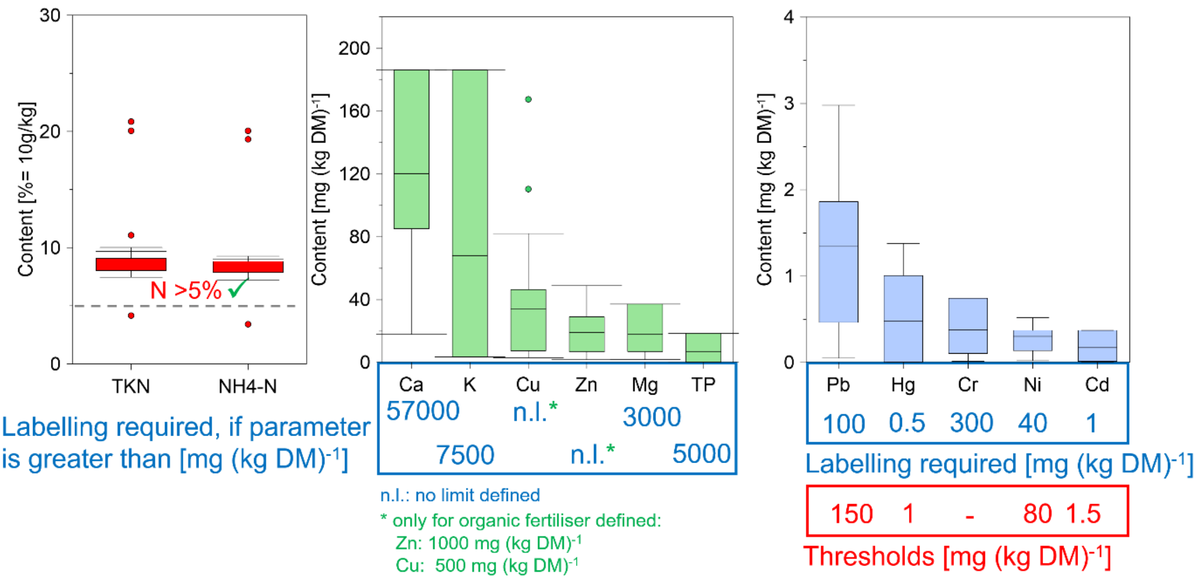

Figure 18 Chemical composition of the ammonium sulphate solution (n= 20 samples) compared to the legal requirements of the German fertiliser ordinance (DüMV 2012): Hg is critical, but the other parameters are far below the legal thresholds

For Ca, K, Mg, TP, Pb, Cr, Ni and Cd, their contents are below their defined thresholds and below the limit value, for which they have to be labelled. For Cu and Zn, the

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German fertiliser ordinance (DÜMV 2012) does not provide any values as thresholds or for labelling. However, the ordinance provides values for organic fertilisers in terms of Cu and Zn. For a rough estimation, those values are used for comparison. The actual contents are on average a factor 10 and a factor 50 below the limit for labelling indicating a good quality. However, for Hg, its content is for every fourth sample above its legal threshold and for every second sample very close to the limit value for labelling. Hence, for Hg the ammonium sulphate solution does not always comply with the German fertiliser ordinance (DüMV 2012).

In order to investigate, what the source for the Hg contamination is, the concentration of Hg was measured in the effluent from the struvite production unit that is equal to the influent to the ammonia stripping unit (Figure 19).

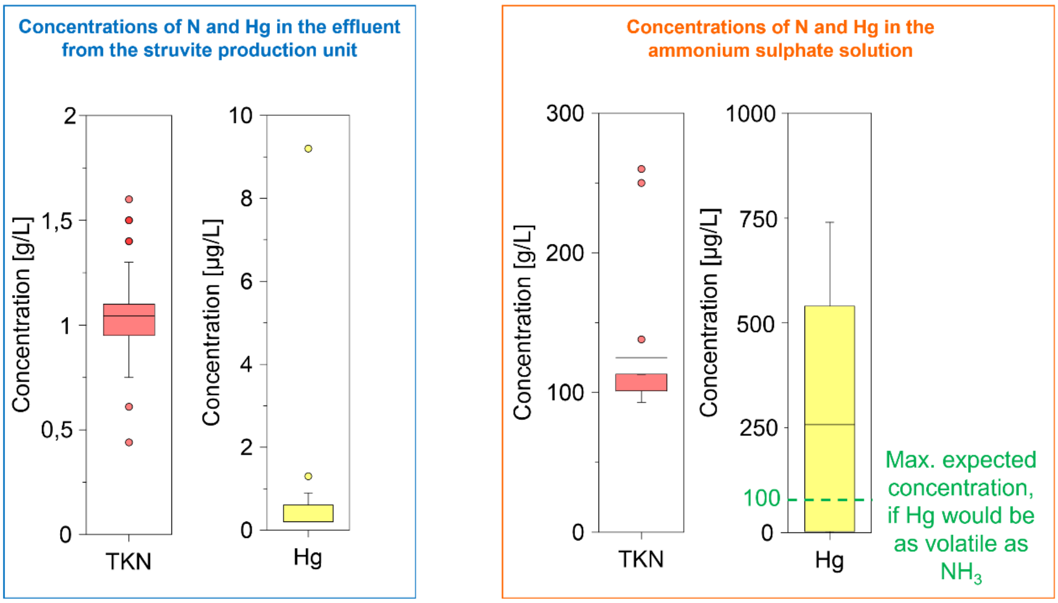

Figure 19 Concentrations of N and Hg in the effluent from the struvite production unit compared to the concentrations in the ammonium sulphate solution units.

The Hg concentration in the influent stream to the stripper is mainly below 1 µg/L. According to Heidel et al. 2014, the gaseous emission of Hg in its elemental form is enhanced via aeration and alkalisation at a temperature of 60 °C. Those conditions are met in the air stripping unit with a pH at around 9.5 and a temperature of 65° C. Assuming, that Hg is as volatile as NH_3, the maximum expected concentration of Hg in the ammonium sulphate concentration is estimated by the same concentration factor as for the nitrogen (TKN). It should be noted that Heidel et al. 2014 observed a gaseous emission rate of only 35%, what is much lower than that assumed here with 85-97% referring to the nitrogen recovery rate. Hence, in this worst case scenario, the expected concentration of Hg would be equal to 1 µg/L *100 = 100 µg/L. Due to the actual concentration in the ammonium sulphate solution which is a factor of 7.5 higher than the expected one, the Hg contamination must have another origin. This suggests the sulphuric acid to be the potential source for the contamination with Hg. Therefore, an analysis of the sulphuric acid will be conducted in the near future.

In the Fertilising Products Regulation (EC 2019/1009), ammonium sulphate recovered from sewage sludge and/or wastewater is not explicitly considered until now. Because the ammonium sulphate solution will be used in Germany, the focus in NextGen was on the compliance with the German fertiliser ordinance.

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8. Comparison of baseline situation and Nextgen KPIs

8.1 Thermal pressure hydrolysis

Before the implementation of NextGen (baseline situation), the primary and excess sludge as well as fat, oil and grease (FOG) were digested in three one-stage digesters. The system did not involve a thermal pressure hydrolysis. The digesters were operated parallel at a temperature of 38 °C. With the implementation of the thermal pressure hydrolysis, the one stage digesters were connected to a two stage digestion system and one reactor was operated at an elevated temperature of 55 °C (Table 5). As already shown in chapter 7.1, the biogas production rate increased because of the effect of the thermal pressure hydrolysis. Correspondingly, the methane production rate increased on average by a factor of 1.2. Also, the dewaterability of the digestate increased by a factor of 1.1.

Table 5 Biogas production rates after the implementation of the THP

WITH IMPLEMENTED NEXTGEN SYSTEM		Units	Mean	Standard deviation	Frequency or number of measurements	Comments
Dry matter content of digestate after dewatering		%	24	2	**once a week**	2020-2022
Digester 1 (1st stage)	Operating temperature	°C	38			
	Digester Volume	m^3	4.450			
	Gas production rate	Nm^3/h	162	35	**continuous flow measurement**	2020-2022
	Methane content	%	61	1.3		
Digester 2 (2nd stage)	Operating temperature	°C	55			
	Digester Volume	m^3	2.100			
	Gas production rate	Nm^3/h	127	40	**continuous flow measurement**	2020-2022
	Methane content	%	61	1.3		
Digester 3 (2nd stage)	Operating temperature	°C	38			
	Digester Volume	m^3	4.450			
	Gas production rate	Nm^3/h	206	60	**continuous flow measurement**	2020-2022
	Methane content	%	61	1.4		

The additional biogas is used for steam production for the thermal pressure hydrolysis and to produce more heat and energy via the CHP. Hence, the heat supply from external sources decreased from 106 to 17 kWh/year by 84% and the electricity production increased from 9000 kWh/year to 9800 kWh/year by 8%. As already explained in chapter 7.1, a future scenario, in which the total biogas is used in the CHP to produce HT heat and electricity could further reduce the heat loss in summer, if the HT heat would be reused for the steam production process.

The increase of 20% in the methane production rate was caused by an improved solubilisation of the sludge that increased the availability of substrate for anaerobic biodegradation due to the effect of the thermal pressure hydrolysis. Hereby, it should be noted, that only 42% of the organic load to the second digestion stage was pre-treated via the thermal pressure hydrolysis. This means that the methane production rate referring only to the hydrolysed substrate increased on average over 20%. However, also the temperature of one digester was increased from 38°C to 55°C compared to the baseline situation (Digester 2) and thus, more effects might have contributed to the higher methane production rate as the higher temperature.

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An increase in the biogas production rate due to the thermal hydrolysis process was also observed by Neyens and Baeyens (2003) and Razavi et al. (2021). Razavi et al. (2021) even showed an increase of 40% in their methane yield. However, the German network of experts for water, wastewater and waste (DWA) indicates in its guidelines that typical increasing rates in biogas production due to a thermal treatment are between 15 and 25% (DWA 2014) what is in the range of the observed enhancement of the biogas production process in Braunschweig.

The better dewaterability of the digestate due to the thermal pressure treatment was also shown by Zhen et al. 2017. Neyens and Baeyens (2003) and Metcalf et al. 2013 even reached dry solids contents between 30% and 52%. In Braunschweig the dry solids content of the digestate increased only from 22% to 24% on average. However, in this case, only 15% of the influent to the second digestion stage was pre-treated via the thermal pressure hydrolysis and hence, 85% was not affected by the treatment, but contributed to the dry solid content. Thus, to achieve a better dewaterability of 10% of the mixed digestate, the hydrolysed fraction must have had a dry solid content of 42%. This is in accordance with the observed results by Neyens and Baeyens (2003) as well as with the indications of Metcalf et al. (2013).

8.2 Struvite production

Before the implementation of NextGen in the baseline scenario, the phosphorus was eliminated from the wastewater via the enhanced biological phosphorus removal process and a chemical phosphorus removal process with $FeClSO_4$. This resulted in a phosphorus concentration in the effluent of the WWTP of 0.7 mg/L on average.

Due to the new struvite production plant, the phosphorus in the return load to the WWTP decreased and hence, the phosphorus concentration in the effluent was 0.6 mg/L on average in 2021, even though the struvite recovery plant was not permanent in operation (Table 6). Thus, with the struvite recovery plant in operation the legal requirement is easily fulfilled with a phosphorus concentration below 1 mg P/L in the effluent as required by the German wastewater directive (AbwV 2022).

Before NextGen, the phosphorus was reused in agriculture via the application of the sludge on the fields and via reusing the effluent for irrigation of the fields. Due to legal restrictions regarding the application of digestate on the fields, its fraction decreased from 70% in 2019 to 60% with 2365 t/a on average for 2020 and 2021 (Table 6). Thereby, the remaining 30% and 40% were incinerated. However, since the implementation of the nutrient recovery units, the phosphorus is recovered via struvite in addition. Due to the optimisation phase of the process, the planned yearly rate of struvite production was not reached yet during a full year as shown in chapter 7.2. However, 250 t struvite/year are anticipated and thus, 30 t P/year are planned to be recovered in addition (Table 6). This corresponds to 12% of the influent phosphorus load to the WWTP.

Under optimised conditions, the performance of the struvite production unit was good and the phosphorus recovery rate reached its expected range above 80% as detailed outlined in chapter 7.2. A similar result was also obtained by Park et al. 2020, who used digested sludge filtrate as well and reached recovery rates between 83 and 91%. However, they used MgO instead of $MgCl_2$. The molar ratio of Mg:P was in a similar range between 0.6 and 1.5 at a pH between 8.25 and 8.5 as for the process in Braunschweig with 0.8 and 1 at a pH at 8.5. Rahman et al. (2014) compared 16

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different struvite production plants obtaining phosphorus recovery rates mainly between 81 and 99% with Mg:P molar ratios mainly between 0.8 and 1.6 and at pH values ranging between 7 and 11. For the pH values below 8, used Mg:P molar ratios were between 1.2 and 2.4. Those observations correspond to the results from Braunschweig, where also at a lower pH of 7.8 in combination with a higher molar ratio Mg:P of around 2, phosphorus recovery rates of 97% were obtained.

Table 6 Crucial parameters to evaluate the phosphorus related processes after implementation of the NextGen technologies

Wastewater to the WWTP	Flowrate	m^3/a	18.665.400	242.009	average values of three years	2019-2021
Effluent from WWTP	Flowrate	m^3/a	17.784.307	225.118		
Solids from WWTP to **field**	Massflow	t/a	2365	633	average values of two years	2020-2021
Solids from WWTP to **incineration**	Massflow	t/a	1549	250		
Struvite production	Production rate	t/a	250	Optimisation of the processes is ongoing: estimated flowrate after optimisation phase of the nutrient recovery plant; actual recovery rate: 30% of expected rate		
Wastewater to the WWTP	TP	mg P /l	13.9	3	continuously measured	2021
	TKN	mg N /l	89	10		
	TSS	mg/L	439	125		
	COD_{hom}	mg/L	1009	151		
	COD_{filt}	mg/L	420	34		
Effluent from WWTP	TP	mg P /l	0.6	0.5		
	TKN	mg N /l	9.3	4		
	TSS	mg/L	7.2	5		
	COD_{hom}	mg/L	43	8		
	COD_{filt}	mg/L	37	5		
Struvite production	TP	g P /kg DM	115	3.1	4	
	TN	g N / kg DM	52	2.2		

As presented in chapter 7.2, the chemical composition of the struvite crystals showed extremely low heavy metals contents which were below their legal thresholds with factors between 5 (e.g. for Tl and Hg) and 300 (for e.g. Pb) (see also Table 7).

Table 7 Quality parameters of the struvite crystals

Parameter		Units	Mean	Standard deviation	Number of measurements	Comments
Struvite	Ca	mg/(kg DM)	4398	219	4	2021
	Na		972	127		
	S		156	62		
	Mg		96575	2528		
	K		1348	126		
	B		33	10		
	Co		<0,5	-		
	Fe		325	47		
	Al		65	12		
	Mn		15	1		
	As		<0.1	-		
	Pb		<0.5	-		
	Cd		<0.1	-		
	Cr		3.1	0.6		
	Cu		1.4	0.2		
	Ni		0.6	0.1		
	Ti		<0.2	-		
	Zn		3.1	1.4		
	Hg		<0.2	-		

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This observation is in accordance with González et al. (2021) and Muy et al. (2021) who also showed lower heavy metal contents struvite compared to those in biosolids and lower contents than defined as limits in the European fertiliser regulation.

8.3 Ammonium sulphate production unit via air stripping and gas scrubbing

Before the implementation of the ammonium sulphate production unit, nitrogen was eliminated only via nitrification and denitrification in the WWTP in Braunschweig. The effluent concentration of total nitrogen was on average 12 mg/L, what is very close to the legally required 13 mg/L by the German wastewater directive (AbwV 2022). However, for Braunschweig, the local authority defined even a stricter nitrogen concentration in the effluent of 12 mg/L.

Due to the implementation of the ammonium sulphate production unit, the nitrogen return load to the WWTP significantly decreased and thus, the resulting nitrogen concentration in the effluent also decreased to 9.3 mg/L on average (Table 8). Hence, the requirements of the German wastewater directive and local authority are fulfilled. The results in terms of the ammonium sulphate production process and the ammonium sulphate quality are outlined and discussed in detail in chapter 7.3.

Table 8 Crucial parameters to evaluate the nitrogen related processes after implementation of the NextGen technologies

Parameter		Units	Mean	Standard deviation	Number of measurements	Comments
Wastewater to the WWTP	Flowrate	m^3/a	18.665.400	242.009	average values of three years	2019-2021
Effluent from WWTP	Flowrate	m^3/a	17.784.307	225.118		
Solids from WWTP to **field**	Massflow	t/a	2365	633	average values of two years	2020-2021
Solids from WWTP to **incineration**	Massflow	t/a	1549	250		
Ammonium sulphate solution production	Production rate	t/a	2200	Optimisation of the processes is ongoing: estimated flowrate after optimisation phase of the nutrient recovery plant; actual recovery rate: 30% of expected rate		
Wastewater to the WWTP	TP	mg P /l	13.9	3	continuously measured	2021
	TKN	mg N /l	89	10		
	TSS	mg/L	439	125		
	COD_{hom}	mg/L	1009	151		
	COD_{filt}	mg/L	420	34		
Effluent from WWTP	TP	mg P /l	0.6	0.5		
	TKN	mg N /l	9.3	4		
	TSS	mg/L	7.2	5		
	COD_{hom}	mg/L	43	8		
	COD_{filt}	mg/L	37	5		
Ammonium sulfate solution	TN	g N /l	125	52	20	
	TP	mg P /l	3.6	4.75		

As already explained for the phosphorus, also the nitrogen was partly reused in agriculture through the application of the digestate on the fields and the irrigation with the effluent of WWTP. Now, to the additional recovery of ammonia from the liquor of dewatered digestate, 2200 t ammonium sulphate solution is expected to be recovered (Table 8). Thus, as soon as the nutrient recovery plants will be operated during an

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entire year under optimised conditions, 170 t N/year will be recovered via ammonium sulphate production and 15 t N/year will be recovered via struvite production in addition. This corresponds to 11% of the influent load to the WWTP.

In Braunschweig, high nitrogen recovery rates between 80 and 97% were reached for two different conditions: pH 11 at a temperature of 55 °C and pH 9.5 at a temperature of 65 °C as shown in chapter 7.3. This was also observed in six other studies summerised by Sengupta et al. (2015). They report about nitrogen recovery rates between 80 and 97% at pH conditions between 8 and 11 and at temperatures at 50°C, 75°C and 80°C. The higher the temperatures were and/or the higher the pH was, the higher the recovery rates were. Hence, a higher process temperature allows the process to be operated at a lower pH in order to save chemicals. This was also shown in Braunschweig. The increase from 55°C to 65 °C allowed the decrease in pH from 11 to 9.5 maintaining the expected recovery rate above 85% at both conditions. Hence, 30% of NaOH was saved due to the process temperature increase.

As already shown and discussed in chapter 7.3, the quality of the ammonium sulphate solution highly depends on the quality of the sulphuric acid. In the case of the ammonium sulphate produced in Braunschweig, the increased mercury concentration obviously resulted from the sulphuric acid. For the other pollutants, the legal thresholds were far above the measured concentrations indicating a high quality of the produced fertiliser. Table 9 shows the corresponding average values and standard deviations for the quality parameters referring to the ammonium sulphate solution and not to its dry matter content as in chapter 7.3.

Table 9 Quality parameters of the ammonium sulphate solution

Parameter		Units	Mean	Standard deviation	Number of measurements	Comments
Ammonium sulphate solution	TKN	g/L	125	52	20	2021
	Ca	mg/L	65	28		
	Mg		10	8		
	K		37	47		
	Pb	µg/L	722	447		
	Cd		93	97		
	Cr		203	156		
	Cu	mg/L	18	21		
	Ni	µg/L	163	76		
	Zn	mg/L	10	8		
	Hg	µg/L	258	281		

9. Lessons learned

At the case study in Braunschweig, three different technologies were implemented, that are interconnected. The interaction of the single technical units is complex and has to be considered in the system design. The system design, the installation, system control and automation of the technological units worked well and only minimal optimisation was necessary.

However, as with many other innovative processes, numerous unexpected problems also occurred here, some of them were or are very time-consuming to deal with. Therefore, it is important to have employees who are open to new processes and that technology suppliers are available for a longer time period even after the commissioning of the system. In the following tables, more details about the lessons learned are presented per technology.

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9.1 Thermal pressure hydrolysis

Required competence	LOW  HIGH

An intensive training is needed to provide a knowledge that is far beyond the "standard" wastewater treatment knowledge such as:

- Thermal hydrolysis process
- Operation and maintenance of a high pressure and high temperature (145 - 165 °C) system
- Explosion proof systems/environments
- Steam production

Due to the innovative technology, open minded and solution oriented personnel is beneficial to operate such a technology. A daily manual process control and maintenance is conducted during at least 2h/d.

Maintenance	LOW  HIGH

The thermal pressure hydrolysis unit is a high-maintenance product. Under normal conditions the effort for maintenance and manual process control is 2 h/d. Due to unforeseen events such as broken elements or unexpected gas leakages, the effort increases above 2h/d.

Twice a year extensive maintenance work is required lasting around one week. In this case, the following steps are required:

- Intensive investigation regarding wearing of plant components
- Functional tests
- Cleaning of plant components

For this work, usually external experts support the extensive maintenance work.

During the first three years of operation, the plant usually had two downtimes per month.

Technological risks	LOW  HIGH

- Leakages of gas, steam or hot sludge can occur; in the case of methane emissions → explosion proof design of the unit is required. Only with an explosion proof design the technological risk is considered as relatively low.
- Depending on the temperature non-biodegradable soluble COD can form (~10 mg/L) → not critical for Braunschweig (COD_{eff}= 35 mg/L < 50 mg/L)
- Due to the innovative technology, it is important that the supplier of the technology is available for a longer time period after the installation and commissioning of the system in order to optimize the plant

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9.2 Struvite production

Required competence LOW  HIGH

An intensive training is needed to provide a knowledge that is far beyond the “standard” wastewater treatment knowledge such as:

- Chemistry and process engineering (especially: struvite formation)
- Operation of a precipitation system

Due to the innovative technology, open minded and solution oriented personnel is beneficial to operate such a technology. A daily manual process control and maintenance is conducted during at least 2h/d at the moment and is expected to decrease in the future.

Depending on the fate of the produced struvite, knowledge on fertiliser marketing might be necessary. Otherwise, a cooperation with the fertilising industry might be beneficial.

Maintenance LOW  HIGH

The struvite production unit is also a high-maintenance product. Under normal conditions the effort for maintenance and manual process control is 2 h/d. Due to unforeseen events such wash out of small struvite crystals and clogging of pipes, the effort increases above 2h/d.

Twice a year extensive maintenance work is required lasting around one week. In this case, the following steps are required:

- Intensive investigation regarding wearing of plant components
- Functional tests
- Cleaning of plant components

For this work, usually external experts support the maintenance work.

During the first three years of operation, the plant usually had two downtimes per month.

Technological risks LOW  HIGH

It is difficult to predict, how good the precipitation process will work for a certain feed stream quality. Furthermore, the crystal growth to a certain crystal size (e.g. 3 mm) can be difficult to control also depending on the feed stream quality.

Correspondingly to the challenge of a controlled crystal growth, the risk of wash out of smaller crystals can occur and therefore, those small crystals can clog pipes.

Thus, the commissioning time was and is still very long (already 3 years) in the case of Braunschweig.

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9.3 Ammonium sulphate production unit via air stripping and gas scrubbing

Required competence

LOW  HIGH

A comprehensive training is needed to provide the knowledge that is needed and does not belong to the classical wastewater treatment knowledge of a WWTP operator in Germany such as:

- Ammonia air stripping
- Ammonia gas scrubbing in sulphuric acid
- Handling of hazardous substances (H_2SO_4 96%, NaOH 50%, HCl 31%)

However, the process is easy to control, so that the recovery rate can be adjusted as required. Due to the technology maturity, challenges during operation are rare compared to the thermal pressure hydrolysis or the struvite production unit.

Maintenance

LOW  HIGH

The ammonium sulphate production unit is a mature and robust technology. It can be easily switched on and off and is a low maintenance technology, if the requirements such as a particle-free feed stream are fulfilled. In the case of the occurrence of scaling on the heat exchangers and/or on the packing, the maintenance work of the plant becomes challenging.

However, in the case this technology depends on a pre-treatment such as the recovery of struvite, downtimes of the pre-treatment will also cause downtimes of this technology.

Technological risks

LOW  HIGH

The technological risk depends mainly on the chemical composition of the feed stream. For the ammonia recovery unit, the feed stream must be free of particles. In the case, the feed stream is prone to precipitation of certain minerals such as calcite or struvite, a pretreatment is required to avoid precipitation in the ammonia recovery unit. In Braunschweig for example, a struvite precipitation unit was implemented upstream of ammonia recovery unit. In the case, the struvite precipitation unit does not retain the struvite crystals completely, there is a risk of clogging or scaling, too.

The product quality of the ammonium sulphate solutions highly depends on the quality of the sulphuric acid. Therefore, its quality should be considered and controlled, before it is applied in the gas scrubber.

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10. Best practice guideline for operating the technology

10.1 Thermal pressure hydrolysis

Important aspects to consider during the design and construction of the plant:

- Reuse of excess heat increases energy efficiency of the whole system
- Enabling the recirculation of exhaust gas and/or exhaust steam
- Required operating conditions for pressure, temperature and hydraulic retention time must be maintained, but should also be adjustable if needed
- Suitable materials must be used for the system (corrosion resistant, explosion proof, etc.)
- Explosion proof environment and system due to methane content and possible leakages
- Compliance with the country specific requirements for health and safety during technology operation

Crucial parameters for the optimisation of the production process:

Pressure, temperature and hydraulic retention time (HRT) (Table 10) were observed to deliver the best results for 145 °C at 4 bars with an HRT of 90 min. In general, higher temperatures with a shorter HRT such as 165 °C at 6 bars and a HRT of 30 min are also possible. However, the lower the temperature, the lower is the formation of non-biodegradable dissolved organic matter. Simultaneously, the necessary HRT increases with decreasing temperature.

Table 10 Crucial operating parameters for the thermal pressure hydrolysis: ranges for the best results regarding the release of dissolved organic matter

Parameter	Units	Min	Max
TS feed	%	**10**	**13**
Pressuriser • **Temperature** • **Pressure** • **HRT**	°C bar min	**105** **0 → 8** **5**	
Reactor • **Temperature** • **Pressure** • **HRT**	°C bar min	**145** **4** **90**	
Economiser • **Temperature** • **Pressure** • **HRT**	°C bar min	**105** **0.2** **10-15**	

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10.2Struvite production unit

Important aspects to consider during the design and construction of the plant:

- Suitable materials must be used for the system (corrosion resistant, etc.)
- Compliance with the country specific requirements for health and safety regarding the operation of the process (handling of chemicals, etc.)
- System should be flexible and adjustable (also accessible for retrofitting work) in order to increase the reaction time in the struvite reactor, to adjust the settling conditions of the crystals and/or to reinject small crystals in the reactor to allow for a longer growth time

Important aspects to consider during the start-up of the plant:

- The process water must be as free as possible of particles → functioning test is even recommended to be done with clean water
- The chemical composition of the process water should be as constant as possible and the flow rate should be sufficient high to run the process properly
- Sampling plan should be considered and the sampling documented

Crucial parameters for the optimisation of the production process:

- Chemical composition of the process water (phosphate and ammonium concentrations, TSS) and pH as shown in Table 11,
- The $MgCl_2$ dosing rate depends highly on the phosphorus concentration in the influent to the reactor and thus, the Mg:P molar ratio in the influent is crucial. Best results were obtained for Mg:P > 0.8 (see chapter 7.1)
- Rotational speed of the agitator in the struvite reactor: the best results were obtained in this case using a rotational speed between 1620 and 2700 rpm; however, this is very case specific.
- Hydraulic retention time of the crystals should be: in this case longer then 7d.

The indicated mixing conditions and retention time allowed for the best crystal growth during the presented investigations.

Table 11 Crucial operating parameters for the struvite production process: ranges for the best results

Parameter	Units	Min	Max
PO_4-P feed	mg/L	**250**	**500**
NH_4-N feed	mg/L	**770**	**1800**
TSS	mg/L	**<600**	
pH in reactor	-	**8.5**	
$MgCl_2$ dosing rate	L/(m^3 feed)	**1.9**	**6**
Mg:P molar ratio feed	-	**0.8:1**	**2:1**
HRT of crystals in reactor	d	**>7**	
Rotational speed in reactor	rpm	**1620**	**2700**

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10.3 Ammonium sulphate production via air stripping and gas scrubbing

Important aspects to consider during the design and construction of the plant:

- Suitable materials must be used for the system (corrosion resistant, etc.)
- Compliance with the country specific requirements for health and safety regarding the operation of the process (handling of chemicals, etc.)
- System should be flexible and adjustable (also accessible for retrofitting work)
- Enabling heat recovery contributes to a lower CO2 footprint of the process
- Using as much excess heat as possible to enable the operation of the process at a higher temperature in order to run the process at a lower pH allowing to save NaOH
- Recommendation: pre-experiments should be conducted to investigate, whether undesired precipitation processes might occur in the stripping unit, heat exchangers, etc.

Important aspects to consider during the start-up of the plant:

- The process water must be as free as possible of particles.
- The chemical composition of the process water should be as constant as possible and the flow rate should be sufficient high to run the process properly.
- Compliance with the country specific requirements for health and safety
- Sampling plan should be considered and the sampling documented.
- Functioning test for electricity and mechanics should be done.
- Leakage test should be done.

Crucial parameters for the optimisation of the production process:

- Chemical composition of the process water (phosphate and ammonium concentrations, TSS) (Table 12),
- To control the ammonia recovery rate, temperature and pH are the crucial parameters. As shown in chapter 7.3, the best results were obtained at a temperature between 55 °C and at a pH of 9.5.

Table 12 Crucial operating parameters for the ammonium sulphate production process: ranges for the best results

Parameter	Units	Min	Max
NH_4-N feed	mg/L	**>700**	
TSS feed	mg/L	**<600**	
pH/T in stripping unit	-/°C	**9.5/55**	

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11. Literature references

AbwV (2022). Verordnung über Anforderungen an das Einleiten von Abwasser in Gewässer (Abwasserverordnung – AbwV vom 17. Juni 2004 BGBl. I S.1108, 2625 und vom 20. Januar 2022 BGBl. I S. 87). Bundesministerium der Justiz und Bundesamt für Justiz. http://www.gesetze-im-internet.de/abwv/AbwV.pdf

Barber, W. (2016). Thermal hydrolysis for sewage treatment: a critical review. Water Research, 104, 53–71. https://doi.org/10.1016/j.watres.2016.07.069

Böhler, M., Büttner, S., Liebi, C., Siegrist, H. (2012). Ammoniakstrippung mittels Luft zur Behandlung von Faulwasser und Urin auf der auf der Kläranlage Kloten/Opfikon. Aqua & Gas, 1, 1-7. https://doi.org/10.2166/wst.2009.045

Bougrier, C., Albasi, C., Delgenès, J., Carrère, H. (2006). Effect of ultrasonic, thermal and ozone pre-treatments on waste activated sludge solubilisation and anaerobic biodegradability. Chemical Engineering and Processing: Process Intensification, 45, 8, 711–718. https://doi.org/10.1016/j.cep.2006.02.005

Cornel, P., Schaum, C. (2009). Phosphorus recovery from wastewater: needs, techniques and costs. Water Science and Technology, 59, 1069–1076. https://doi.org/10.2166/wst.2009.045

Desmidt, E., Ghyselbrecht, K., Zhang, Y., Pinoy, van der Bruggen, B., Verstraete, W., Rabaey, K., Meesschaert, B. (2015). Global phosphorus scarcity and full-scale P-recovery techniques, Critical Reviews in Environmental Science and Technology, 45, 336-384. https://doi.org/10.1080/10643389.2013.866531

DüMV (2012). Verordnung über das Inverkehrbringen von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln (Düngemittelverordnung – DüMV vom 5. Dezember 2012, BGBl. I S. 2482), Bundesministerium der Justiz und Bundesamt für Justiz. https://www.gesetze-im-internet.de/d_mv_2012/D%C3%BCMV.pdf

DWA 2014. Merkblatt DWA-M 302 Klärschlammdesintegration, DWA Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., Hennef, 82 S., ISBN 978-3-88721-227-8

EU (2019/1009) Regulation of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32019R1009 accessed on Oct. 7th 2022.

EU (2021/2086) Commission Delegated Regulation of 5 July 2021 amending Annexes II and IV to Regulation (EU) 2019/1009 of the European Parliament and of the Council for the purpose of adding precipitated phosphate salts and derivates as a component material category in EU fertilising products, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021R2086&qid=1665136891038 accessed on Oct. 7th 2022

González, C., Fernández, B., Molina, F., Camargo-Valero, M., Peláez, C. (2021). The determination of fertiliser quality of the formed struvite from a WWTP. Water Science and Technology. 83, 12, 3041-3053. https://doi.org/10.2166/wst.2021.162

Heidel, B., Rogge, T., Scheffknecht, G. (2014). Controlled re-emission of mercury in waste water treatment. Energy Procedia 61, 2307-2310. https://doi.org/10.1016/j.egypro.2014.11.1190

Heinze, J. (2022). Own data (personal communication), Abwasserverband Braunschweig.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Higgins, M., Beightol, S., Mandahar, U., Suzuki, R., Xiao, S., Lu, H., Le, T., Mah, J., Pathak, B., DeClippeleir, H., Novak, J., Al-Omari, A., Murthy, S. (2017). Pretreatment of a primary and secondary sludge blend at different thermal hydrolysis temperatures: impacts on anaerobic digestion, dewatering and filtrate characteristics. Water Research, 122, 557–569. https://doi.org/10.1016/j.watres.2017.06.016

Kleyböcker, A., Kraus, F., Moermann, W., Pudova, N., Holba, M., Dünnebeil, A. (2020). Efficient carbon, nitrogen and phosphorus cycling in the European agri-food system and related up- und down-stream processes to mitigate emissions, Circular Agronomics, Deliverable 3.1, Grant Agreement Number 773649. https://www.circularagronomics.eu/wp-content/uploads/CA-D3.1-E-0820-Classification-streams.pdf

Kratz, S., Vogel, C., Adam, C. (2019). Agronomic performance of P recycling fertilizers and methods to predict it: a review, Nutrient Cycling in Agroecosystems, 115, 1-39. DOI: https://doi.org/10.1007/s10705-019-10010-7

Kuhn, E., Rensch, D., Haueter, R., Kopp, J. (2013). Stand der Technik für die (mechanische) Entwässerung von Klärschlamm, Ermittlung und Beschreibung, AWEL Amt für Abfall, Wasser, Energie und Luft, Abteilungen Abfallwirtschaft und Betriebe sowie Gewässerschutz, Baudirektion Kanton Zürich, Schweiz, 16 S. http://docplayer.org/53056282-Stand-der-technik-fuer-die-mechanische-entwaesserung-von-klaerschlamm.html (accessed on 2020-12-14)

Liu, X., Xu, Q., Wang, D., Yang, Q., Wu, Y., Li, Y., Fu, Q., Yang, F., Liu, Y., Ni, B.J., Wang, Q., Li, X., 2019. Thermal-alkaline pretreatment of polyacrylamide flocculated waste activated sludge: process optimization and effects on anaerobic digestion and polyacrylamide degradation. Bioresource Technology, 281, 158–167. http://hdl.handle.net/10453/131838

Metcalf & Eddy, Inc., Tchobanoglous, G., Stensel, H., Tsuchihashi, R. Burton, F. (2013). Wastewater Engineering: Treatment and Resource Recovery, Fifth Edition, McGraw-Hill Education, New York, 2018 p. ISBN 978-0-07-340118-8

Muy, M., Phukana, R., Brader, G., Samad, A., Moretti, M., Haiden, B., Pluchonc, S., Roeste, K., Vlaeminck, S., Spiller, M. (2021). A systematic comparison of commercially produced struvite: Quantities, qualities and soil-maize phosphorus availability. Science of the total Environment, 56, 143726, 1-12. https://doi.org/10.1016/j.scitotenv.2020.143726

NuReSys 2020: http://www.nuresys.be/references.html (accessed on 2020-12-14)

Neyens, E., Baeyens, J. (2003). A review of thermal sludge pre-treatment processes to improve dewaterability. Journal of Hazardous Materials B98, 51-67. https://doi.org/10.1016/S0304-3894(02)00320-5

Park, N., Chang, H., Jang, Y., Lim, H., Jung, J., Kim, W. (2020). Critical conditions of struvite growth and recovery using MgO in pilot scale crystallization plant. Water, Science and Technology, 81, 12, 2511-2521. https://doi.org/10.2166/wst.2020.306

Phothilangka, P., Schoen, M., Wett, B. (2008). Benefits and drawbacks of thermal pre-hydrolysis for operational performance of wastewater treatment plants. Water Science and Technology, 58, 8, 1547-1553. https://doi.org/10.2166/wst.2008.500

Pilli, S., Yan, S., Tyagi, R., Surampalli, R. (2015). Thermal pretreatment of sewage sludge to enhance anaerobic digestion: a review. Critical Reviews in Environmental Science and Technology, 45, 6, 669-702. https://doi.org/10.1080/10643389.2013.876527

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Rahman, M., Salleh, M., Rashid, U., Ahsan, A., Hossain, M., Ra, C. (2014). Production of slow release crystal fertilizer fromwastewaters through struvite crystallization – A review. Arabian Journal of Chemistry, 7, 139-155. http://dx.doi.org/10.1016/j.arabjc.2013.10.007

Razavi, A., Kaker, F., Koupaie, E., Hafez, H., Elbeshbishy, E. (2021). Biomethane production improvement by hydrothermal pretreatment of thickened waste activated sludge, Water, Science and Technology, 83, 2, 487-500 https://doi.org/10.2166/wst.2020.598

Sengupta, S., Nawaz, T., Beaudry, J. (2015). Nitrogen and Phosphorus recovery from wastewater. Curr Pollution Rep, 1, 155-166. https://doi.org/10.1007/s40726-015-0013-1

Shaddel, S., Ucar, S., Andreassen, J., Østerhus, S. (2019). Engineering of struvite crystals by regulating supersaturation – Correlation with phosphorus recovery, crystal morphology and process efficiency. Journal of Environmental Chemical Engineering, 7, 102918. https://doi.org/10.1016/j.jece.2019.102918

Szymańska, M., Sosulski, T., Szara, E., Wąs, A., Sulewski, P., van Pruissen, G., Cornelissen, R. (2019). Ammonium sulphate from a bio-refinery system as a fertilizer - agronomic and economic effectiveness on the farm scale. Energies, 12, 4721, 1-15. https://doi.org/10.3390/en12244721

Watson, C., Clemens, J., Wichern, F. (2019). Plant availability of magnesium and phosphorus from struvite with concurrent nitrification inhibitor application. Soil Use and Management, 35, 4, 675-682. https://doi.org/10.1111/sum.12527

Zhen, G., Lu, X., Kato, H., Zhao, Y., Li, Y. (2017). Overview of pretreatment strategies for enhancing sewage sludge disintegration and subsequent anaerobic digestion: current advances, full-scale application and future perspectives. Renewable and Sustainable Energy Reviews 69, 559–577. https://doi.org/10.1016/j.rser.2016.11.187

Zhou, P., Meshref, M., Dhar, B. (2021). Optimization of thermal hydrolysis process for enhancing anaerobic digestion in a wastewater treatment plant with existing primary sludge fermentation. Bioresource Technology 321, 124498. https://doi.org/10.1016/j.biortech.2020.124498

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