The main aim of the STEP project was to analyze trends and develop tools and decisions to increase the quality of sewage sludge and it's reuse for wastewater treatment plants (WWTP) of small and medium size. Small wastewater treatment plants in the South Baltic area are facing problem with sewage sludge reuse technologies and processing efficiency. The existing tools are mostly developed for big WWTP.

The project involved 5 entities from 4 Member States countries (Poland, Denmark, Lithuania, Sweden). The partners represented academic/research sector (Universities) and practitioners managing and operating the wastewater treatment plants (WWTP's and municipality). During the last 3 years the project consortium has performed impressive work and has analyzed different aspects of sludge in the scope of different work packages including:

- Clean sludge (measurements, sensors, heavy metal detection and pollutant removal technologies, leakage control),
- Energy efficiency (efficient sludge handling, dewatering, composting),
- Nutrient reuse (optimized nutrient content, efficient composting and modern deodorization).

I hope we were able to summarize our most important results in this whitebook. I also hope that it will help other WWTPs and researchers in the South Baltic Region to find better and more sustainable solutions to existing sludge problems. For the purpose of the planet all the neighbours gathered around the Baltic Sea!

Marcin Hołub

2021

STEP

SLUDGE TECHNOLOGICAL ECOLOGICAL PROGRESS

- increasing the quality and reuse of sewage sludge

SLUDGE
TECHNOLOGICAL ECOLOGICAL PROGRESS
– increasing the quality and reuse of sewage sludge

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SPIS TREŚCI

Introduction to the STEP project whitebook

During the last decades the environmental and ecosystem protection became one of the most important pressure factors on the natural and socioeconomic environment worldwide. The wastewater treatment product – the sludge generated in the Baltic Sea region also influences the development of ecosystems. In total 3 928 000 tons of dry solid per year (report from PURE project) will be produced in water treatment plants in the Baltic sea region. According to the report that has been prepared by Milieu Ltd, WRc and RPA for the European Commission, DG, Environment under Study Contract DG ENV.G.4/ETU/2008/0076r in the EU27 10,135,745 tons of dry solid per year are produced while only 39% are reused in agriculture. While sewage sludge contains nutrients and organic matter that are beneficial for the soil, it also contains contaminants such as heavy metals, organic compounds and pathogens. This implies the need for further adapting the developed tools which increase the quality of sewage sludge. STEP project is an answer to EC Directives and provide protection against potential health risks from residual pathogens.

The main aim of the STEP project was to develop tools to increase the quality of sewage sludge that can be reused, our studies were performed for water treatment plants of small and medium size. Small wastewater treatment plants in the South Baltic area are facing problem with sewage sludge reuse efficiency. The existing tools are mostly developed for big WWTP.

Our specific objectives were arranged into work packages and they include:

- reuse of nutrients and lower pollution of the outflowing water;
- studies regarding heavy metal pollution and incoming water content in the SBR;
- a construction of a robust network of different scientific and technical entities so that a creative environment can be developed for innovative solutions leading to generation of projections of future of use of a good quality sewage sludge,
- education of the society and an increase in public awareness so that the public understands the challenges that the water treatment plants are facing;
- an exchange of good practices of the use of different sludge handling technologies between different countries and municipalities.

This whitebook gives You a condensed insight in main project results. Three main work axes were explored: clean sludge (measurements, sensors, heavy metal detection and pollutant removal technologies, leakage control), energy efficiency (efficient sludge handling, dewatering, composting) and nutrient reuse (optimized nutrient content, efficient composting, modern deodorization). STEP project included an efficient partnership having knowledge in different phases of wastewater purification and sludge handling. We hope that You can learn from our studies and adopt our results in Your daily operations.

Chapter 1 CLEAN SLUDGE

Elin Olsson – The municipality
of Höör / Mittskåne Water

1 INTRODUCTION

The overall goal with the activities included in work package 3 (WP3) was to study the influence of wastewater quality and pollutants on the wastewater sludge – this since sludge can be a very valuable resource if the composition of the sludge aligns with national and international legislation. High concentrations of heavy metals and other pollutants can restrict the reuse of sludge and therefore limit its potential as a product.

Within the scope of WP3 several aspects of the topic clean sludge were studied, and a pilot plant was set up in Hörby municipality, Sweden, to further investigate the effects of separate handling of external sludge (sludge not generated at the wastewater treatment plant (WWTP)). The pilot plant project showed how external sludge handling indeed could have a positive effect on the overall composition of the sludge generated in the WWTP – heavy metals in the outgoing sludge were in this case reduced by 5-15%. However, if to invest in such a process further evaluation in relation to both feasibility and efficiency needs to be studied with regards to local conditions and economical aspects.

An extensive comparison between national sludge handling rules was carried out in Deliverable 3.2. The results pointed out that there is no accumulated scientific evidence that there are adverse effects of using sludge from WWTPs in agriculture, that barriers to the use of sludge from WWTPs as a fertilizer in agriculture are sometimes psychological, that extremely strict national limiting values can be a barrier for reuse of sludge and that the use of heavy metals and persistent chemicals in different products needs to be further restricted.

Deliverable 3.1, Small and medium scale WWTP wastewater quality assessment and its influence on sludge quality, was carried out focusing on three different aspects (resulting in several different reports). Focused aspects were wastewater treatment processes and its influence on sludge quality (main focus on nutrients and heavy metals), distribution of phthalate acid esters (PAEs) in wastewater and sludge (study carried out in Lithuania, Denmark and Poland), and quantity and quality of leakage and drainage water – how it might influence the wastewater and how it may may be detected and reduced. These studies highlighted different sources of pollutants. E.g., the concentration of PAEs showed to be very high in the vicinity of industrial parks, residential areas, and roadside drains, which in turn showed that the concentration and distribution of PAEs is highly affected by human activities, and heavy metals may origin both from point sources such as mentioned above but also from diffuse sources such as the bedrock. Results pointed out that it is important to further restrict the use of heavy metals and persistent chemicals, to avoid large primary sources of these substances or apply heavy metal reduction technology and to focus on producers' and consumers' education, application of economic incentives and environmental management in order to address pollution by phthalates.

Further on the agricultural use if sludge in the different project partner countries was studied resulting in Deliverable 3.3.

Overall, the activities carried out within WP3 gave a good overview of the influence of wastewater quality and pollutants on wastewater sludge and many important key factors were identified.

2 SMALL- AND MIDDLE-SIZED WASTEWATER TREATMENT PLANTS – WASTEWATER QUALITY ASSESSMENT AND ITS INFLUENCE ON SLUDGE QUALITY

For the STEP project small- and middle-sized wastewater treatment plants (WWTPs) were studied by all project partners during 2019 This in order to further assess wastewater quality and its influence on sludge quality. Five WWTPs were studied in four countries – giving a wide range of conditions to analyse and compare.

Sludge quality is important when aiming for high reuse of sludge for e.g., agricultural purposes. Reuse of sludge can turn sludge into a useful resource, which can be seen as a product itself, and contribute to increased use of resources following a European circular economy actions' plan.

3 ASSESSMENT – RESULTS & DISCUSSION

3.1 Bornholm Energy & Supply

Rønne WWTP is the largest of the seven biological WWTPs on Bornholm. It was built in 1995 with capacity of 60 000 PE. Wastewater and sludge quality reflect that it is mostly household wastewater without much industry, except the slaughterhouse, the hospital, and a few metal processing industries in Rønne.

Methods for wastewater & sludge quality assessment

At Rønne WWTP inlet and outlet samples were taken as 24-hour flow proportional samples at programmable sampling stations. According to the municipal permit only organics and nutrients were analysed – chemical oxygen demand (COD), biological oxygen demand (BOD_5), total nitrogen (N_{tot}), and total phosphorous (P_{tot}). All collected samples were sent to a certified laboratory (Eurofins) for analysis. Internal analysis was carried through more frequently, as well as on-line monitoring of nitrate, ammonium, oxygen, and phosphorus. Applicable threshold limits at Rønne WWTP were as follows. COD 75 mg/l, BOD_5 15 mg/l, N_{tot} 8 mg/l and P_{tot} 1,5 mg/l as a yearly average.

For sludge, a sample was collected every month by the certified laboratory (ALS). The samples were mixed and sent for analysis every third month. The percentage of dry matter (DM) and concentrations of nutrients, metals, and organic micropollutants were all analysed.

Wastewater quality assessment at WWTP of project partners

The influent levels of BOD_5 to Rønne WWTP were observed to be on average 348 mg/l, and average COD 909 mg/l. The outlet concentrations were of BOD_5 were observed to be on average 2,7 mg/l, and average COD 22 mg/l (se figure 1).
Increased outlet values were seen during mid-February and were connected to high flows.

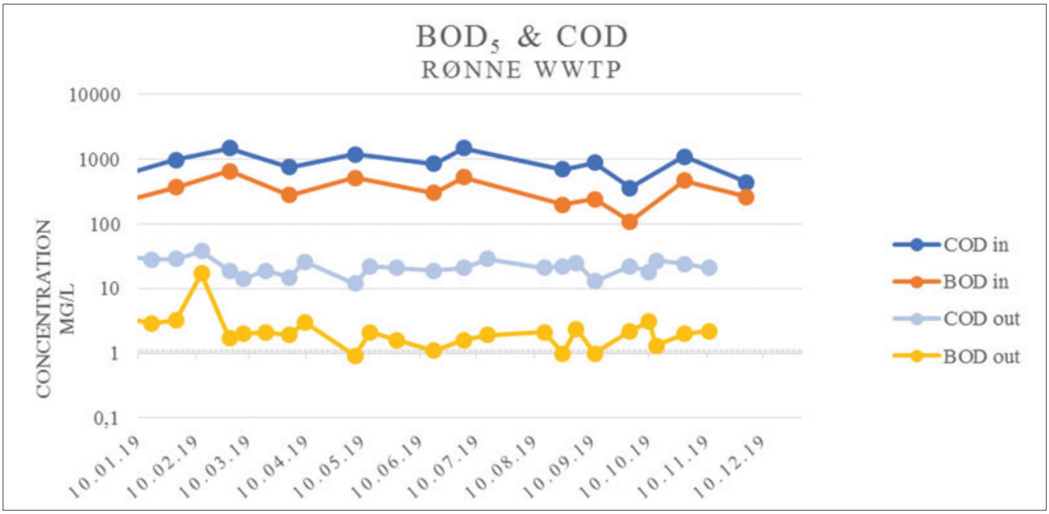

Figure 1 Inlet and outlet concentretions of BOD_5 and COD at Rönne WWTP (OBS! logarithmic scale).

The average ratio between COD and BOD_5 (COD/BOD_5) was 2,7 and 9,2 in the inlet respectively the outlet – thus illustrating effective removal of BOD_5 in contrast to COD, with a larger fraction of organic matter slowly degradable biologically. In average the reduction of BOD_5 was 99,1% and COD 97,4% throughout 2019.

The limiting yearly average concentration for the outlet from Rønne WWTP was not exceeded for neither COD nor BOD_5 (75 mg/l respectively 15 mg/l).
The concentration of TSS was not analysed at Rønne WWTP, this since it is not required by the authorities.
Inlet concentrations of N_{tot} to Rønne WWTP were observed to be on average 50,8 mg/l, and for P_{tot} the inlet concentrations showed to be on average 8 mg/l. The outlet concentrations of N_{tot} were observed to be on average 4 mg/l, and 0,27 mg/l for P_{tot}. The inlet concentrations of N_{tot} and P_{tot} showed to follow the same general pattern.

The limiting yearly average concentration for the outlet from Rønne WWTP was not exceeded for neither N_{tot} nor P_{tot} (8 mg/l respectively 1,5 mg/l).

Measuring the concentration of inorganic nitrogen and phosphorous is not demanded by the Danish authorities and was therefore not a part of the official analysis programme at Rønne WWTP. However, internal analysis of the substances was conducted as well as on-line monitoring. Internal analysis showed that the ammonia concentration in the outlet from Rønne WWTP was generally around 0,4 mg/l and nitrate concentration about 3 mg/l.

For the STEP project, micropollutants and PFAS were analysed at three occasions in the inlet and outlet from Rønne WWTP. The analysed micropollutants were linear alkylbenzene sulphonates (LAS), polycyclic aromatic hydrocarbons (PAH), nonylphenols (NPE), diethylhexylphthalat (DEHP) and per- and polyfluoroalkyl substances (PFAS). The outlet concentrations of LAS, PAH and NPE were all observed to be below detection limit.

Analysis and discussion on pollution by microplastics are seen in *Study of distribution of PAE in water and sludge.*
Heavy metals were not analysed in the wastewater (in/out) from Rønne WWTP, only in the sludge.

Sludge quality

The dry matter content of dewatered sludge from Rønne WWTP was quite even throughout the year, generally between 22-25 % DM.

The average level of N_{tot} in the sludge at Rønne WWTP was approximated to 50 g/kg dry matter, ranging between 47 – 54 g/kg dry matter. For P_{tot} the corresponding value was approximated to 20 g/kg dry matter, ranging between 19-23 g/kg dry matter.

In addition, the sludge showed to contain a significant amount of potassium and sulphur, approximated to 8 g/kg dry matter respectively 9 g/kg dry matter. Both

potassium and sulphur are macro-nutrients that benefit plant growth just like nitrogen and phosphorous.
The concentration of potassium and N_{tot} seem to have followed the same pattern however, the low frequency of measurements prevented from clarifying any correlations or drawing any clear conclusions.

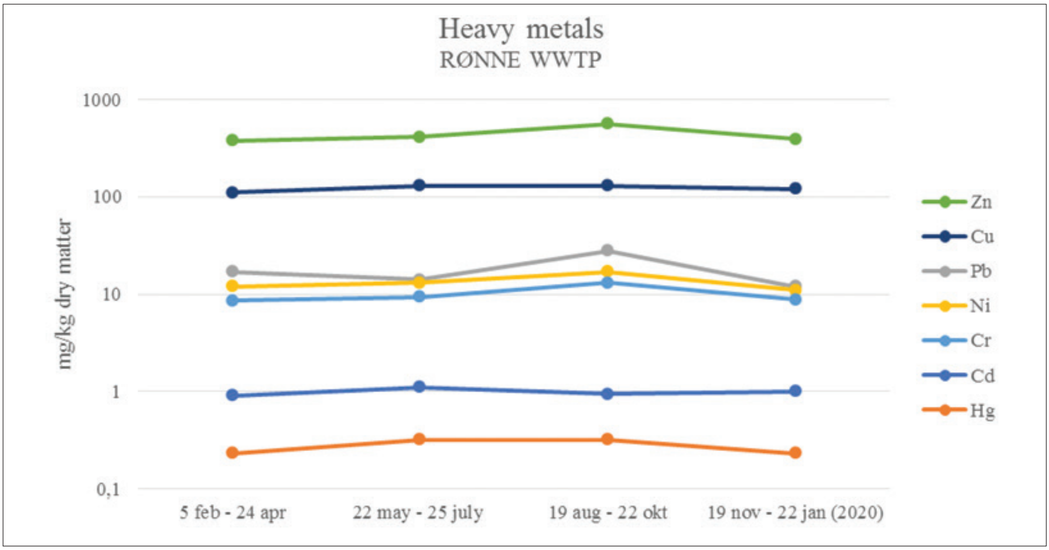

Figure 2

Generally, average levels of heavy metals in the sludge were low and stable throughout the year (see figure 2), reflecting that it was primarily household wastewater that was treated in the WWTP. All concentrations, except for cadmium on some occasions, stayed below the limiting threshold values.

In Denmark, the sludge must be analysed for four groups of micropollutants, which are linear alkylbenzene sulphonates (LAS), polycyclic aromatic hydrocarbons (PAH), nonylphenols (NPE) and diethylhexylphthalat (DEHP). The detection limit for LAS was 50 mg/ kg dry matter, and all measurements from 2019 gave values below the detection limit. For sumNPE the two first measurements of the year gave values below the detection limit of 0,6 mg/kg dry matter.

An increase in concentrations were seen towards the end of the year for both DEPH and NPE. This could imply less decomposition of the substances withing the WWTP since the biological processes are slower during winter, however, the low frequency of measurements prevented from drawing any clear conclusions.
All micropollutants in the sludge were found to be below limiting values.

Further analysis and discussion on phthalates are seen full report *Study of distribution of PAE in water and sludge.*

3.2 Klaipeda University

The Klaipeda WWTP (AB ”Klaipėdos vanduo“) is the main biological sewage treatment plant in Klaipeda, build in 1998 with a capacity of 305.333 PE. Wastewater and sludge quality reflect that it is household and industrial wastewater from cigarette production, paper mill, wood timber, wood processing, furniture as well as food production and service companies which is treated at Klaipeda WWTP.

Methods for wastewater & sludge quality assessment

At Klaipeda WWTP wastewater sampling was performed in accordance with ISO 5667-10:2011.
Applicable threshold limits, as maximum allowed concentrations, at the WWTP of Klaipeda were as follows. COD 125 mg/l, BOD_7 17 mg/l, N_{tot} 10 mg/l and P_{tot} 0,5 mg/l as a daily average for COD and BOD_7 and as an annual average for N_{tot} and P_{tot}.
The quantities of sludge that can be used in agriculture and forestry in Lithuania are determined in the national legislation documents (LAND 20-2005) allowing to use the sludge (compost) with a rate of 33 tons per hectare at the areas for growing energy plants, nurseries, at plantations of raw wood and shrubs, forestry plantations and in greeneries. One of the main and most recent requirements are the concentrations of the heavy metals in the sewage sludge (compost), these are given in table 1 below.

Table 1 Requirements for wastewater sludge to be used in agriculture in Lithuania (LAND 20-2005).
**Can be used every 3 years in agriculture except in planting industry of vegetables and fruits*
***Forbidden to use*

REQUEREMENS FOR SLUDGE TO BE USED IN AGRICULTURE								
mg/kg		Zn	Cu	Cr	Cd	Pb	Ni	Hg
CLASS	I	<300	<75	<140	<1.5	<140	<50	<1.0
	II*	300-2500	75-1000	140-400	1.5-20	140-400	50-300	1.0-8.0
	III**	>2500	>1000	>400	>20	>400	>300	>8.0

Wastewater quality assessment at WWTP of project partners

At Klaipeda WWTP, the inlet concentrations of BOD_7 and COD were fluctuating throughout the year (see figure 3). The highest inlet BOD_7 concentration of 667.8 mg O_2/ l was observed in June 2019. The lowest outlet concentration of BOD_7 was observed in July 2019, it reached 3.16 mg O_2/l.

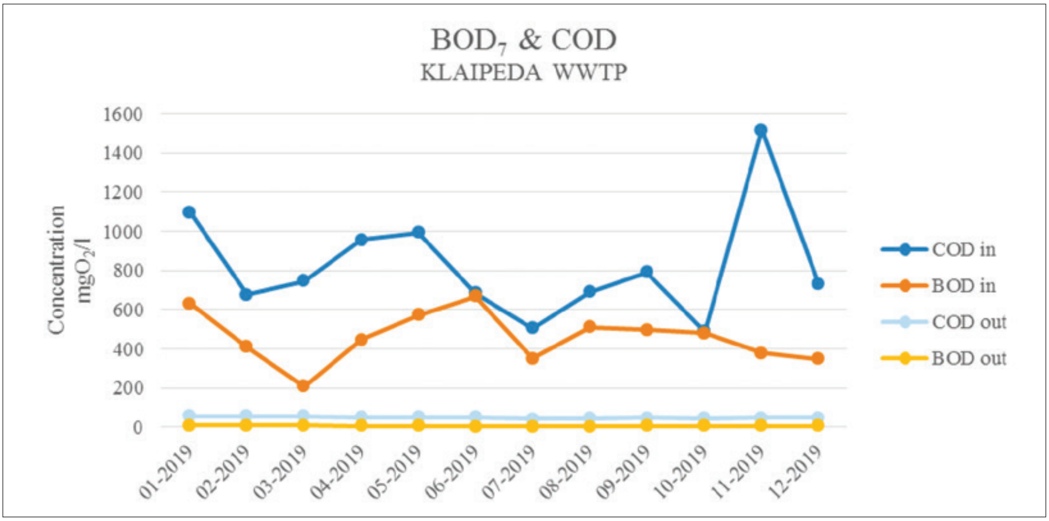

Figure 3 Inlet and outlet concentretions of BOD_7 and COD_{Cr} at Klaipeda WWTP.

The highest inlet COD concentration of 1518.7 mg O_2/l was observed in November 2019.

The lowest outlet concentration of COD was 42 mg O_2/l in July 2019.
The COD inlet concentrations showed that sometimes there was a high chemical wastewater pollution at Klaipeda WWTP. However, due to the efficiency of the complex mechanical and biological wastewater treatment, the outlet concentrations of BOD and COD did not exceed threshold limits. Inlet concentrations of COD increased from October to November 2019 due to the acceptance of untreated wastewater from the cardboard company AB Grigeo Klaipeda. The average COD concentration in the wastewater from this company was approximately 7500 mgO_2/l. The impact of such pollution on the BOD_7 concentrations was managed in the biological wastewater treatment.

The dynamic of the monthly BOD_7 concentrations during 2014–2018 demonstrated a tendency of higher BOD_7 outlet concentrations during the colder periods. The corresponding dynamic for COD showed a more stable trend and implied that the COD treatment was less affected by temperature changes.

The concentration of TSS was not analysed at Klaipeda WWTP.

The average inlet concentration of P_{tot} to Klaipeda WWTP during was 9.56 mg/l. The outlet concentration of P_{tot} was max 0.51 mg/l, and the threshold limit of an annual average of 0,51 mg/l was not exceeded. Corresponding average inlet concentration of total N_{tot} was 108.8 mg/l. The annual average outlet concentration of N_{tot} at Klaipeda WWTP did not exceed the threshold limit of 10 mg/l.

The dynamic of the monthly average concentrations of P_{tot} in the outlet from Klaipeda WWTP 2014–2018 showed how the treatment was more efficient during the summer months. This stands in contrast to the dynamic of the monthly average concentration of N_{tot} (2014–2018) which showed to be more stable throughout the years. Despite the trend differences the results of the biological treatment at Klaipeda WWTP regarding nutrients showed that both the anaerobic and the aerobic part of the treatment process was working well.

Nowadays, Klaipeda WWTP reliably treats the city's domestic and industrial wastewater. In the current urban WWTP, wastewater is treated using mechanical and biological methods, and the effluent treatment effect over the last 10 years was 98-99% in terms of BOD_7 concentration, 85–92% in terms of N_{tot} and 93–97% in terms of P_{tot}.

Analysis and discussion on pollution by microplastics are seen in full report *Study of distribution of PAE in water and sludge.*

At Klaipeda WWTP, the outlet concentrations of mercury (Hg), lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn), copper (Cu) and Nickle (Ni) were measured. Inlet concentrations were not analysed.

Among all the analysed metals the lowest concentrations were found belonging to mercury. It reached a concentration of 0.04 µg/l in April, May, July, August and October 2019, and for remaining months a bit higher with a maximum of 0.12 µg/l. The concentrations of cadmium and chromium were also found to be low – generally below the detection limit of 0.2 µg/l (Cd) respectively 1.0 µg/l (Cr). Twice the chromium concentrations were observed above detection limit.

The highest outlet concentrations during 2019 were observed belonging to zinc which causes big issues for the sewage treatment at Klaipeda WWTP. The highest zinc outlet concentration, of 0.64 mg/l, was observed in July 2019. The lowest outlet concentration of zinc was observed in June 2019 and reached 0.05 mg/l.

The remaining analysed heavy metals were copper, nickel and lead. The highest copper outlet concentration of 48.8 µg/l was observed in January 2019. The lowest concentrations of copper in the outlet were observed in May and November 2019 and reached 3 µg/l. The highest nickel outlet concentrations of 4 µg/l were observed in January, May, July and November 2019. The lowest outlet concentrations of nickel were observed in September 2019 and reached 2.5 µg/l. Inlet concentration data was not provided. Among these three heavy metals the lowest concentration was observed for lead. The mean concentration ranged below 2 µg/l.

The heavy metal concentrations remaining in the wastewater after treatment were small, and about 70% of the metals remained in the sludge.

The pH value at the Klaipeda WWTP was quite stable during 2019. The highest inlet pH was observed in February and March 2019 and reached 7.9. The lowest inlet pH was 7.7. The lowest pH in the outlet was detected in January and February 2019 and was 7.5. The outlet level of pH was observed as highest in September 2019 at a level of 7.9.

Also, oil products, grease and detergents were measured at Klaipeda WWTP. The results show that the mechanical treatment steps at the Klaipeda WWTP are functioning successfully in relation to reduction of the above-mentioned pollutants.

Sludge quality

Water is the main component of sludge and the amount depends on the sludge sort (primary-, secondary or tertiary sludge) and the way of stabilization (aerobic, anaerobic). The second main component is the dry substance, which is made up of organic and inorganic substances.

Beside the water and dry matter, sludge contains a large variety of components that have been separated from the wastewater. Organic and inorganic elements and compounds, which have its origin in wastewater, sometimes, could be found enriched in the dewatered or dried sludge.

The dry matter content in the dried sludge at the Klaipeda WWTP was quite uniform within 88-98%. Raw sludge has a water content of 93 % to 99 %. Therefore, dewatering (up to approx. 35 % dry substance content) or drying (to over 85 % dry substance content) can be necessary for further utilization. At Klaipeda WWTP, the sludge was dried whilst at the other project's studied sites the sludge was dewatered, that giving a higher dry matter content at Klaipeda WWTP.

At Klaipeda WWTP, the monthly average level of N_{tot} in the sludge ranged between 47, 97 and 66,64 g/kg during 2019. The corresponding levels of P_{tot} ranged between 27,31 and 36,50 g/kg during 2019.

The N_{tot} concentrations showed to be sufficient to allow sludge from Klaipeda WWTP as a suitable substrate for soil-enrichment with regards to nitrogen.

The dynamic of the monthly average N_{tot} concentration showed that the concentration stayed quite stable and high throughout the year, and that the P_{tot} concentration was more than sufficient for the usage of sludge as fertilizer independent of season.

Potassium and sulphur were not sampled during the year of 2019.

The copper content of the dewatered sludge from Klaipeda WWTP was quite stable throughout the year with concentrations between 231 and 282 mg/kg, see figure 4. The corresponding concentration for zinc was between 697 and 952 mg/kg. According to the

requirements for wastewater sludge to be used in agriculture in Lithuania (LAND 20-2005), the heavy metals copper and zinc belong to class II, which means that the vegetable or fruit industry cannot use this type of sludge as fertilizer.
The highest concentration of cadmium in the dewatered sludge from Klaipeda WWTP was observed in February 2019, reaching 1.56 mg/kg, and the lowest concentration was 0.75 mg/kg, observed in September 2019 (See figure 4). The reason for the varying cadmium concentrations was mainly due to the industrial pollution sources. The corresponding concentrations for mercury ranged from 0,26 to 1,2 mg/kg. According to the requirements for wastewater sludge to be used in agriculture in Lithuania (LAND 20-2005), the heavy metals cadmium and mercury also belong to class II. Class II sewage sludge can be used every third year in the same area except for the planting industry of vegetables and fruits used for food.

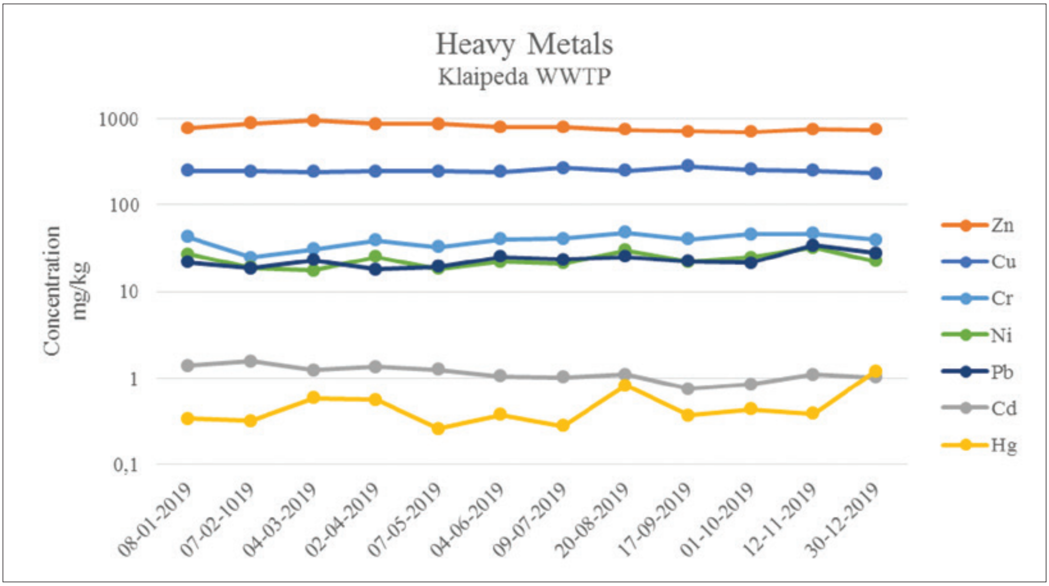

Figure 4 Concentration of heavy metals in the dry matter of the sludge from Klaipeda WWTP.

The chromium content of the dewatered sludge from Klaipeda WWTP ranged between 24,7 and 48 mg/kg (see figure 4). The nickel and lead concentrations in the dewatered sludge were very similar, the content ranged from 17.4 to 34.3 mg/kg. According to the requirements for wastewater sludge to be used in agriculture in Lithuania (LAND 20-2005), the heavy metals chromium, nickel and lead belong to class I. Class I sewage sludge can be used in agriculture without the restrictions in agriculture and forestry areas.

The results regarding sludge quality disclosed the potential of the Klaipeda WWTP to produce sewage sludge for further composting and its application capabilities for agriculture fertilization needs. The analysis of the data showed that the concentrations of some heavy metals, such as zinc and copper were slightly high and followingly this sludge fell into class II according to the Lithuanian national legislation (LAND20-2005).

The produced sludge contended heavy metal concentrations exceeding the concentrations regulated for class I. These concentrations could be removed applying various heavy metal removing technologies. The compost prepared from sludge of class I can be used for agricultural fertilization needs every year in Lithuania, whilst the compost prepared from class II sludge can be used every 3rd year with some restrictions.
Analysis and discussion on phthalates are seen in full report *Study of distribution of PAE in water and sludge.*

3.3 Mittskåne Vatten

In Sweden two treatment plants were studied Lyby WWTP in Hörby and Ormanäs WWTP in Höör which are the two largest WWTPs operated by Mittskåne Vatten. Lyby WWTP was built in 1976 and was rebuilt in 1988 to include treatment of nitrogen. Lyby WWTP has a capacity of 18000PE. Ormanäs WWTP was built in 1978 and expanded twice to include treatment of nitrogen and further pre-sedimentation etc. It has a capacity of 15000PE. Wastewater and sludge quality at both Lyby and Ormanäs WWTP reflect that mainly household wastewater is treated in the WWTPs – except for a slaughterhouse in Hörby whose wastewater is treated at Lyby WWTP.

Methods for wastewater & sludge quality assessment

At Lyby WWTP the sampling of the inlet concentrations was done after a preliminary sand filter. In contrast, the sampling at Ormanäs WWTP was done before the sand filter, but after mechanical screening. At both plants, outlet concentrations were sampled before the treated water was diverted to the receiving water bodies.

For BOD_7, N_{tot}, ammonium nitrogen (NH_4-N) and P_{tot} outlet values composite samples were taken once a week. For the heavy metals as well as inlet values for P_{tot}, weekly flow proportional samples were collected. All collected samples were sent to a certified laboratory (SYNLAB) for analysis. When concentrations of a compound were found to be below the detection limit, then half that concentration was used for the calculations.

The overall wastewater treatment process has as its goal not to exceed threshold limits set by the Swedish authorities. The threshold limits are adapted to the circumstances seen at each site e.g., susceptibility of the recipient will be considered when the limits are set. Therefore, the limits differ from site to site (see table 2).

Table 2 Threshold limits as set by the Swedish authorities for concentrations of compounds in the effluent.

	Ormanäs WWTP		Lyby WWTP	
Parameter	**Concentration (mg/l)**	**Type**	**Concentration (mg/l)**	**Type**
BOD7	10	Guiding value & monthly average	10	Guiding value & monthly average
	10	Threshold value & quarterly average	10	Threshold value & quarterly average
Ntot	12	Guiding value & yearly average	15	Yearly average
NH4-N	5	Guiding value & average May-October	3	Guiding value & average June-October
			5	Yearly average
Ptot	0,2	Guiding value & monthly average	0,3	Guiding value & monthly average
			0,25	Guiding value July-September
	0,3	Threshold value & quarterly average	0,3	Threshold value & quarterly average

For the sludge, a sample was collected every week and frozen. The frozen samples were then sent for joint analysis every second month at Lyby WWTP and every third month at Ormanäs WWTP. All samples were sent to a certified laboratory (SYNLAB) to determine percentage of dry matter (DM) and concentrations of nutrients and metals.
Wastewater quality assessment at WWTP of project partners

At Lyby WWTP the influent concentrations of BOD_7 were observed to be on average 241 mg/l. Outlet concentrations of BOD_7 were all found to be below the lowest detectable limit of 3 mg/l (see figure 5).

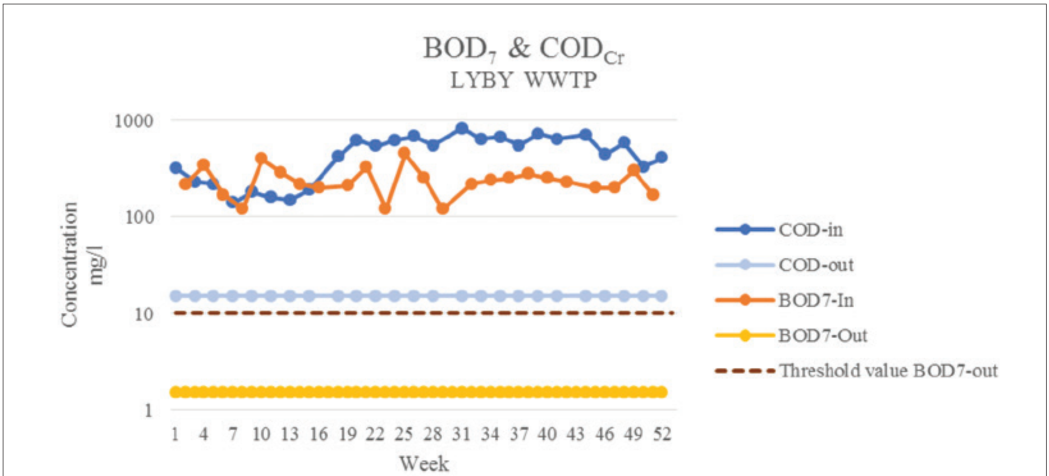

Figure 5 Inlet and outlet concentretions of BOD_7 and COD_{Cr} at Lyby WWTP (OBS! logarithmic scale). Outlet levels for BOD_7 were not noted to exceed the detection limit of 3mg/l and are therefore presented as 1,5mg/l which is half the detection limit. Outlet levels for COD_{Cr} were not noted to exceed the detection limit of 30mg/l and are therefore presented as 15mg/l which is half the detection limit.

For COD_{Cr} the inlet concentrations, to Lyby WWTP, were found to be relatively low during the beginning of the year, with an average concentration of about 200 mg/l up until week 15. For the remainder of the year the average inlet concentration was higher, 585 mg/l. Despite the difference in average inlet concentrations the outlet concentration was at no point observed to be above the lowest detectable limit of 30 mg/l (see figure 5).
The difference seen for average incoming concentrations of COD_{Cr} could be due to dilution by excess water during the wetter months. Data from the Swedish Meteorological and Hydrological Institute (SMHI) shows how the precipitation during February, March, September and October 2019 was normal or above normal whilst January, April – August and November – December had precipitation between 5-75% of the monthly normal precipitation. This corresponds to the dilution of COD_{Cr} during February and March and that no effect is seen during September and October may be because precipitation during these months probably would be soaking the dry soils.

For both BOD_7 and COD_{Cr} the treatment efficiency was high and gave sufficient treatment before the effluent was discharged into the recipient.
For Ormanäs WWTP the average inlet and outlet concentrations of BOD_7 were found to be 114 mg/l and 2,6 mg/l respectively. Peak inlet concentration occurred during week 32 and 41 with observed levels of 190 and 220 mg/l (see Figure 6), and generally the inlet concentrations were seen to be quite fluctuating. This was due to an overload of the filters. However, the corresponding outlet concentrations were not registered above the detection limit. Instead, a peak in outlet concentration was determined to 23 mg/l during week 31. The lowest measured treatment efficiency stems from this period at 94%.

The COD_{Cr} inlet concentrations were, as the BOD_7 inlet concentrations, found to be fluctuating. The maximum inlet concentrations were recorded during the first week of the year and week 42, with levels of 400 and 410 mg/l respectively (see figure 6). Week 18, inlet concentrations were observed to be at a minimum of 87 mg/l. This week outlet concentrations were also relatively high (44 mg/l) and treatment efficiency at its lowest (49%). This was since the filters in the final treatment step was not functioning properly. Seen was also a higher COD_{Cr} outlet concentration during week 11.

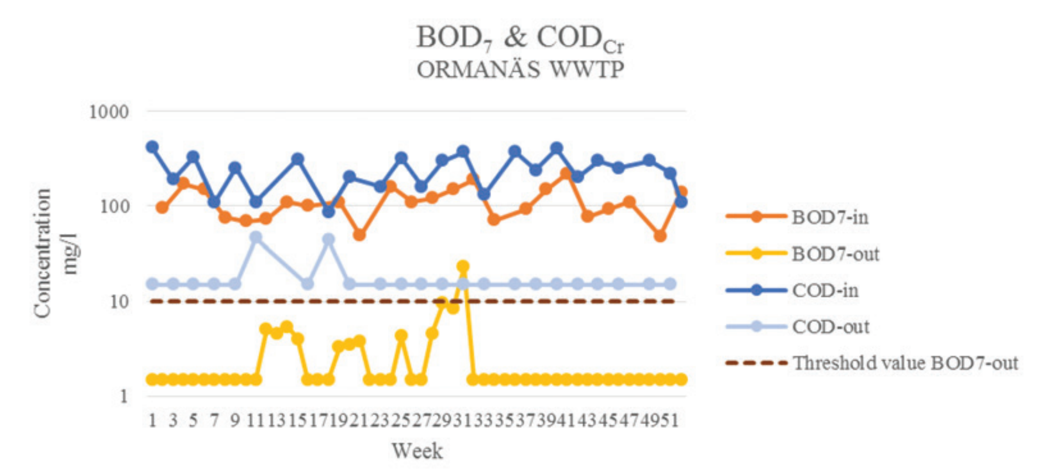

Figure 6 Inlet and outlet concentretions of BOD_7 and COD_{Cr} at Ormanäs WWTP (OBS! logarithmic scale). If outlet levels for BOD_7 were noted not to exceed the detection limit of 3mg/l they are presented as 1,5mg/l which is half the detection limit. If outlet levels for COD_{Cr} were noted not to exceed the detection limit of 30mg/l they are presented as 15mg/l which is half the detection limit.

Seen in the results was that higher inlet concentrations of BOD_7 were observed at Lyby WWTP compared to Ormanäs WWTP. The main reason for this was that Lyby WWTP received wastewater from a slaughterhouse which increased the BOD_7 concentrations substantially.
Ormanäs WWTP is known to be highly affected by excess water and the efficiency of the aerators at Ormanäs WWTP is not optimal. The system showed very little resilience towards excess water and this could have been one reason for the highly fluctuating values – even small rainfall events may have had a large effect at the WWTP. This may also have been a reason for concentrations at Ormanäs WWTP being in general lower (more diluted by excess water) than the concentrations seen at Lyby WWTP during the dry period but at the same time higher than the concentrations seen during the wet period.

During the summer months there were problems with large amounts of sludge at Ormanäs WWTP. Manual removal of sludge was needed as well as extra rinsing of the filters. In addition, the flows to the treatment plant during March were very high which led to a hydraulic overload which in turn caused sludge from the biological treatment step to block the filters. The filters were rinsed on several extra occasions however despite this, particles were washed out with the outflow. An increased amount of sludge in the outflow caused high concentrations of BOD_7, TSS, $COD_{Cr,}$ N_{tot} and P_{tot}.

Further on, wastewater which is diluted with large amounts of excess water is colder than the non-diluted wastewater which leads to less efficient treatment.

The inlet concentrations of N_{tot} to Lyby WWTP were found in the interval of 30 – 60 mg/l except for one occasion during week 37 when a concentration of 67 mg/l was noted. Outlet concentrations were below the threshold limit of 15 mg/l except for week 3 when precisely that concentration was recorded. Treatment efficiencies were on average 84%.

Ammonium inlet concentrations at Lyby WWTP were not measured during 2019. The outlet levels were all below 0,5 mg/l.

For Ormanäs WWTP the inlet concentrations of N_{tot} were found to be roughly 30 mg/l. A peak occurred during week 39 when a level of 62 mg/l was noted. However, this increase did not seem to influence outlet concentrations as these were found to be below 10 mg/l in most cases and the threshold limit of 15 mg/l was never exceeded. Treatment efficiencies were on average 78%.

Ammonium levels into Ormanäs WWTP were on average approximately 20 mg/l. A peak occurred during week 39 when a level as high as 36 mg/l was noted. However, outlet concentrations were found to not exceed 5 mg/l. The results clearly show how the inorganic nitrogen was coupled to the amount of N_{tot} – the inlet concentrations follow the same pattern. At Ormanäs WWTP drops in the treatment efficiency of both inorganic nitrogen and N_{tot} was noted when corresponding inlet concentrations were at a yearly low. The reason for this was most probably due to the large volumes of excess water giving low concentrations and low temperatures leading to less efficient treatment. Which was also implied by the relatively low inlet concentrations seen for TSS, COD and $BOD_{7.}$

On average, the inlet concentration TSS to Lyby WWTP was observed to about 450 mg/l with maximum and minimum levels at 750 mg/l (week 32) and 220 mg/l (week 29) respectively. All outlet concentrations were found to be below the lowest detectable limit of 5 mg/l.
The inlet concentrations of P_{tot} to Lyby WWTP were observed to be relatively low during the first 10 weeks of the year. However, an increase from an average concentration of 3 mg/l to 6 mg/l followed by a peak reaching a concentration of 9,4 mg/l during week 35 was noted. Treatment efficiency was at least 97% for the whole year.

No clear correlation was seen between inlet concentrations of TSS and P_{tot}.
At Ormanäs WWTP the average inlet concentration of TSS was found to be about 150 mg/l. A peak of 320 mg/l was noted during week 39. During week 30 a relatively high inlet concentration of 300 mg/l was observed coupled with a maximum outlet concentration of 85 mg/l. The treatment efficiency was at the same time at its lowest, 69%.

For P_{tot} the inlet concentrations were observed in the interval of 1 – 6 mg/l with an average level of 3,2 mg/l. Outlet concentrations were found to increase between weeks 10 to 19. During this period, the threshold limit of 0,3 mg/l was exceeded four times. Two occurrences of low treatment efficiencies were also observed within this time frame, week 11 and week 18 with efficiencies of 45% respectively 59%.

The results showed how the outlet concentrations were affected when there were large amounts of sludge in the system which clogged the filters – both during March and the summer months there were increased amounts of sludge in the outflow form Ormanäs WWTP.
The outlet concentrations of heavy metals seen at Lyby WWTP were relatively stable, and due to the lower number of measurements it was hard to see any clear trends. Some "peak" increases were seen, and these could be due to occasional point source effluents to the wastewater system. It is also known that the bedrock around Höör and Hörby contain high amounts of cadmium and lead, and peaks in concentration for these substances might then be due to large amounts of drainage water, and as said above the precipitation during February, March, September and October 2019 was normal or above normal, aiding this theory – however this would be more accurate if seen in the inlet concentrations.

15 April – 16 May (week 16-20) the pilot plant at Lyby was operating. This could have given decreased concentrations of heavy metals in the outflow from the WWTP however this was not reflected in the results. One reason for this may be the low concentrations and operation close to the detection limit of the analysis methods.

The same was seen at Ormanäs WWTP – the concentrations of heavy metals in the outflow were relatively stable. Again, some increases were seen, and these could be due to occasional point source effluents to the wastewater system or large amounts of excess water bringing substances from the bedrock into the WWTP.

Phthalates were not measured at neither Ormanäs WWTP nor Lyby WWTP.

Sludge quality

The percentage of DM in the sludge was seen to be in general lower at Lyby WWTP than at Ormanäs WWTP. For both treatment plants the percentage of dry matter in the sludge increased during late spring and seemed to decrease again during summer. However, the low frequency of measurements prevented patterns to show in the results and from drawing any clear conclusions.

The concentrations of N_{tot}, inorganic nitrogen and P_{tot} in the dry matter of the sludge followed the same pattern at each treatment plant. At Ormanäs WWTP a decrease in concentrations was seen in June and at Lyby WWTP there was a slight decrease in concentrations in April which rose again in June-August to then decrease slightly again in October. In general, the concentrations at Ormanäs WWTP were less fluctuating than the concentrations at Lyby WWTP.

Potassium and sulphur were not sampled during the year of 2019.

As described in the section regarding wastewater there were some troubles with large amounts of sludge in the outflow at Ormanäs WWTP during the summer. This might have been reflected in the lowered concentrations of nutrients in the sludge during this period. However, in general, the low frequency of measurements prevented from drawing any clear conclusions.

The concentration of heavy metals in the dry matter of the sludge was almost without exception higher at Ormanäs WWTP than at Lyby WWTP (see figure 7). Only chromium was seen in higher concentrations in the DM of the sludge at Lyby WWTP than at Ormanäs WWTP. This suggests that the treatment process at Ormanäs WWTP is more efficient by means of heavy metals than the treatment process at Lyby WWTP. Alternatively, the inlet concentrations were higher at Ormanäs WWTP than at Lyby WWTP and the treatment efficiency was equivalent at the both treatment plants however, since no inlet concentrations of heavy metals were measured this could not be validated.

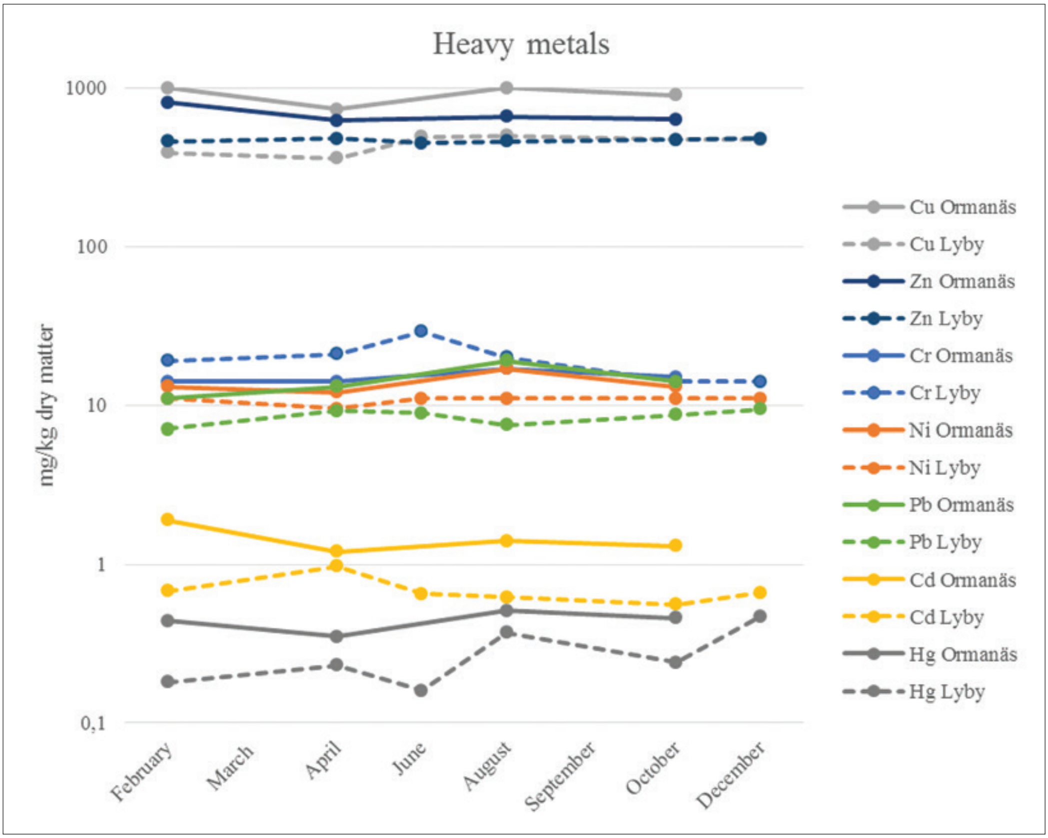

Figure 7 Concentrations of heavy metals in the dry matter of the sludge at Ormanäs and Lyby WWTPs. OBS! Logarithmic scale.

The evaluation of the concentrations of heavy metals in the sludge was clearly limited by the low number of measurements giving general trends rather than revealing special events. For example, the pilot plant at Lyby was operating 15 April – 16 May and this would

theoretically give a decrease of heavy metals in the dry matter during this period. There was a slight implication that the concentrations might have been lower during this period however the frequency of the measurement prevented from drawing any clear conclusions regarding this.
The concentrations generally stayed below the limiting threshold values, however, for copper and zinc the threshold limits were occasionally crossed at Ormanäs WWTP. This hindered the sludge from being reused for agricultural purposes.

Phthalates were not sampled during the year of 2019.

3.4 Goleniów Water and Sewage Company

Goleniów WWTP is a biological WWTP situated in Goleniów city, West Pomeranian District, North-western Poland. It was built in 1994 and rebuilt in 2011-2012 with the current capacity of 63 805 PE. Wastewater and sludge quality reflect that it is mostly household wastewater with some industrial sewage from the sectors of plastics production, meat processing, car washes and sewage delivered from septic tanks which is treated at Goleniów WWTP.

Methods for wastewater & sludge quality assessment

At the Goleniów WWTP, flow-proportional sampling of the daily average of raw and treated wastewater took place twice a month using an automatic sampler in accordance with the PN – ISO 5667-10 1997 (A). Samples were analysed in an accredited laboratory. According to the water permit the parameters COD, BOD_5, P_{tot}, N_{tot} were analysed together with total suspended solids (TSS). As part of the internal quality control, the effluent was tested daily for total P_{tot} and N_{tot}.

Applicable threshold limits, as maximum allowed concentrations, at the WWTP of Goleniów were as follows. COD 125 mg/l, BOD_5 15 mg/l, N_{tot} 15 mg/l, P_{tot} 2 mg/l and TSS 35 mg/l. This as a daily average for COD, BOD_5 and TSS and as an annual average for N_{tot} and P_{tot}.

National legislation on the treatment and final disposal of municipal sewage sludge, which constitutes waste, is set out in the Act on Waste of 14 December 2012 (Journal of Laws of 2012, No. 101, item 1571). U. 2020, pos.797), and the Regulation of the Minister of Environment of 6 February 2015 on Municipal Sewage Sludge (OJ Cf. U. 2015.pos. 257). The aforementioned legal acts define the conditions, frequency and types of sludge and soil which should be performed before the application of sludge, as well as the obligations of the sludge producer and the landowner. It is also possible to use stabilized municipal sewage sludge for the production of fertilizer or plant growth promoter, which is regulated by Announcement of the Marshal of the Sejm of the Republic of Poland of June 7, 2018 on the publication of the consolidated text of the Act on fertilizers and fertilization (Journal of Laws of 2018, item 1259) and the Ordinance of the Minister of Agriculture and Rural

Development of June 18, 2008 on the implementation of certain provisions of the Act on fertilizers and fertilization (Journal of Laws 2008 No. 129, item 76). These Acts define the conditions for the placing on the market of products made from municipal sewage sludge and indicate the way to obtain an authorisation to place a product on the market by obtaining an opinion from the relevant research institutes.

Sewage sludge testing must be performed in certified laboratories and include pH reaction, DM, organic matter content in dry matter of sludge, N_{tot} including ammoniacal nitrogen, P_{tot}, calcium (Ca) and magnesium (Mg) content, heavy metal content in the dry matter of the sludge (see table 3) and salmonella count (intestinal parasite egg count Ascaris sp. Trichuris sp. and Toxocara sp).

The presence of Salmonella live eggs from intestinal parasites prevent the use of sludge in agriculture and for land reclamation for agricultural purposes. The total number of live eggs of the intestinal parasite Ascaris sp, Irichuris sp., Toxocara sp. allowed in 1 kg of dry matter of sludge to be used for testing in agriculture and for land reclamation for agricultural purposes is 0 and for recultivation of land, for adaptation of land to specific needs resulting from waste management plans, spatial development plans or decisions on land development conditions, for growing plants intended for compost production, for growing plants not intended for consumption and for fodder production is not more than 300.

Table 3 Maximum content of heavy metals in municipal sewage sludge.

		Heavy Metals (mg/kg of dry matter of sludge)						
		Cadmium	Copper	Nickle	Lead	Zinc	Mercury	Chromium
Threshold limit for heavy metal content when using municipal sewage sludge:	in agriculture and for the reclamation of land for agricultural purposes	20	1000	300	750	2500	16	500
	for the reclamation of land for non-agricultural purposes	25	1200	400	1000	3500	20	1000
	when adapting land to specific needs resulting from waste management plans, spatial development plans or decisions on land development conditions, to growing plants intended for compost production, to growing plants not intended for food or feed production	50	2000	500	1500	5000	25	2500

Sludge shall not be applied to soils at risk of heavy metal contamination. Before applying the sludge, it is necessary to test the soil in order to assess its initial condition and further monitoring. The maximum dose of sewage sludge that can be used in agriculture and for recultivation of land for agricultural and other purposes is shown in table 4. Moreover, the dose of sludge should be determined in such a way that its application on a given land will not result in exceeding permissible levels of heavy metals according to table 5.

Table 4 Permissible concentrations of heavy metals in soil when sewage sludge is used in relation to the agronomic category of soil. S.m is dry matter of sludge.

<table>
<tr><th>Objective</th><th>Use throughout the year</th><th>Use 1x for 2 years</th><th>Use 1x for 3 years</th></tr>
<tr><td>Agriculture</td><td rowspan="2">3 Mg s.m./ha</td><td rowspan="2">6 Mg s.m./ha</td><td rowspan="2">9 Mg s.m./ha</td></tr>
<tr><td>Reclamation of land for agricultural purposes</td></tr>
<tr><td>Reclamation of land for non – agricultural purposes</td><td rowspan="4">15 Mg s.m./ha</td><td rowspan="4">30 Mg s.m./ha</td><td rowspan="4">45 Mg s.m./ha</td></tr>
<tr><td>Adaptation of land to specific needs resulting from waste management plans and land use plans</td></tr>
<tr><td>Growing of plants intended for compost production,</td></tr>
<tr><td>Growing of plants not intended for use for fodder production</td></tr>
</table>

The sludge produced at the Goleniów WWTP is subject to the recovery process R3 composting. There are no legal regulations that impose an obligation to test batches of sludge submitted to the composting process, however, in order to maintain the high quality of the product, the sludge submitted to the composting process is tested by an accredited laboratory for percentage of dry mass, concentration of nutrients, heavy metals and microbiological aspects.

Table 5 Permissible concentrations of soil heavy metals when sewage sludge is applied – depending on the agronomic category of soil.

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="7">Heavy Metals (mg/kg of dry matter of sludge)</th></tr>
<tr><th>Cadmium</th><th>Copper</th><th>Nickle</th><th>Lead</th><th>Zinc</th><th>Mercury</th><th>Chromium</th></tr>
<tr><td rowspan="3">The limit value for the amount of heavy metals in the different soil types</td><td>Light</td><td>20</td><td>1000</td><td>300</td><td>750</td><td>2500</td><td>16</td><td>500</td></tr>
<tr><td>Medium</td><td>25</td><td>1200</td><td>400</td><td>1000</td><td>3500</td><td>20</td><td>1000</td></tr>
<tr><td>Heavy</td><td>50</td><td>2000</td><td>500</td><td>1500</td><td>5000</td><td>25</td><td>2500</td></tr>
</table>

Wastewater quality assessment at WWTP of project partners

The influent concentration of BOD_5 to the Goleniów WWTP was found to be on average 396 mg/l with a maximum level of 625 mg/l in the middle of March and a minimum of 22 mg/l by the end of February (figure 8). During the sampling in February, treatment levels were at a yearly low of 62%. Outlet concentrations were however never found to exceed 14 mg/l.

Influent and effluent concentrations of COD were observed to be on average 1017 and 35 mg/l respectively. The highest effluent concentration, 67 mg/l, was noted during the beginning of January when treatment efficiency also was at its lowest of 91% (figure 8).

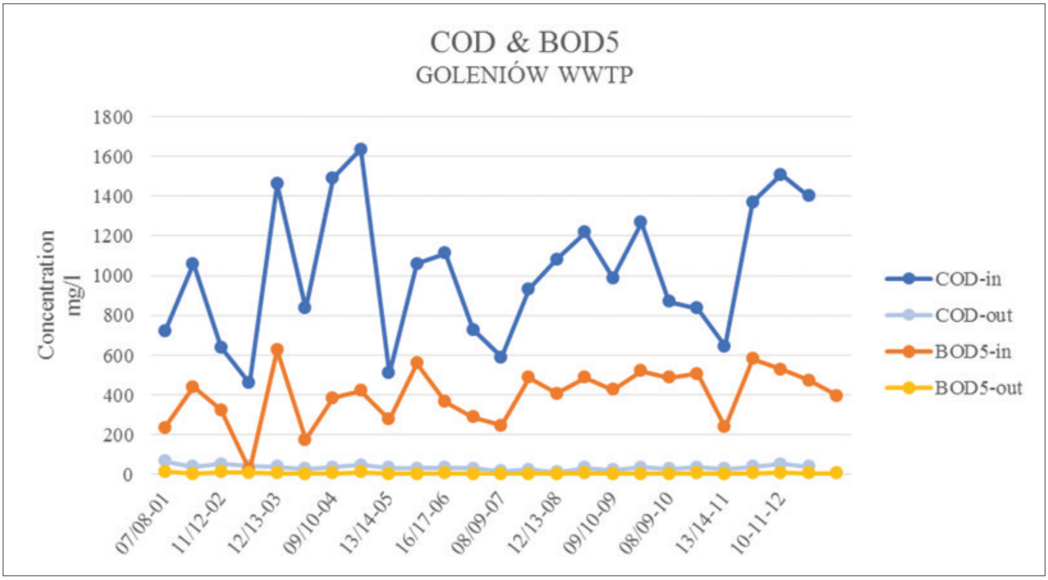

Figure 8 Inlet and outlet concentretions of BOD_5 and COD_{Cr} at Goleniów WWTP

The influent concentrations of BOD_5 and COD seemed to follow the same general pattern and are both highly fluctuating during the year. This may have been due to periodical high pollution of organic compounds. Despite the fluctuating inlet values the outlet concentrations were shown to be quite stable, implying that the treatment process was resilient towards varying input values.

Inlet concentrations of P_{tot} were found to be in general below 20 mg/l except for three occasions. These occurred in the end of January (26 mg/l) as well as in the middle of June (21 mg/l) and the end of November (22 mg/l). However, on all these occasions the effluent concentrations were observed to be below the average of 0,65 mg/l. This indicated a well-functioning treatment process with regards to phosphorous independent of inlet concentrations. The estimated treatment efficiency was never lower than 88%. June through November seemed to have a higher average outlet concentration of total phosphorous than the rest of the year, this probably caused by development of filamentous bacteria and foaming in the biological reactor chambers.

The concentrations of TSS were found to be on average 358 mg/l in the influent and 6 mg/l in the effluent. Treatment efficiencies never dropped below 93%. However as for the BOD_5 and COD the concentration of TSS was quite fluctuating throughout the year.
Average inlet and outlet concentrations of N_{tot} were found to be 70 and 10 mg/l respectively. On one occasion, influent levels above 100 mg/l was noted (30/31 of January, 103 mg/l). Treatment efficiencies were estimated to be in the interval 77-93 %. Despite fluctuating inlet values the outlet concentrations were shown to be quite stable, implying that the treatment process was resilient towards varying input values.

Metals in the wastewater are tested once a year at Goleniów WWTP. Over a period of 5 years, both the inlet and outlet parameters showed a constant, very low level of the content of the given parameters in sewage. This is directly connected with the catchment area of the Goleniów wastewater treatment plant, where there are no heavy industry plants that would generate large quantities of particularly harmful compounds for the environment. In order to monitor the wastewater flowing to the treatment plant in Goleniów, the company carried out regular inspections of industrial plants in Goleniów and the GPP in Lozienica that discharge wastewater to the sewerage system and has a direct impact on the quality of the wastewater through the conditions imposed in the agreements regarding the parameters of the wastewater discharged. Inspections of businesses in the Lozienica GGP area confirm that the majority of wastewater discharged into the sanitary sewerage system is domestic wastewater, wastewater from the food industry or car washes.

Analysis and discussion on pollution by microplatics are seen in *Study of distribution of PAE in water and sludge.*

Sludge quality

The dry matter content in the dried sludge at the Goleniów WWTP was quite uniform within 12,5-14,5%, and the organic content of the dried sludge varied between 64 and 81%.

At Goleniów WWTP the percentage of N_{tot} in the sludge was about 7% at all the measurement occassions. The corresponding level for P_{tot} was about 3%. For the nutrients calcium, potassium and manganese the percentage was about 2%, 1% and 0,7% respectively. Potassium, calcium and manganese are nutrients that benefit plant growth just like nitrogen and phosphorous.
The concentrations of heavy metals ranged from 0,4 mg/kg (mercury) up to 10 g/kg (iron) in the sludge at Goleniow WWTP (see figure 9).

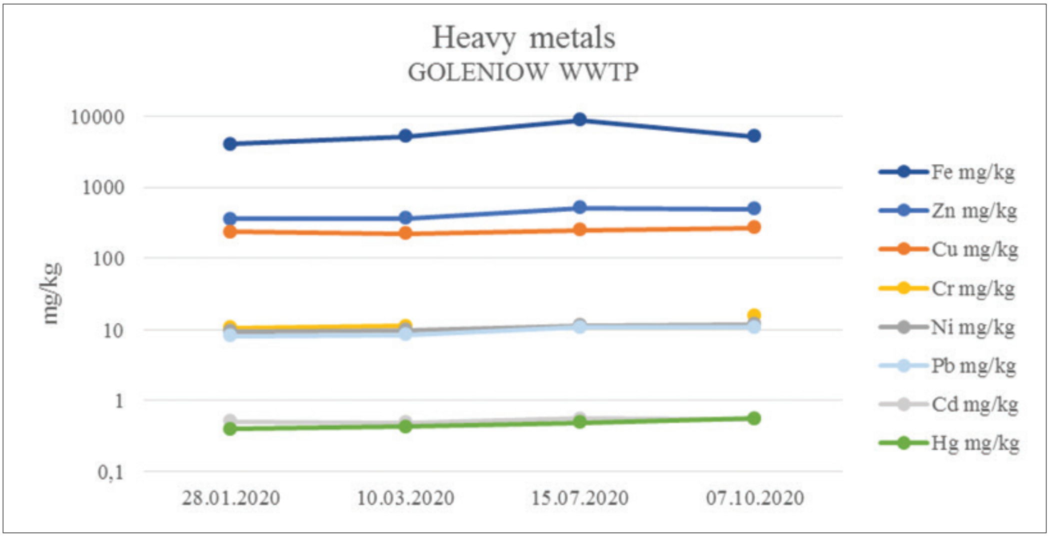

Figure 9 Heavy metal content in sludge at Goleniow WWTP.

Analysis and discussion on pollution by phthalates are seen in *Study of distribution of PAE in water and sludge.*

No pathogens were detected at the four measurement occasions.

In the light of the obtained results the tested sludge could be used in agriculture, for land reclamation for agricultural and non-agricultural purposes as well as for land adjustment to specific needs resulting from waste management plans, spatial development plans, for growing plants intended for compost production, for growing plants not intended for consumption and for fodder production. Currently, the sludge was directed to a newly built composting plant using GORECover membranes and processed through the R3 recovery process. The compost resulting from the process had product status and was marketed as a soil improver in accordance with the authorisation of the Minister of Agriculture.

4 JOINT CONCLUSION

4.1 Wastewater

Results from all studied sites showed satisfactory and reliable treatment processes giving effluents with concentrations of nutrients and pollutants which lied below regulatory limiting values. The limiting values vary from country to country, however the limiting values for COD, BOD, total nitrogen and total phosphorous are quite similar between Denmark, Lithuania, Poland and Sweden. For heavy metals on the other hand the limiting values vary more.

No clear correlation was seen between the treatment of heavy metals and other measured parameters however as stated above there is an implication that a stable process is preferable – sludge-particles in the outflow give a general increase of pollutants in the outflow. Limiting various substances in the outflow is the goal of the treatment process. It is also essential to stress that whatever substances that enter the treatment process either follows the effluent to the recipient or ends up in the sludge – it is therefore important to prevent and/or limit the amount of pollutants that enter the sewage system as well as reduce the number of point sources of pollutants at their origin.

4.2 Sludge

Sludge is a valuable resource. As little as possible of organic matter, heavy metals and chemicals should end up in the treated wastewater and pass on to the recipients – these substances should be collected in the sludge together with nutrients. However, high concentrations of heavy metals and chemicals in the sludge could restrict the reuse of the sludge. Therefore, it is important to further restrict the use of heavy metals and persistent chemicals and avoid large primary sources of these substances or apply heavy metal reduction technology.

This assessment showed that the studied WWTPs are efficient and reliably treat the incoming wastewater. However, residues of the wastewater treatment process that end up in the sludge determine how the sludge can be further used. Furthermore, it was seen the governing legislation is one of the main limiting factors to the reuse of sludge. A categorisation of sludge allows for a larger fraction of the sludge to be reused for different purposes, whilst stricter regulations limit the reuse of sludge but with the aim to avoid spreading of pollutants etc. To balance the possibilities of reuse and to limit the spread of pollutants is a key question to be addressed by governing authorities. For further comments on this matter see *Deliverable 3.2 National Sludge Handling Rules – Comparison.*

Sewage sludge has a high fertilizing value since it is rich in nitrogen and phosphorus. The nutritive elements it contains should be included in the general policy of fertilizers for agricultural lands if the amount of the organic pollutants and heavy metals are in line with national and EU requirements. However, since nutrients can have a negative effect on the environment, causing for instance eutrophication of lakes and oceans, there is a limit to the amount of sludge that can be used on arable land also with regards to the surplus of nitrogen and phosphorous, not only organic pollutants and heavy metals. The analysis of total nitrogen and phosphorus is therefore an important part of the European policy to increase soil fertility and at the same time to protect the environment from pollution.

4.3 Influence of wastewater quality on sludge quality

The sludge process is slower than the wastewater treatment process (sludge recirculates and is reused within the wastewater treatment process before taken out as a residue) making it hard to see any direct effects and correlations between what happens in the sludge and what happens in the wastewater. For example, heavy metal pollution from a point source may be clearly seen when analyzing incoming wastewater to the treatment plant but may not be clearly seen as a peak in heavy metal concentration in the sludge but rather a slightly increased level over time.

It is important to emphasize that any pollutants that enter the treatment process require significant energy to remove them from the water stream and will eventually end up in the sludge – therefore, the most important thing is to limit the amount of pollutants that enter the sewer and limit point sources of pollution.

Seen from the pilot plan project at Lyby WWTP, where external sludge during a test period was treated separately before the reject water from this process was inserted in the main wastewater treatment process was that external treatment processes could have a positive effect on the overall treatment in the WWTP. Results from the pilot plan project can be found in report *Main Output WP3 – Pilot plant for external sludge handling.* Since the project was time limited a large impact in the results described in this report was not evident and a further evaluation in relation to both feasibility, efficiency and economical aspect would be needed in order to evaluate an investment in equipment for external sludge handling.

4.4 Sources of errors & limitations

While the project provided excellent opportunities to compare the overall trend in wastewater pollution, treatment efficiency and technology, and sludge utilization methods, some particular conditions couldn't be agreed upon in advance and brought some confines in the analysis.

Limits to the project have been for example discrepancies in the analysis methods. Sludge and wastewater samples were not taken at similar intervals – most often wastewater samples are collected more frequently. When comparing trends this then poses a limitation since a lower frequency of measurements gives more general trends rather than revealing special events and correlations. It is therefore hard to directly compare the results in the sludge analysis (fewer samples) with the results in the wastewater analysis (more samples) and draw any direct correlations between them.

During 2020 a great limitation was also the Covid-19 pandemic limiting the possibility to make use of the same sampling techniques and using the same laboratories. Without the same methods for sampling and analysis, as well as maximum allowed concentrations, at all the sampling sites it is hard to make a straight comparison.

Chapter 2 STUDY ON DISTRIBUTION OF PHTHALATE ACID ESTERS (PAES) IN WATER AND SLUDGE

Dr. Olga Anne –
Klaipeda University

1 INTRODUCTION

Phthalate acid esters (PAEs) are micro-pollutants of great public concern due to their negative impact on ecosystem and human health. Phthalates are dialkyl or alkyl aryl esters of phthalic acid, which are primarily synthesized from phthalic anhydride and the corresponding alcohol by the Fischer esterification in the presence of a catalyst.

PAEs are used to increase a material's flexibility, transparency, pliability, plasticity, strength, endurance and longevity [1]. They are important plasticizers and additives, which depending on the alcohol that make up the alkyl chain, are widely used in industrial production in numerous plastic applications due to their high performance and low cost [2]. PAEs can account for up to 40% of the final plastic product [3]. Long-chain PAEs (di(2-ethylhexyl) phthalate (DEHP), diisononyl phthalate (DiNP), diisodecyl phthalate DiDP), are primarily used in plastic polymers and applications such as building and construction materials (wires and cables; electrical cords; flooring, roofing and cladding; wall coverings and floor tiles; films and sheets; paints and lacquers). Long-chain PAEs also find in adhesives, clothing, furniture (PVC flooring), car and public transport interior (automobile upholstery, leather for car interiors), cosmetic products, medical devices, toys and child care products, food and packaging material [4-8]. Short-chain PAEs (dimethyl phthalate (DMP), diethyl phthalate (DEP), butyl benzyl phthalate (BBzP), di-n-butyl phthalate (DnBP), diisobutyl phthalate (DiBP)) are used in non-PVC applications as personal care products, adjuvants in pesticide formulations, paints, glue, lubricants [9, 5, 10].

PAEs eventually can enter the environment through multiple pathways among which are industrial and municipal wastewaters, land application of sewage sludge, and leaching after the disposal of industrial and municipal solid waste [11, 12, 7, 13].

Hereby, phthalate acid esters can enter the water system through wastewater treatment plants. Because of high lipophilicity of PAEs they tend to be adsorbed and concentrated to suspended organic matter and sludge and are removing through the anaerobic digestion [14, 13]. In addition, the use of fertilizers, pesticides and the irrigation with polluted water in agriculture increase the diffusion of phthalate acid esters in the environment as well as its accumulation in plant biomass and introduction in food chain [15-17].

Moreover, PAEs are not persistent and readily biodegrade in the aquatic environment under aerobic and anaerobic conditions [18, 17]. Higher molecular weight PAEs biodegrading slowly than the lower molecular weight chemicals and may accumulate in the aquatic environment [19, 20].

The objective of this study was to determine the levels of dimethyl phthalate, diethyl phthalate, dipropyl phthalate, dibutyl-phthalate, diisobutyl phthalate, dicikloheksil phthalate, di(2-ethylhexyl) phthalate in water and sediment samples. Samples were collected from 35 locations in Lithuania, 9 locations in Poland as well as 4 locations in Denmark. The discussion of the potential sources with the goal of helping decision-makers to develop PAEs minimization's strategy is presented as well.

2. MATERIALS AND METHODS

2.1. Study area and sampling strategy

In 2019/2020 a total of 44 water and 6 sludge samples were collected from 50 locations in Lithuania, Poland and Denmark. Details of each sampling site are included in Table 1.

Table 1. Sampling site description

<table>
<tr><th rowspan="2">Samples</th><th colspan="3">Sampling points</th></tr>
<tr><th>Lithuania</th><th>Poland</th><th>Denmark</th></tr>
<tr><td>Water</td><td>No 1. PET factory
No 2. PET factory
No 3. Klaipeda region landfill
No 4. Furniture production
No 5. Shopping Center I
No 6. Wood processing
No 7. Laundry services
No 8. Cruise ship terminal
No 9. Tobacco Factory
No 10. Fish processing
No 11. Shopping center II
No 12. Food factory
No 13. Bread Factory
No 14. Biodiesel production plant
No 15. Energy supply, maintenance and repair services
No 16. Hotel
No 17. Concrete production
No 18. Bear factory
No 19. Domestic sewage
No 20. Sewage pumping station II
No 21. Sewage pumping station VI
No 22. Sewage pumping station XVII
No 23. Sewage pumping station XIX
No 24. Klaipeda Republican Hospital
No 25. Kindergarten
No 26. Truck wash services
No 27. Publishing-printing house
No 28. Sewage pumping station in Gargzdai II
No 29. Care home
No 30. District WWTP
No 31. Klaipeda WWTP outlet
No 32. Klaipeda WWTP inlet</td><td>No 0. Treated sewage from Goleniów sewage treatment plant (outlet)
No 1. Sewage pumping station Source: cosmetics company, concrete plant, catering, laundry, processing of furskins.
No 2. Sewage pumping station Source: restaurants, café.
No 3. Manhole. Sewage from: fast-food restaurant, gas station, kindergarten.
No 4. Manhole. Sewage from: restaurants, hairdresser, beautician.
No 5. Manhole. Source: restaurants, café.
No 6. Sewage pumping station Source: supermarket, market, restaurants, café.
No 7. Manhole. Source: shopping center, production of cardboard packaging, train station.
No 8. Manhole on the sewage treatment plant. Source: all Industrial Park.
No 9. Raw sewage Goleniów sewage treatment plant (inlet). Source: Goleniów town and commune (inlet)</td><td>No 1. Inlet of the Rønne WWTP
No 2. Outlet of the Rønne WWTP</td></tr>
<tr><td>Sludge</td><td>Klaipeda WWTP:
No 33. Primary sludge
No 34. Excess sludge
No 35. Digestate
No 36. Dried sludge</td><td>–</td><td>Rønne WWTP:
No 1. Sludge of the WWTP
No 2. Sludge of the WWTP</td></tr>
</table>

2.2. Methodology

2.2.1. Water samples analysis

The Standard EN ISO 18856:2005 and ISO 18856:2004 (Water quality. Determination of selected phthalates using gas chromatography/mass spectrometry) specifies a method for the determination of phthalates in water after solid phase extraction and gas chromatography/ mass spectrometry.

The method is applicable to the determination of phthalates in ground water, surface water, wastewater and drinking water in mass concentrations ranging from above 0,02 μg/l up to 0,150 μg /l, depending on the individual substance and value of the blank.
Principle: extraction of the compounds from the water by solid-phase extraction. Then separation is accomplished using capillary columns by gas chromatography and followed by identification and quantification of the phthalates by mass spectrometry.

2.2.2. Sludge samples analysis

CEN/TS 16183:2012 standard "Sludge, treated biowaste and soil – determination of selected phthalates using capillary gas chromatography with mass spectrometric detection (GC-MS)". Describes a method for the determination of selected phthalates in sludge, treated biowaste and soil, after extraction and gas chromatographic analysis with mass spectrometric detection.
The method is applicable for the determination of phthalates (Table 3) at the lowest mass content of 0,1 mg/kg to 0,5 mg/kg (expressed as dry matter), depending on the individual substance.
The applicability of the method to other phthalates not specified is not excluded except the isomeric mixtures e. g. DiNP (Di-isononylphthalate) but shall be verified in each case.
Principle: the dried sample, dried by freeze-drying or with sodium sulphate is extracted with ethyl acetate on the shaking device. An aliquot of the extract is cleaned with aluminium oxide (if necessary) followed by gas chromatographic separation using capillary columns and identification and quantification of the phthalates by mass spectrometry.

3. RESULTS AND DISCUSSION

3.1. Lithuania

The highest contamination with phthalates in Lithuania was attributed to DEHP which ranged from 0,05 to 159 μg/l in water sampling points (Table 2). Moreover, the mean concentration of DEHP reached 15,7 μg/l. This kind of phthalate is primarily used in plastic polymers and wares such as building and construction materials, furniture, cosmetic products, medical devices, toys and child care products, food and packaging material etc. The highest DEPH concentrations of 159 μg/l and 112 μg/l was observed in the Truck wash and Laundry sampling points respectively. The concentrations of others PAEs at those sampling points were also very high. In the Truck wash water sampling point the concentration of DiBP reached 2,2 μg/l, DBP – 1,8 μg/l, DEP – 0,26 μg/l and DMP – 0,18 μg/l. However, in the Laundry sampling point DBP concentration reached 6,9 μg/l, DEP – 4,8 μg/l, DiBP – 3,3 μg/l and DMP – 0,14 μg/l. PAEs compounds include in lubricants that influence the truck wash sewage's pollution. Phthalates have been detected in content of detergents that explain laundry's wastewater pollution by PAEs.

Meanwhile, near Real estate rental services providing company sampling point the concentration of DEHP was also very high – 50 μg/l. Moreover, the concentration of the DEP in this sampling point reached – 78,0 μg/l, DiBP – 4,9 μg/l, DBP – 2,6 μg/l and DMP – 0,17 μg/l. It can be explained by the fact that the site is located near several car washing and repair shops, and catering companies as well.

The results showed that the concentration of DEHP in domestic sewage sampling point reached 40 μg/l and was several times higher than in some industrial sampling points. Moreover, the DEHP concentrations in different Sewage pumping stations ranged from 0,7 μg/l (No. 19) to 9,7 μg/l (No. 2). Although the number of employees at each of above-mentioned enterprises is not small (average 500 employees), the biggest affect to the water pollution by phthalates was detected by household activities provided by citizens and based on phthalates active usage as part or substitute of PVC and other resins products. However, the wastewater treatment plant ensures effective phthalates precipitation at least two times per wastewater cleaning process and phthalates concentrate in the sedimentation.

It was determined that DEHP concentration in water near Shopping center "Banginis" sampling point reached 14 μg/l as well as DiBP – 26 μg/l, DEP – 17,0 μg/l and DBP – 6,1 μg/l. It can be explained by the fact that cars' washing as well as filling stations are situated close to shopping center. Active catering services and products' plastic packaging also contribute to the total PAEs compounds' concentration in the sewage.

DEHP concentration was also measured in regional dump of Klaipeda region waste management center. It was found that DEHP concentration in water sample was up to 7,2 μg/l as well as concentrations of other PAEs ranged from less than 0,05 μg/l to 0,1 μg/l (DBP). Based on the statistics [21] shown that the amount of the plastic waste has tendency to increase over the world (380 million tons in 2015) and taking into account the low DEHP biodegradability in the water, the DEHP concentration is higher than others measured phthalates [22].

In this Study, distribution of total PAEs (∑7PAEs) in the sludge samples (Table 3.) was as follow: Decomposed sludge (95,6 mg/kg) > Primary sludge (30,02 mg/kg) > Dried sludge

(16,2 mg/kg) > Excess sludge (4,8 mg/kg). The highest concentrations of phthalates in all samples were associated with DEHP, which concentrations ranged from 95.0 mg kg-1 in digestate to 3.8 mg kg-1 in excess sludge. After the biodegradation of sludge in the biogas reactor, its volume decreases by 1/3 of the original, and the concentration of phthalates in both sludge becomes higher.

3.2 Poland

The highest contamination with phthalates was observed in sewage pumping station No 6 where sewage from supermarket and industrial area are collected before transferring them to the sewage treatment plant (Table 4). The concentration of DMP reached 210 µg/l. Moreover, the concentrations of DEP as well as DEHP in this sampling point were high as well and reach 15 µg/l and 1.8 µg/l respectively. The concentration of DiBP and DBP exceeded the maximum permitted concentration of 0.05 µg/l by 9 and 5 times respectively. The well-known method for phthalates removal from water is biological treatment based on PAEs aerobic and/or anaerobic degradation by microorganisms [23]. The obtained PAEs concentrations shown that long-chains alkyl are quite resistible and require effective biological treatment.

However, it was determined that the total concentrations of seven PAEs (∑7PAEs) in the sewage No 1 of Industrial Park was much lower – 7.03 µg/L. It could be explained by variety of smaller number of companies and their size. The DEHP (2.6 µg/l), DEP (2.2 µg/l) and DMP (1.1 µg/l) were the main phthalate's compounds in this sampling point.

The results of manhole observation No 3, No 4, No 5 and No 7 points showed that the highest concentration has DEHP – up to 15 µg/L and DMP – up to 7.7 µg/L. The main source of the high concentrations of PAEs at that observation points are fast-food restaurants, hairdresser, and beautician, shopping center, gas and train stations.
It was found that the total concentrations of seven PAEs in the inlet of the sewage treatment plant (No 9) reached 22.7 µg/l. The dominant PAEs were DEHP > DEP > DiBP > DBP. DMP, DPP and DCHP concentrations were less than 0.05 µg/l.

It is important to state that concentration of DPP and DCHP in all sampling points were less than 0.05 µg/l that in accordance with proposition of the other scientists [24] and based on small industrial/domestic sewage proportion at the wastewater treatment plant.

Table 2. Results of phthalates analysis of water samples (Lithuania), 2019

No	Sampling point	DMP	DEP	DPP	DBP	DiBP	DCHP	DEHP	$\sum_7$PAEs
		µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
1	PET factory	2.5	3.7	<0.05	0.22	1.1	<0.05	0.16	7.68
2	PET factory	<0.05	2	<0.05	0.11	1.2	<0.05	0.05	3.36
3	Klaipeda region landfill	<0.05	0.47	<0.05	0.1	0.78	<0.05	7.2	8.55
4	Furniture production	0.06	4	<0.05	0.14	1	<0.05	19	24.2
5	Shopping center I	0.6	17	<0.05	6.1	26	<0.05	14	63.67
6	Wood processing	<0.05	0.23	<0.05	<0.05	0.5	<0.05	14	14.73
7	Laundry services	0.14	4.8	<0.05	6.9	3.3	<0.05	112	127.14
8	Cruise ship terminal	<0.05	<0.05	<0.05	0.07	0.43	<0.05	0.12	0.62
9	Tobacco Factory	<0.05	3.2	<0.05	<0.05	0.74	<0.05	2.1	6.04
10	Fish processing	<0.05	1.2	<0.05	0.15	1.0	<0.05	0.67	3.02
11	Shopping center II	0.17	78.0	<0.05	2.6	4.9	<0.05	50	135.67
12	Food factory	0.06	1.9	<0.05	<0.05	0.33	<0.05	1.2	3.49
13	Bread Factory	1.4	5.5	<0.05	0.32	0.56	<0.05	26	33.78
14	Biodiesel (methyl ester) production plant	3.1	1.8	<0.05	34	2.7	<0.05	6.8	48.4
15	Energy supply, maintenance and repair services	<0.05	0.3	<0.05	0.1	0.48	<0.05	0.41	1.29
16	Hotel	0.05	9.6	<0.05	1.3	2.5	<0.05	4.8	18.25
17	Concrete production	0.06	0.25	<0.05	<0.05	0.64	<0.05	0.13	1.08
18	Bear factory	0.05	<0.05	<0.05	0.06	0.17	<0.05	0.8	1.08
19	Domestic sewage	0.08	3.1	<0.05	0.6	1.8	<0.05	40	45.58
20	Sewage pumping station II	0.07	0.84	<0.05	0.4	1.5	<0.05	9.7	12.51
21	Sewage pumping station VI	0.41	6.6	<0.05	0.14	1	<0.05	2.7	10.85
22	Sewage pumping station XVII	0.07	0.14	<0.05	0.14	1.1	<0.05	9.5	10.95
23	Sewage pumping station XIX	0.27	2.6	<0.05	0.07	0.47	<0.05	0.7	4.11
24	Republican Hospital	0.68	2.5	<0.05	0.18	0.79	<0.05	0.39	4.54
25	Kindergarten	<0.05	0.64	<0.05	0.45	0.9	<0.05	1.8	3.79
26	Truck wash services	0.18	0.26	<0.05	1.8	2.2	<0.05	159	163.44
27	Publishing-printing house	<0.05	1.7	<0.05	<0.05	0.34	<0.05	0.22	2.26
28	Sewage pumping station in Gargzdai II	<0.05	0.84	<0.05	0.07	0.34	<0.05	1.6	2.85
29	Care home	<0.05	4.2	<0.05	0.05	0.3	<0.05	0.44	4.99
30	District WWTP outlet	<0.05	0.07	<0.05	<0.05	0.11	<0.05	0.14	0.32
31	Klaipeda WWTP outlet	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.07	0.07
32	Klaipeda WWTP inlet	0.08	3.35	<0.05	0.68	2.35	<0.05	2.51	9.07

Table 3. Results of phthalates analysis of sludge samples (Lithuania), 2019

No	Sampling point	DMP	DEP	DPP	DBP	DiBP	DCHP	DEHP	$\sum_7$PAEs
		mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
33	Primary sludge	<0.05	0.52	<0.05	2.4	4.1	<0.05	23	30.02
34	Excess sludge	<0.05	<0.05	<0.05	0.25	0.7	<0.05	3.8	4.8
35	Digestate	<0.05	<0.05	<0.05	<0.05	0.6	<0.05	95	95.6
36	Dried sludge	<0.05	<0.05	<0.05	<0.05	0.2	<0.05	16	16.2

Table 4. Results of phthalates analysis of water samples (Poland), 2020

No	Sampling point	DMP	DEP	DPP	DBP	DiBP	DCHP	DEHP	$\sum_7$PAEs
		μg/L	μg/L	μg/L	μg/L	μg/L	μg/L	μg/L	μg/L
0	Treated wastewater outlet to the river	<0.05	NA	NA	NA	NA	<0.05	12,2 / 23,6	NA
1	Sewage pumping station Source: cosmetics company, concrete plant, catering, laundry, processing of furskins.	1.1	2.2	<0.05	0.92	0.21	<0.05	2.6	7.03
2	Sewage pumping station Source: restaurants, café.	NA (Lost during transportation)							
3	Manhole. Sewage from: fast-food restaurant, gas station, kindergarten.	<0.05	1.3	<0.05	1.2	1.8	<0.05	7.4	11.7
4	Manhole. Sewage from: restaurants, hairdresser, beautician.	<0.05	3.7	<0.05	0.68	0.92	<0.05	8.8	14.1
5	Manhole. Source: restaurants, café.	0.18	0.22	<0.05	0.70	0.12	<0.05	0.44	1.66
6	Sewage pumping station Source: supermarket, market, restaurants, café.	210	15	<0.05	0.27	0.46	<0.05	1.8	227.53
7	Manhole. Source: shopping center, production of cardboard packaging, train station.	<0.05	3.0	<0.05	0.54	0.84	<0.05	15	19.38
8	Manhole on the sewage treatment plant. Source: all Industrial Park.	0.94	7.7	<0.05	0.52	0.31	<0.05	2.7	12.17
9	Raw sewage Goleniów sewage treatment plant (inlet). Source: Goleniów town and commune.	<0.05	4.2	<0.05	1.7	1.8	<0.05	15	22.7 / 43,7

3.3 Denmark

Background and objectives

At Rønne WWTP sewage samples were taken at inlet and outlet of sampling stations during the summer 2019 in order to analyse the efficiency of the WWTP regarding phthalates reduction based on technological sewage's sludge sedimentation.

The results of the Rønne's wastewater pollution by phthalates are presented in the Table 5. The analysis of the data showed the main trends of the PEAs compounds amounts' distribution in the samples. The predominant quantity of the DEHP and following DEP concentrations are in the same proportion as in above analysed Lithuanian and Polish WWTPs and reflect the common tendency of sewage pollution characterizing small and middle water treatments. The positive alteration of the total amount of PEAs after sewage treatment at Rønne WWTP does not connect with special or additional sewage handling regarding microorganic pollution.

Table 5. Concentration (μg/l) of PAEs in water samples (Denmark), 2019.

	Cas No	Method detection limit, μg/l	Inlet	Outlet
DMP	131-11-3	0.05	<0.05	<0.05
DEP	84-66-2	0.05	0.20	<0.05
DPP	131-16-8	0.05	<0.05	<0.05
DBP	84-74-2	0.05	0.14	<0.05
DiBP	84-69-5	0.05	0.05	<0.05
DCHP	84-61-7	0.05	<0.05	<0.05
DEHP	117-81-7	0.05	1.2	0.07
$\sum_6$PAEs	-	-	<1.74	**<0.37**

The distribution of PAEs in the water samples of Rønne WWTP was as follow: DEHP > DEP > DBP > DiBP. DMP, DPP and DCHP concentrations were less than 0.05 μg/l.

By the quality of the sludge can be judged on wastewater pollution. Such organic pollutant, as DEHP is oily organic carcinogen and slightly (2.70x10-1 mg/l at 25 °C) dissolve in the water [25], and has the inclination to bind to the sludge. The main samples for determination of the Rønne wastewater quality came from inlet and outlet of the Rønne sewage system. Besides that, the results of the samples of sludge, which were collected on-side for DEHP determination every month, then mixed and analysed every 3 months, were taking into account for correct evaluation of the sludge pollution by DEHP at Ronne WWTP in 2019 (Fig. 1). The DEHP concentration increased twice during the year. The analysis of the data shows that the amount of the phthalates in the sludge has tendency to change during the year, but there is no seasonal relationship [26]. The main reasons for an increase in the concentration of DEHP in sludge depend on the quality of wastewater, especially on its industrial component, the type of treatment facilities and their efficiency.

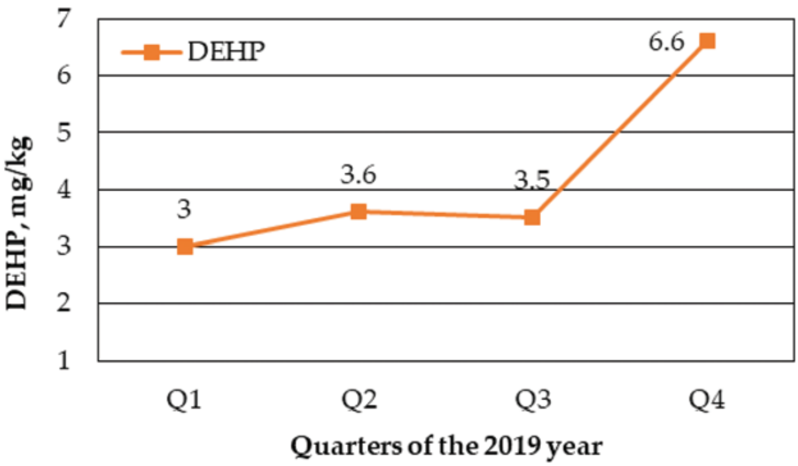

Figure 1. The Diethylhexylphthalate (DEHP) in the Rønne dewatered sludge in 2019.

In accordance with active Danish Environmental Protection Agency (EPA) policy and attention to pollution sources identification as well as publishing a list of undesirable substances and other numerous actions, such as voluntary agreement with manufacturers for the environmentally friendly alteration in products' production and use. The total/partial prohibition of PAEs, stricter standards, emission controls, environmental labelling, green guidelines, and information campaigns as well as the guideline for manufacturer and taxation are the main actions, which helped to reduce of the PAEs in environment [27]. Furthermore, in Denmark there are a special regulation about toys, which since 1999 has banned the manufacturing, import and selling toys and certain articles for young children with phthalates, especially for children under 3 years of age. From 2007, the manufacture and sale of toys and articles for children with the phthalates DEHP, DBP, DINP, DIDP and DNOP and BBP has been forbidden as well.

Denmark successfully adopted directive, regarding harmful substances monitoring implementation on the state level (priority substances in the field of water policy). Lithuania is still under preparation for directive's implementation. Each middle and big size economic unit should organise air and water pollution control, inform regional environmental protection agency on PEAs compounds and their concentrations. Monitoring of the entity is carried out in Poland as well.

The EC has adopted a decision to amend the REACH Regulation and restrict the use of the phthalates – DEHP, BBP, DBP and DIBP in consumer products on the EU market. The restriction started from 8 July 2020 and is expected to reduce organic contaminants amount in the air, water, soil and sediments.

4 CONCLUSIONS

The concentration of PAEs is very high in the vicinity of industrial parks, residential areas, and roadside drains, which shows that the concentration and distribution of PAEs in water are more affected by human activities.

Considering the risk of phthalates presence in the environment more studies are needed to identify and quantify the main sources of PAEs contamination and their dynamics, especially in Lithuania (Klaipeda) and Poland (Goleniow).

At the same time, the next step should be addressed to pollution by phthalate's prevention's challenge created on producers' and consumers' education, economic incentives application, and environmental management. Moreover, the findings may provide reliable data for decision-makers regarding phthalates reduction strategy's development in Lithuania, Poland, and similarly Eastern countries.

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Chapter 3 chapter “THE ADDITIONAL ANALYSIS OF THE PHTHALATES ACID ESTERS (PAEs) IN LITHUANIA”

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Based on the first PAEs report presented in the D3.1 the use of the raw materials and products containing phthalates are widely distributed. Consequently, still many European countries allow to import and export materials including phthalates’ compounds, the only decision at the moment is to control the wastewater treatment plants capability to diminish pollution by microplastics.

Taking into account the fact that in Lithuania (Klaipeda WWTP) and Poland (Goleniow WWTP) the different types of PAEs had higher concentration than in Denmark (Ronne WWTP), the conclusion to continue the investigation have been made. Unfortunately, during the Covid-19 events, the organization and transportation of the wastewater and sludge samples from Poland for the determination of the pollution by phthalates in Lithuania was not available. Therefore, the solution to arrange in Lithuania the control of small and middle-sized WWTP water and sludge contamination by microplastics’ pollutants before and after mechanical and biological treatment has been done. The main idea was to check how efficient different wastewater treatment facilities reduce the inflow’s concentration of phthalates acid esters after mechanical and biological treatments.

For this purpose, 13 different capacities WWTPs were chosen: Kvietiniai, Girkaliai, Lapiai, Judrenai, Kretingale, Plikiai, Vezaiciai, Endriejavas, Dauparai, Zadeikiai, Dreverna, Siupariai and Veivirzenai. Wastewater samples from above mentioned plants were organised from two main points – before treatment and after mechanical and/or biological treatment. The sludge pollution by phthalates were analysed at the Klaipeda WWTP analogically to the first evaluation presented in D3.1: primary sludge, excess sludge, digestates, dried sludge.

Table No. 1 illustrates the results of the wastewater contamination by PAEs before and after mechanical and/or biological treatment at the different small sewage treatment facilities. The results of the PAEs concentrations’ analysis show that the most important phthalate’s compound is di(2-ethylhexyl) phthalate. The concentration of this phthalate is the highest in the table and maximum concentration before water treatment equal 8,9 µg/l at Vezaiciai wastewater treatment point before sewage treatment. Most of the analysed small wastewater treatment plants have good mechanical and biological treatment capabilities and can reduce phthalate concentration by 93-98% (except Dauparai 86 % and Zadeikiai 67%). The biggest amount of the di(2-ethylhexyl) phthalate was observed at the Siupariai treatment plant, which facilities were limited by mechanical treatment. So, this fact supports our hypothesis done in the first report (D3.1.) that the biological treatment and its microbial communities contributes to the decomposition of organic pollutants.

Table No. 2 shows the concentration of the pollution by phthalates for different types of sludge. It is important to mention that the quite high PAEs concentration of di(2-ethylhexyl) phthalate (95mg/kg) for the digestates in the first investigation (D3.1.) decreased until 26 mg/kg for primary sludge. The di(2-ethylhexyl) phthalate was determined as the most widespread phthalates' compound in the wastewater sludge. It was found, that Diisobutyl phthalate also was detected in the sludge as the second PAEs compound, after di(2-ethylhexyl) phthalate, which concentration are reached 0,52mg/kg. Others analysed PAEs compounds were not related with significant risk of pollution by microplastics.

Table 1. The PAEs concentrations in the wastewater of the different samples' points before and after mechanical and biological treatment.

Date	**Sampling point**	**Dimethyl phthalate**	**Diethyl phthalate**	**Dipropyl phthalate**	**Dibutyl phthalate**	**Diisobutyl phthalate**	**Dicyclohexyl phthalate**	**di(2-ethylhexyl) phthalate**
	CAS No.	131-11-3	84-66-2	131-16-8	84-74-2	84-69-5	84-61-7	117-81-7
	Setting limit (µg/l)	0,05	0,05	0,05	0,05	0,05	0,05	0,05
		µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l
2021-02-22 **Kvietiniai WWTP**								
	Before treatment	<0,05	1,3	<0,05	1,1	1,3	<0,05	3,1
	After treatment	<0,05	<0,05	<0,05	0,07	0,19	<0,05	0,09
2021-02-23 **Girkaliai WWTP**								
	Before treatment	<0,05	1,1	<0,05	0,44	0,80	0,15	1,4
	After treatment	<0,05	<0,05	<0,05	<0,05	0,06	<0,05	0,08
2021-02-22 **Lapiai WWTP**								
	Before treatment	<0,05	9,4	<0,05	1,2	1,4	<0,05	8,4
	After treatment	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05	0,12

Date	Sampling point	Dimethyl phthalate	Diethyl phthalate	Dipropyl phthalate	Dibutyl phthalate	Diisobutyl phthalate	Dicyclohexyl phthalate	di(2-ethylhexyl) phthalate
	CAS No.	131-11-3	84-66-2	131-16-8	84-74-2	84-69-5	84-61-7	117-81-7
	Setting limit (µg/l)	0,05 µg/l	0,05 µg/l	0,05 µg/l	0,05 µg/l	0,05 µg/l	0,05 µg/l	0,05 µg/l
2021-02-17 **Judrenai WWTP**								
	Before treatment	<0,05	1,1	<0,05	0,34	1,6	<0,05	7,2
	After treatment	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05	0,15
2021-02-23 **Kretingale WWTP**								
	Before treatment	0,09	7,4	<0,05	0,56	1,2	<0,05	8,4
	After treatment	<0,05	<0,05	<0,05	0,05	0,15	<0,05	0,13
2021-02-22 **Plikiai WWTP**								
	Before treatment	<0,05	0,61	<0,05	0,83	1,1	<0,05	1,1
	After treatment	<0,05	<0,05	<0,05	0,07	0,17	<0,05	0,08
2021-02-17 **Vezaiciai WWTP**								
	Before treatment	<0,05	1,8	<0,05	0,2	1,6	<0,05	8,9
	After treatment	<0,05	0,05	<0,05	<0,05	<0,05	<0,05	0,14
2021-02-17 **Endriejavas WWTP**								
	Before treatment	0,08	3,9	<0,05	0,23	1,2	<0,05	5,1
	After treatment	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05	0,08
2021-02-23 **Dauparai WWTP**								
	Before treatment	<0,05	4,1	<0,05	0,45	0,83	0,15	3,6
	After treatment	<0,05	0,13	<0,05	0,08	0,51	<0,05	0,52
2021-02-17 **Zadeikiai WWTP**								
	Before treatment	<0,05	0,99	<0,05	0,20	0,45	<0,05	0,85
	After treatment	<0,05	0,28	<0,05	0,05	0,13	<0,05	0,28

Date	Sampling point	Dimethyl phthalate	Diethyl phthalate	Dipropyl phthalate	Dibutyl phthalate	Diisobutyl phthalate	Dicyclohexyl phthalate	di(2-ethylhexyl) phthalate
	CAS No.	131-11-3	84-66-2	131-16-8	84-74-2	84-69-5	84-61-7	117-81-7
	Setting limit (μg/l)	0,05	0,05	0,05	0,05	0,05	0,05	0,05
		μg/l	μg/l	μg/l	μg/l	μg/l	μg/l	μg/l
2021-02-17 **Dreverna WWTP**								
	Before treatment	<0,05	1,2	<0,05	0,23	1,1	<0,05	6,7
	After treatment	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05	0,11
2021-02-26 **Siupariai WWTP**								
	After treatment	<0,05	1,9	<0,05	0,12	0,31	<0,05	2,1
2021-02-17 **Veivirzenai WWTP**								
	Before treatment	<0,05	1,6	<0,05	0,31	0,95	<0,05	8,1
	After treatment	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05	0,09

Table 2. Sludge samples from Klaipeda WWTP

Samp-ling Date	Sampling point	Dimethyl phthalate	Diethyl phthalate	Dipropyl phthalate	Dibutyl phthalate	Diisobutyl phthalate	Dicyclo-hexyl phthalate	di(2-ethylhexyl) phthalate
Klaipeda WWTP after treatment (μg/l)		<0,05	<0,05	<0,05	<0,05	0,1	<0,05	0,17
2021-02-17								
Curonian lagoon, above outlet (μg/l)		<0,05	<0,05	<0,05	<0,05	0,06	<0,05	0,08
Curonian. lagoon, below outlet (μg/l)		<0,05	<0,05	<0,05	<0,05	0,06	<0,05	0,08
Setting limit (mg/kg)		0,05 mg/kg	0,05 mg/kg	0,05 mg/kg	mg/kg	0,05 mg/kg	0,05 mg/kg	0,05 mg/kg
Primary sludge (mg/kg)		<0,05	<0,05	<0,05		0,52	<0,05	26
2021-02-23								
Excess sludge (mg/kg)		<0,05	<0,05	<0,05		0,26	<0,05	9
Digestate (mg/kg)		<0,05	<0,05	<0,05		0,12	<0,05	16
Dewatering sludge (mg/kg)		<0,05	<0,05	<0,05		0,07	<0,05	22

Chapter 4 DEWATERING OF EXTERNAL SLUDGE TO DECREASE LEVELS OF HEAVY METALS, CASE STUDY REPORT

Elin Olsson – The municipality
of Höör /Mittskåne Water

In rural areas in Sweden, it is common for households to store sludge from e.g., toilets or dishwashers in septic tanks. These tanks are collected once a year by trucks and emptied at the municipal wastewater treatment plant (WWTP) where the sludge is treated together with incoming wastewater. The sludge from the septic tanks have often been found to have elevated levels of heavy metals. Experiences from wastewater utilities indicate that this type of external sludge, gathered from rural areas, should be handled separately. If dewatering is done exclusively on this fraction it would still be possible to add the supernatant, which would ideally have a low metal content, to the ordinary wastewater treatment stream.

Höör and Hörby WWTPs have been experiencing elevated levels of heavy metals in the treated sludge (Table 1). Since there are no heavy industries connected to the sewage networks, the reason for the observed levels is thought to be the septic tanks.

Table 1. Average sludqe quality on outgoing fraction from the WWTP:s compared to the external sludge for Höör and Hörby. Values within parentheses are measured peak levels.

Heavy metals (mg/kg TS)	*Existing regulation*	*New proposal for legislation*	*Average sludge Hörby WWTP*	*Average external sludge Hörby WWTP*	*Average sludge Höör WWTP (no lime)*	*Average sludge Höör WTTP (lime)*	*Average external sludge Höör WWTP*
Pb	100	25	8,8	13	33	16	68 (750)
Cd	2	0,8	0,9	0,9 (1,8)	2,2	1	1,3 (16)
Cu	600	475	400	340	913	485	417 (1200)
Cr	100	35	19	16	15	10	24
Hg	2,5	0,6	0,4	0,56 (1,4)	0,9	0,3	0,32
Ni	50	30	11	15	13	8	28 (150)
Zn	800	700	480	770 (1300)	760	420	670 (2400)
Cd/P			45	94 (186)	85	69	128 (1600)

In total, there are about 7 000 septic tanks that are treated at the WWTP. Since these plants in total treat the water from 22 000 persons, the external sludge represents a considerable share of the incoming load and thus a considerable share of the incoming load of metals (Table 2). The bedrock in the area has been found to have elevated levels of lead (Pb) and cadmium (Cd). According to previous analyses, this is likely the source of the heavy metals ending up at the WWTP. Therefore, an alternative method of separation is needed. The sludge from the septic tanks should ideally not be emptied into the regular wastewater inflow.

Table 2. Percentage of metals which the external sludge are contributing at the Höör treatment plant. The data comes from an internal report.

External sludge contribution	*Lead (Pb) %*	*Cadmium (Cd) %*	*Copper (Cu) %*	*Nickel (Ni) %*	*Zinc (Zn) %*
2013	52,9	36,5	9,0	81,0	25,6
2014	33,3	11,1	15,6	40,6	23,0
2015	70,0	15,0	17,1	45,4	27,2

The main aim of the case study was to investigate to what extent the heavy metal inflow to the WWTP could be reduced by separate handling of the external sludge. It was also expected that the organisation would receive valuable experiences from running this type of new treatment design and hopefully, this could form basis for future investments.

SETUP

The pilot plant set up with a separate handling process for the external sludge can be seen in figure 1. The plant was operational April 15 through May 16, 2019. Although the Höör WWTP had been found to have higher levels of heavy metals, the decision was taken to set-up the pilot plant at the Hörby WWTP. This due to practical issues. More space was available in Hörby and this facility had a pool available for intermittent storage of the sludge.

A roto-sieve and a wash press were hired from a consultant. After the preliminary step, the sludge was led to a pool for intermediate storage (this was done since the capacity to handle the water differed between the process steps) before it was pumped to the dewatering step (figure 2). To avoid foul smell, the dewatered sludge was stored in a covered container. The polymer used during the first three weeks was Superfloc C-1592RS. The last week Superfloc SD-6065 was used. The roto-sieve and the wash press was operating during working hours.

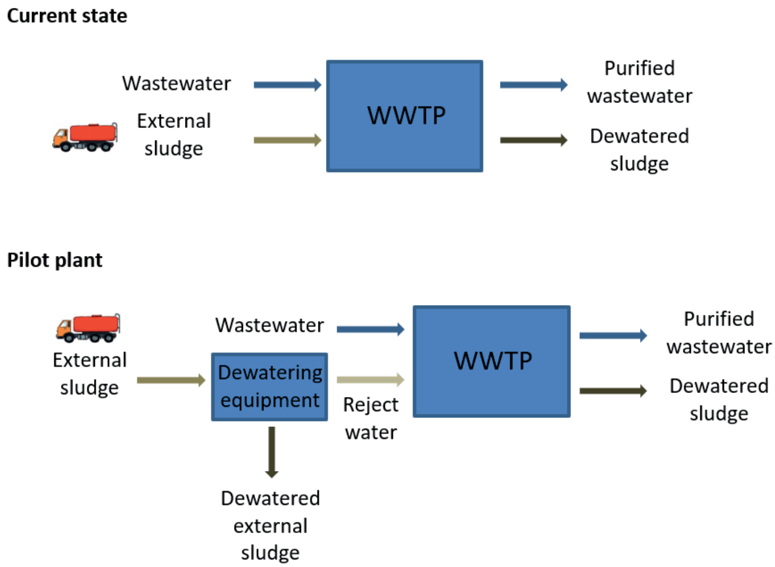


Figure 1. The pilot plant set-up during the phase of operation.

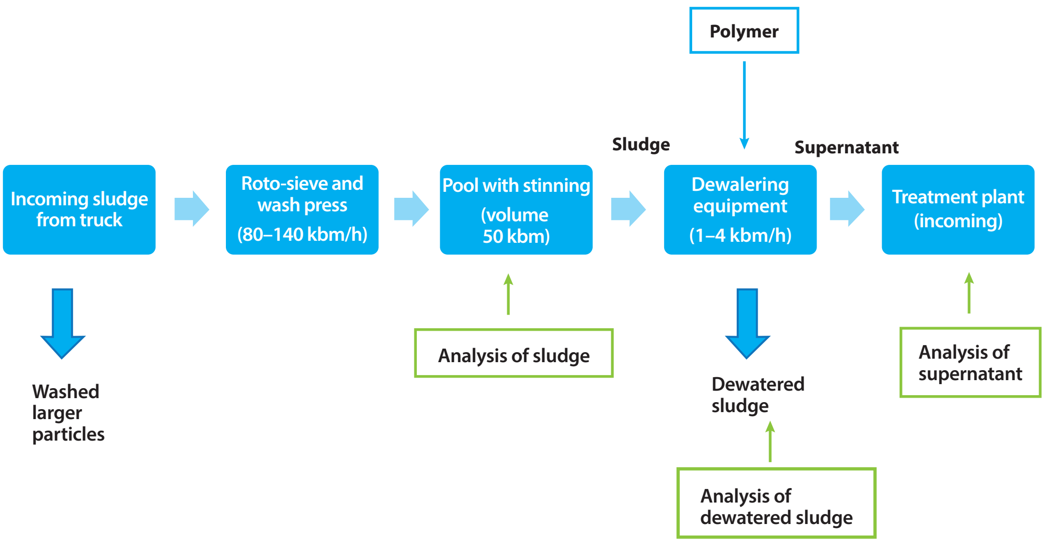


Figure 2. The process for the handling of external sludge and the points of analysis.

Figure 3. Roto-sieve and wash press

Figure 4. Dewatering equipment

Typically, two to three trucks per day carrying external sludge were emptied at Hörby WWTP. During the trial period, the trucks were emptied in a separate receiver instead of directly in the wastewater inflow. An exception was made for the trucks carrying sealed tanks as these were considered not to be containing elevated levels of metals.

Figure 5. Dewatered external sludge.

Analysis was carried out on the pre-screened sludge, the screened sludge, the supernatant and the dewatered sludge (figure 5). Flows and operational data were noted every day. Sampling was performed once every ten minutes. For the dewatered sludge, the samples were weighed to a daily composite. The samples were frozen and then mixed to a weekly composite.

In total, four weekly composite samples and ten daily samples were sent to a certified laboratory for metal analyses. Screened sludge, supernatant and dewatered sludge were analysed in this manner. The dewatered sludge was analysed for the content of 60 trace elements according to Swedish sludge quality standards. Among these it is important to trace cadmium, lead and mercury. A composite sample from the sludge was taken and then analysed for all 60 trace elements based on a dispersal of phosphorous around 22 kg/ha. Analysis concerning BOD and COD were done for the supernatant to investigate the treatment capacity of this fraction.

The various fractions were analysed in different manners. The supernatant and the screened sludge were analysed as ”wastewater”, while the dewatered sludge was analysed as ”sludge”. This meant that different methods were used for the same compound. Undoubtedly this might have constituted a source of error but nevertheless it was necessary given the difference in material between the stages.

RESULTS & DISCUSSION

The pilot plant operated without major malfunctions during the trial period. The external sludge was observed to be easily dewatered and the level of dry matter ranged between 28 to 41%. It would have been of interest to estimate the dosage of polymer but because of malfunctions there was no reliable information. According to the consultant who delivered the dewatering equipment, a typical dosage of polymer for the dewatering of external sludge could be found in the interval of 5 – 6 kg/ton dry matter.

The total amounts of heavy metals and nutrients in the different fractions (i.e., pre-treated sludge, supernatant and dewatered sludge) were calculated (see table 5). Theoretically, the amounts of metals in the supernatant together with that in the dewatered sludge should be equal to the amount in the pre-treated sludge, but this is not the case. The reason for this is likely because different methods have been used to measure the various phases.

Although the amount of metals was not in agreement, it was possible to see that the largest share of metals ended up in the dewatered sludge. Therefore, it was demonstrated that this process indeed is one way to decrease the incoming level of metals to WWTPs. This is the case for all metals; however, some bind harder to the sludge than others (e.g., nickel and zinc).

Table 5. Amount of metals and nutrients in the pre-treated sludge, the supernatant and the dewatered sludge, calculated based on concentrations and volume in the various fractions. The share of heavy metals in the supernatant compared to the dewatered sludge can also be seen.

Metal	*Amount in pre-treated sludge (g)*	*Amount in supernatant (g)*	*Amount in dewatered sludge (g)*	*% supernatant/dewatered sludge*
Pb	8,55	0,47	6,29	7/93
Cd	0,66	0,059	0,40	13/87
Cu	525	17,39	358	5/95
Cr	6,40	0,38	5,70	6/94
Hg	0,25	*	0,18	-
Ni	8,3	1,30	5,59	19/81
Zn	789	54,51	501	10/90
Nutrients	*Amount in pre-treated sludge (kg)*	*Amount in supernatant (kg)*	*Amount in dewatered sludge (kg)*	*% supernatant/external sludge*
N-tot	60	35	19	65/35
P-tot	10	4	3,9	53/47

*Below detection limit

The share of nitrogen and phosphorous was higher in the supernatant compared to the heavy metals. Since the WWTPs are constructed to handle these compounds, the observed levels were not considered a problem. On the contrary, a high load of phosphorous may be wanted as this means that more can be recirculated. However, it should be noted that an adequate method to extract phosphorous from the sludge must be used.

The dewatered external sludge generated by the pilot plant still must undergo treatment. Swedish regulations stipulate that the sludge sorts under domestic waste. A comparison was made between the dewatered sludge from the pilot plant, the ordinary sludge generated at Hörby WWTP and the threshold limits stipulated in Swedish regulations. This analysis showed how the dewatered external sludge would not be permitted for recirculation on arable land due to levels of copper (Cu) and zinc (Zn) exceeding the threshold limit.

The supernatant content revealed elevated levels of nutrients and BOD while the metal concentrations were found to be below the concentrations of the incoming wastewater and legislation stipulated by Mittskåne water. The ratio cadmium/phosphorous was also found to be below the normally observed, and thus the supernatant was considered ok to mix with incoming wastewater at the WWTP.

All metals in the sludge from the WWTP, except chromium and mercury, were found to exceed the threshold limits for dispersal on arable land (table 9). Metals found to have an accumulation rate exceeding 0,2% are to be considered important to work with according to Swedish standards.

Table 9. Proportion of metals based on a phosphorus dispersal of 22 kg/hectare per year.

Metal	*Added from sludge (g/ha)*	*Threshold limits (g/ha)*	*% of threshold limit*
Pb	37,29	25	149%
Cd	2,61	0,75	348%
Cu	2124,88	300	708%
Cr	38,90	40	97%
Ni	33,80	25	135%
Zn	2680,24	600	447%
Hg	0,85	1,5	57%

Based on the results from the analyses of the sludge, an attempt was made to assess how the sludge quality would be affected with the pilot plant set-up. The levels were calculated based on average levels of metals and dry matter. Hence, the results should only be viewed as an indication of sludge improvement. According to the calculated levels, 81–95% of the metals would end up in the dewatered external sludge. However, since there were some uncertainties concerning the calculation, it was decided to change the interval to 80–90%. Based on this a reduction of about 5-15% of the metals in the sludge from the WWTP could be achieved by external sludge handling (see table 10).

Table 10. Total amount of metals in the sludge from the WWTP and external sludge and the reduction in metal content on outgoing sludge if the amount is reduced by 80 and 90% respectively.

Metal	*Metal amount in sludge (mg/kg TS) per year from Hörby WTTP1*	*Calculated metal amount in external sludge per year (mg/kg TS)*	*Reduction of metals in outgoing sludge from WWTP at 90% reduction.*	*Reduction of metals in outgoing sludge from WWTP at 80% reduction.*
Pb	3,3	0,45	12%	11%
Cd	0,3	0,03	9%	8%
Cu	156	16	9%	8%
Cr	7,4	0,47	6%	5%
Hg	0,2	0,02	9%	8%
Ni	4,2	0,49	11%	9%
Zn	182	30,1	15%	13%

[1] Average value 2016-2018

[2] The values were calculated based on average values from the analyses on external sludge in this project as well as analyses done on external sludge in 2018.

CONCLUSIONS

The project showed that the inflow of metals to the WWTP can be reduced by separate handling of the external sludge. Additionally, the quality of the supernatant was sufficient for direct treatment at the WWTP.

The operation and maintenance were relatively straight forward and the sludge easy to dewater. A full-scale version of the pilot plant should not entail major malfunctions. Before the commencement of operations, there was suspicion that foul smell could occur, however this was found not to be a major issue. The only problem came from within the WWTP where foul smell was sensed coming from the pool for intermediate storage.

The dewatered external sludge was found to have elevated levels of copper and zinc. This meant that the sludge couldn´t be used for spreading on arable land. Combustion could be an alternative.

Apart from external sludge from households, it could be further investigated if external sludge from smaller WWTPs in Höör and Hörby should be treated in the same way. There are strong reasons to assume that this sludge as well contains elevated levels of metals.

The cost associated with investment for separate handling of external sludge is high and therefore it would probably be difficult to motivate one facility at each larger WWTP. However, it should be noted that it´s not necessary to have this type of facility at a WWTP. What is necessary is a wastewater pipe for outgoing supernatant. WWTPs do, however, have the advantage of being a protected environment with control over e.g., smell.

Current Swedish legislation regarding use of sewage sludge is under revision and, if passed, this would prohibit the dispersal of sludge on arable land. If this would turn out to be the case, then one can question the logic behind treating sludge in the manner described in this report. However, it could still be worthwhile to handle the sludge externally since it could prevent major pollutants ending up at the WWTPs and destroying treatment processes.

Chapter 5. ANALYSIS OF CAUSES AND QUANTITIES OF INFILTRATION/INFLOW ENTERING THE SEPARATE SEWER SYSTEM

Piotr Sobczak

1 THEORETICAL INTRODUCTION

The amount of wastewater and sewage flowing into the wastewater treatment plant does not match the amount produced by users. Less wastewater and sewage flowing into the wastewater treatment plant than the produced one indicates leaking sewer system, because wastewater infiltrates the ground. However, it may happen that groundwater and rainwater enters the sewer system. Any excess of sewage than the one resulting from the balance is marked as infiltration/inflow (I/I) entering the sewer system.

Water flowing down the road during rainfall or snowmelt flows into the manhole through its service openings.

In order to check the amount of rainwater entering through the manholes a test station was made. The time of filling the measuring tank was tested, and the height of water accumulation above the manhole was measured to draw up the characteristics for the dependence of volumetric flow rate of water running through the service openings in the manholes, as a function of the height of the water level. The research showed that service openings in manholes of sewage chambers are the cause of infiltration/inflow entering the sewer system.

The actual amounts of rainwater entering the sewer system were examined using an underhatch flow measurement device.

2 SUBJECT OF THE RESEARCH

The subject of the present study is to develop the amount of rainwater entering the sewer system in an uncontrolled way.

3 PURPOSE OF THE RESEARCH

The aim of the research is to determine the amount of rainwater entering the sewer system based on measurements made on the experimental model, field tests and analysis of data concerning the catchment area.

4 SCOPE OF THE STUDY

The scope of tests includes the technical development and construction of the test station.
Research on the experimental model includes:
measurements at the test station – manhole flow rate, height of water above the manhole as a function of the intensity of water inflow to the manhole,
comparison of obtained test results with theoretical/literature values.
After the tests were carried out at the test station, field tests were conducted.
Field tests include:

- selecting the catchment area,
- measuring the amount of water flowing into sewage chambers through manholes,
- comparison of field test results with experimental model studies and literature data,
- analysis of sewage inflow in the catchment area.

5 RESEARCH ISSUES

The Polish standard [10] assumes the calculation of flows in the sanitary sewer system based on water consumption by recipients. The dimensioning of sanitary sewer collectors does not provide for considering infiltration/ inflow, as its quantity at the design stage is impossible to determine. The problem of infiltration/inflow in the sewer system and the effects caused by it are faced by the network's operators, who try to identify the reasons for these waters to enter the sewer system.

Climatic factors – mainly an increase in air temperature and frequency of intense precipitation, as well as non-climatic factors – the main increase in building density and sewage flow rate values, directly or indirectly affect the increase in the value of the sewage streams, which are reliable for dimensioning sewer systems. Hence the need to constantly improve the principles of their design and dimensioning methods in order to meet future requirements. The proposed technical guidelines for the dimensioning of sewer systems (WTW) are presented below, based on the current state of knowledge in this area. [2]

Drainage systems for urban areas, i.e. sewer systems with special facilities, are usually designed and built with a view to at least 50÷ 100 years. The exceptions are

technological facilities – wastewater treatment plants and sewage pumping stations – usually designed for a period shorter than 50 years. This applies to the durability (technical viability) of the materials used to build the sewer system, especially the hydraulic capacity of the network and facilities in the future. The basis for safe design and dimensioning of household and industrial sewer systems and stormwater drainage systems (or modernization of the existing combined sewer system) is the proper balance of streams and/or stormwater. [2]
With regard to sewer systems (and combined sewer systems), the sewage balance should consider, among other things, the expected number of inhabitants, type of services and industry in a given settlement unit – from prospective land use plans. On the one hand, the demand for water in cities is decreasing, which is due to, among other things, water efficiency. On the other hand, the density of population and development of urban areas will increase, especially in the perspective of over 50 years. Average daily water demand in Poland and Germany per capita (including services) is currently at a similar level – from 80 to 200 $\frac{dm^3}{d}$ depending on the size of the city and the standard of the flats' installation equipment.

For the preparation of sewage balances, the unit outflow of household and farm sewage from residential areas should be estimated at not less than 150 $dm^3 \cdot d^{-1} \cdot Mk^{-1}$. Due to the lack of data in the Polish literature, especially the daily demand ratio (N_d) and hourly demand ratio (N_h) of the household wastewater outflow, German guidelines according to DWA- A 118 can be used÷2006 [6], which recommend the consolidated indicator : $q_{bg}= 4\div5 \left[\frac{dm^3}{s}\right]$ per 1 000 city residents. On this basis, the maximum stream of household sewage $Q_{bg} \left[\frac{dm^3}{s}\right]$ can be calculated using the formula:

$$Q_{bg}= q_{bg} \cdot Z \cdot \frac{F_{bg}}{1000} \tag{1}$$

Where:
Z- population density $[\frac{Mk}{ha}]$
F_{bg}- area of the household sewage catchment area [ha]

For industrial sites, consolidated indicators can also be used here q_p (according to DWA-A 118: 2006) from where the industrial wastewater stream $Q_p \left[\frac{dm^3}{s}\right]$ will be:

$$Q_{p}= q_p \cdot f_p \tag{2}$$

Where:
$q_{p(n)} = 0.2\div 0,5 \frac{dm^3}{s \cdot ha}$ – for the non-water-intensive industry,
$q_{p(w)} = 0.5\div 1,0 \frac{dm^3}{s \cdot ha}$ – for the water-intensive industry,
F_p – industrial areas [ha].

A reliable flow rate for the dimensioning of gravity systems (networks and sewage facilities) for household and industrial wastewater and infiltration/inflow/wastewater $Q_{śc}$ $[\frac{dm^3}{s}]$ should be calculated using the formula:

$$Q_{śc} = Q_{bg} + Q_p + Q_{przyp} \tag{3}$$

Where:

Q_{bg} – household sewage stream (maximum hourly) $\left[\frac{dm^3}{s}\right]$

Q_p – industrial wastewater stream (maximum hourly) $\left[\frac{dm^3}{s}\right]$

Q_{przyp}- infiltration/inflow/wastewater stream $\left[\frac{dm^3}{s}\right]$

According to the current German guidelines (DWA- A 118:2006), it is recommended to take the consolidated indicator of infiltration/inflow (i.e. infiltration water – from leaks in the sewers, and stormwater – flowing through, among others, manhole vents during the rainy season), as $Q_{przyp} = 0.25 \div 0.85 \frac{dm^3}{s \cdot ha}$. Hence the water/wastewater stream (w $\frac{dm^3}{s}$) can be estimated using the formula :

$$Q_{przyp} = Q_{przyp} \cdot (F_{bg} + F_p) \tag{4}$$

The household and industrial sewers should be selected for h/d ratio $\frac{h}{d}$: between 50 and 70%, corresponding to the total capacity (Q_0= 100%) for circular cross-section from 50 to 83% Q_0. It is therefore recommended to leave a reserve for future development of 50 to 17%. Q_0depending on the importance of the sewer in the system (according to DWA-A 118;2006). [2]

Based on the amount of wastewater produced by customers, wastewater treatment plants are designed. When designing a wastewater treatment plant, it is assumed that the cities will develop, i.e. increase the number of inhabitants, changes in the amount of water taken, connection of subsequent households or industrial plants to the wastewater treatment plant. The plant is therefore designed with a certain 'reserve' to accommodate the additional volume of wastewater or retention tanks are built to allow the wastewater to flow evenly into the plant.

Infiltration/inflow affects not only the functioning of the wastewater treatment plant but also the sewer network. With small sewage flows, it improves the operation of sewage collectors. Increased flow in the sewer means increased speed of sewage, which results in self-cleaning of the sewer. However, problems occur with a large amount of infiltration/inflow. There are situations when sanitary sewers reach their maximum capacity. The filling of the sewer is 100%. Sewage flow does not take place by gravity, but by means of pressure caused by the sewage column. Water flowing under pressure goes along the path where pressure losses are the smallest. Therefore, it is possible that sewage enters the street through various types of leaks, such as ventilation openings in manholes.

In case of significantly oversized wastewater treatment plants, infiltration/inflow improves its performance. It influences the time of sewage retention in wastewater treatment plants. The inflow of larger amounts of wastewater to be treated than the maximum designed flow rate results in too short time of retention for wastewater in the plants, which affects the quality of treated wastewater. *Excessive flow rate of wastewater, compared to the design assumptions, may cause the activated sludge from the biological reactor and secondary settling tanks to be carried away to the receiver.* [3] Part of the raw sewage is discharged to the receiver by means of storm overflows.

Infiltration/inflow affects the composition of the wastewater. Not only does it cause additional substances to be removed, but also increases the load of pollutants in the incoming wastewater, and affects the concentration of dissolved pollutants, the pH of wastewater.
In sanitary sewer systems where sewage pumping stations are located, the additional amount of sewage reduces the time of sewage retention in the pumping station and in the discharge manifold, which reduces the phenomenon of sewage putrification, and reduces the production of hydrogen sulphide. However, it is possible that the pumps will reach their maximum capacity. This will result in wastewater being poured into the pumping station area (or through another manhole, depending on the order of the wells and the height of the water column) and, consequently, contamination of the area.

Increasing the amount of wastewater flowing into the treatment plant increases the cost of its treatment. The user also pays for uncontrolled discharges of wastewater, infiltration/inflow entering the sewer system, because the operator includes the cost of treating more wastewater in the price of a cubic meter.

Extreme natural phenomena, such as heavy or prolonged rainfall and associated floods or sewage floods, have been increasing in recent years and cause considerable economic losses. This should force a continuous improvement of the design and dimensioning methods of sewer systems. Modern research methods used in urban hydrology, including precipitation monitoring, in conjunction with knowledge of statistics, probability calculation and mathematical modelling, are now becoming indispensable tools in engineering practice. [2]

6 INFILTRATION/INFLOW

The detailed determination of the wastewater streams that are reliable to dimension the channels should consider the additional inflow – inflow, including infiltration water.

Mainly, as a result of careless workmanship of the channels and aging of materials, the channels leak, which results in:

- groundwater infiltration into the channels, or
- exfiltration of sewage into the ground and contamination of groundwater. [1]

According to the previous guidelines from 1965, in case the bottom of the duct is submerged under the underground water table: H$\leq$ 4m the infiltration is as follows:

- housing estate network : $q_{inf} = 10 \frac{m^3}{d \cdot km}$ or 0.5/ 2.0 respectively $\frac{m^3}{d \cdot ha}$,
- urban network

$q_{inf} = 10 \frac{m^3}{d \cdot km}$ or $0.5 \div 2{,}0 \frac{m^3}{d \cdot ha}$ – brick and plastic channels,

$q_{inf} = 30 \frac{m^3}{d \cdot km}$ or $1.5 \div 6{,}0 \frac{m^3}{d \cdot ha}$ – stoneware channels,

$q_{inf} = 40 \frac{m^3}{d \cdot km}$ or $2.0 \div 8{,}0 \frac{m^3}{d \cdot ha}$ – concrete channels.

At the recess of the H> 4 m to be increased q_{inf} by 20 % every 1 m, over 4 m. For example: for H=6 m and the stoneware town channel $q_{inf} = 1.4 \cdot 30 = 42 \frac{m^3}{d \cdot km}$.
At present, new channels are being tested for tightness during their technical final inspection (less infiltration). [1]

When sewage channels are laid in irrigated soil below the level of the groundwater table, then groundwater, known as infiltration water, can flow into the sewage system through leaks in channels and manholes. As a guide, it can be assumed that the unit amount of infiltration water is 0.1-0.2 $\frac{dm^3}{s}$ and a hectare of sewage land. [11]

In *PN-92/B-10735 Sewerage. Sewers. Requirements and acceptance tests* [12] have been introduced unambiguously concerning the tightness of the sewer system. According to this standard, the following amounts of infiltration water are permitted:

- In sewers made of iron, steel and plastic sewers $q_1 = 0.01 \frac{dm^3}{m^2h}$,
- In precast concrete sewers and pipes and manholes of monolithic reinforced concrete construction made of vibrationally compacted concrete $q_1 = 0.04 \frac{dm^3}{m^2h}$,
- In sewers made of concrete pipes, longitudinally welded and vitrified clay pipes, and manholes made of prefabricated elements or pipes $q_1 = 0.03 \frac{dm^3}{m^2h}$. [11]

Infiltration/inflow is, apart from infiltration, mainly stormwater and snowmelt, flowing into the sewers, during the so-called wet weather, through:

- ventilation openings in the sewer manholes,
- incorrect connections, e.g. roof gutters, yard inlets, etc. [1]

The size of the inflow, including infiltration and stormwater, depends on the characteristics of the town / housing estate, and the type of the sewer material, the quality of workmanship and age of the sewers, as well as the depression under the groundwater table, slopes of the land surface, the type of road surface, which affect the value of the run-off coefficient. [1]

Sewer network operators try to identify inappropriate connections of rainwater discharge to the sanitary sewer system, by letting smoke into the sewers, renovating the exhausted sewerage systems, replacing manholes.
However, still, street surfaces or improperly finished sewerage chambers result in the manhole being lowered below ground level. Water flowing down during rainfall forms a small catchment area for each manhole. The lower manhole below ground level is flooded with water. Water flowing into this basin gets through the manhole into the sewer system.

Precipitation water gets through the manhole using:

- service openings, the purpose of which is not only ventilation, but also the possibility of inserting a wrench to open the manhole.
- the space between the ring and the manhole. The construction of the manhole consists of a gasket, but its purpose is not to isolate against the ingress of rainwater, but to dampen vibrations from traffic.

In the case of precipitation causing the runoff from the roads, hardened surfaces, roofs, whose downpipes discharge rainwater onto the roadway, manholes are the cause of the inflow into the sanitary sewer system.

Figures 1-2 show sanitary sewer manholes loaded with stormwater.

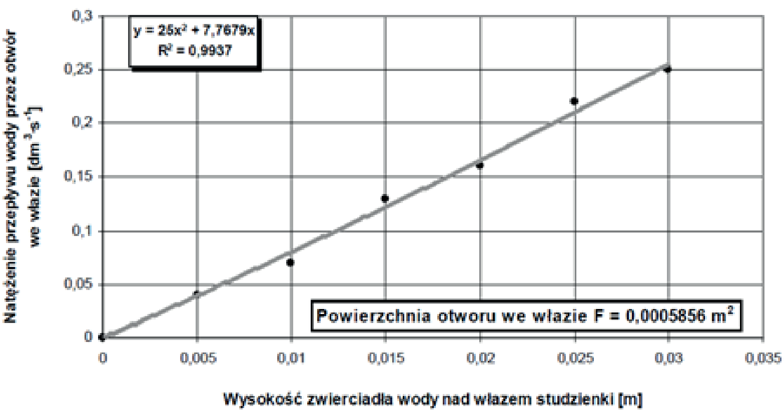
Fig. 1. Water on the manhole

Fig. 2. Water on the manhole – zoom on the holes

7 ANALYSIS OF RESEARCH BY GRZEGORZ KACZOR, PH.D., ENG [3]

Under laboratory conditions, a single-hole manhole model was made with dimensions averaged from field tests. The hole was made at a distance of 80 mm from the manhole edge (based on field measurements). The manhole was flooded with a layer of water- 5, 10, 15, 20, 25 and 30 mm high. After stabilizing the water level, the amount of water flowing through the hole to a water measuring container in a time unit was measured. Measurements were repeated three times. [3]

On the basis of laboratory tests, it has been shown that the inflow of stormwater into the manhole, through the hole for lifting the manhole cover, can be described by the equation: $Q = 25h^2 + 7{,}7679h$ in which h is a manhole level below ground level. (Figure 3)



Key:
wys. zwierciadła wody…–height of the water level above the manhole [m]
natężenie przepływu wody…–Water flow rate through the opening in the manhole

Fig. 3. Stormwater flow rate through the hole in the manhole depending on its level under the ground surface.

Testing part – tests carried out at the test station

8 ANALYSIS OF THE CATCHMENT AREA

8.1 Sewage quantity balance.

Table 1 compares the amount of wastewater produced by recipients and the inflows to the treatment plants operated by the GWiK (Goleniowskie Wodociągi i Kanalizacja) over the years for the Goleniów municipality.

Table 1. Comparison of the amount of sewage produced by recipients and inflows to the treatment plants operated by the GWiK over the years for the Goleniów municipality.

Year	Sewage production at treatment plants	Sewage sales at catchment areas	Sewage balance at catchment areas	
	[m^3]	[m^3]	[m^3]	[%]
2014	2 006 830	1 290 044	716 786	36
2015	2 149 753	1 352 920	796 832	37
2016	2 140 514	1 402 226	738 288	34
2017	2 815 598	1 438 066	1 377 531	49
2018	2 451 091	1 513 074	938 017	38

(source: GWiK archives)

In the analysed catchment area, which is the Goleniów municipality, the infiltration/inflow amount to 34 to 49%, which means that the amount of infiltration/inflow is from about 700 000 m3 per year to over 1 300 000, depending on the precipitation in a given year. The percentage amount of stormwater is different for each wastewater treatment plant, due to the catchment area, the amount of wastewater produced by users, the condition of the network.

Table 2 compares the amount of wastewater produced by recipients and the inflows to the Goleniów WWTP.

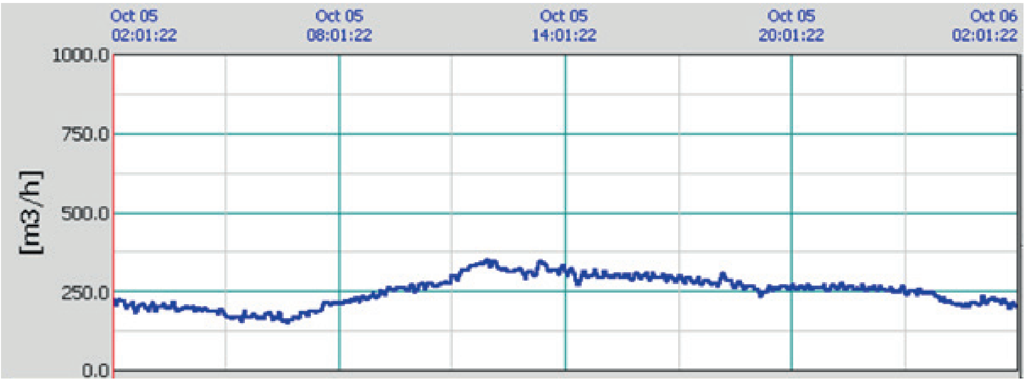
Table 2. Comparison of the amount of wastewater produced by recipients and inflows to the wastewater treatment plant in Goleniów.

Year	Sewage production at treatment plants	Sewage sales at catchment areas	Sewage balance at catchment areas	
	[m^3]	[m^3]	[m^3]	[%]
2014	1 823 731	1 135 791	687 940	38
2015	1 920 583	1 177 015	733 568	38
2016	1 873 493	1 215 584	657 909	35
2017	2 566 270	1 242 735	1 323 535	52
2018	2 200 616	1 301 726	898 890	41

(source: GWiK archives)

At the wastewater treatment plant in Goleniów the largest amount of infiltration/inflow flowing into the plant was recorded; infiltration/inflow constitutes about 38 to 52% of the total sewage inflow.

8.2 Temporary inflows to the wastewater treatment plant in Goleniów during the dry season and during rainfall

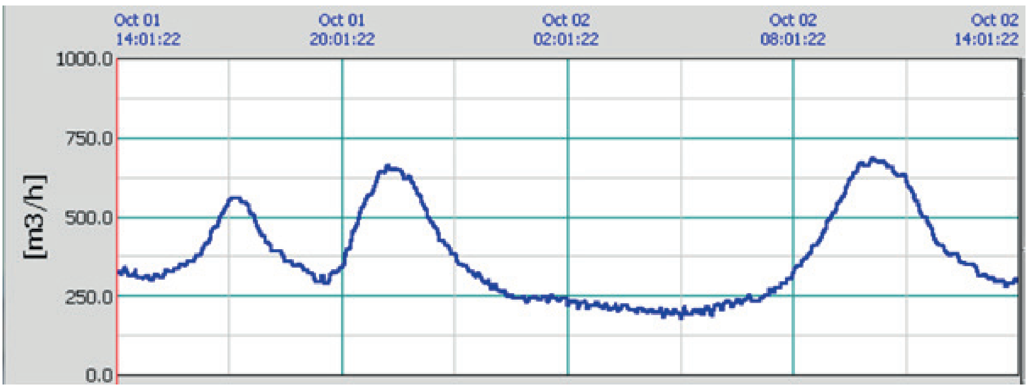


(source: GWiK archives)

Fig. 4. Inflow to the wastewater treatment plant in the dry season

The minimum amount of sewage flowing into the wastewater treatment plant according to Figure 18 is 148 $\frac{m^3}{h}$ maximum: 350 $\frac{m^3}{h}$ and an average: 250 $\frac{m^3}{h}$. The ratio of daily demand Nd is 1.4.

After the analysis of the graphs of the amount of wastewater flowing into the wastewater treatment plant, it was found that the average inflow in the rainless season during the day is about 250 – 300 $\frac{m^3}{h}$.



(source: GWiK archives)

Fig. 5. Inflow to the wastewater treatment plant when rainwater enters the sewer system

The minimum amount of wastewater flowing into the wastewater treatment plant according to Figure 20 is 177 $\frac{m^3}{h}$,maximum: 690 $\frac{m^3}{h}$and an average: 370 $\frac{m^3}{h}$. The ratio of daily demand Nd is 1.9.

9 CONSTRUCTION OF THE TEST STATION

Figure 6 shows the designed test station for determining the volume of uncontrolled stormwater ingress

Fig.6 Measuring device

10 MANHOLE INSPECTION

Assumptions:

- The tests were carried out with hydraulic gradient i=1%.
- The tests were performed until the flow at which the manhole was punctured
- The calculated theoretical value of the water flow through the manhole is a function of the water flow rate in the manhole, as a function of the height of the water column above the manhole. It does not consider the flow rate of water flowing through the space between the ring and the manhole.
- It was assumed that the difference between the actual flow rate of water flowing through the manhole and the theoretical value of the flow rate of the manhole is the amount of water flowing through the space between the ring and the manhole.
- The value of the flow rate ratio =0.6 was assumed.

Table 3. Type of hatch

Hatch	Numer of holes	Hole area [mm2]	Total area of holes	Outer diameter of hatch dz [cm]	Inner diameter of hatch dw [cm]
Type 1	2	628	1256	63,8	65
Type 2	4	932	3728	64,2	65
Type 3	2	868	1736	63,8	64,2
Type 4	1	1290	1290	63,8	64,2

Fig.7. Breakthrough the manhole

Fig.8. Zoom showing the manhole opening

Fig. 9, 10. Position of the manhole in the measuring station, manhole breakthrough.

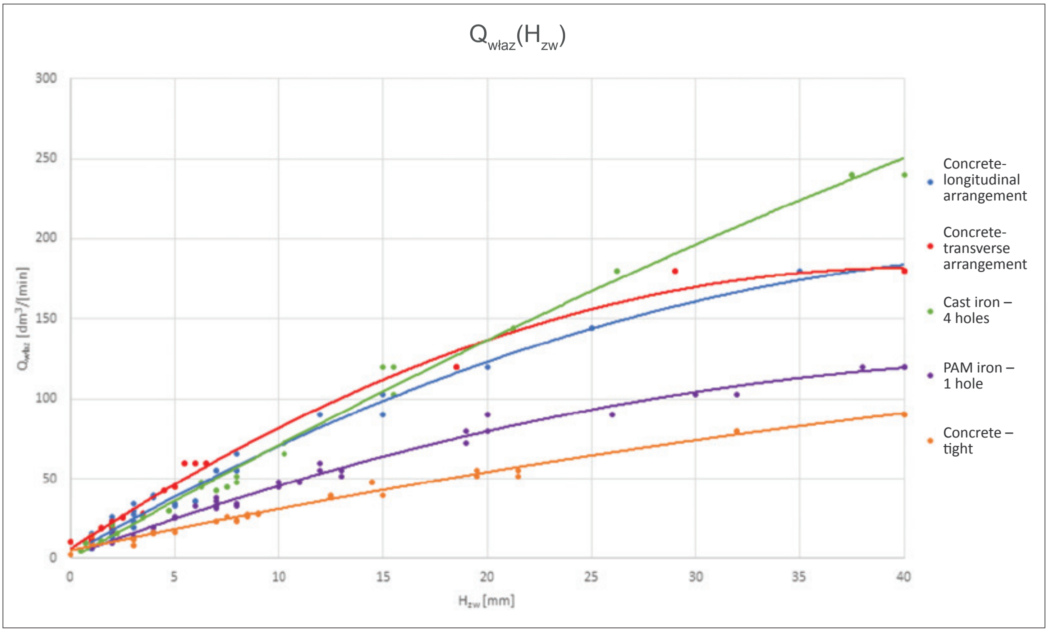


Fig. 11. Diagram of dependence of water flow rate through the manhole as a function of the height of the water level above the Hzw manhole for the manholes tested.

11 CONCLUSIONS:

1. Water enters through the manhole not only through the manhole but also through the space between the ring and the manhole.
2. Hydraulic jump causes water to accumulate on the manhole, which results in different heights of the water level on the manhole.
3. The vortexes at the manholes cause water to accumulate at the holes.
4. The accumulation of water at the measure results in an inaccurate reading of the water level height above the manhole.
5. The construction of the cast iron manhole with concrete filling causes uneven water flow on the manhole surface. Due to numerous irregularities, bumps, manhole holes are not evenly loaded with water.
6. At low flow rates, the measuring device operates below the minimum flow rate, which results in higher error values for measuring the flow rate of water
7. With a manhole sinking of 40mm below the table, it is possible that the space between the ring and the manhole is also sealed. This results in lower water flow through the space.
8. At low flow rates, water enters through the space between the ring and the manhole. Before the water is piled up so that it can overflow through the opening, the maximum load on this space occurs.

9. At low flow rates, water entering the manhole enters the measuring tank through the space between the ring and manhole. When increasing the flow rate, the holes in the manhole begin to be loaded. When the entire manhole is covered with water, the space between the ring and the manhole reaches its maximum capacity. Increasing the flow rate of water flowing into the manhole increases the volume flow rate of water flowing through the manhole.
10. The theoretical value of the water stream flowing through the manhole to the measuring tank considers only the water entering through the holes in the manhole. The difference between the actual value of the water flowing through the manhole and the theoretical value of the volume flow rate of water flowing through the manhole shall be equal to the theoretical volume flow rate of water entering the space between the ring and the manhole.
11. The arrangement of the manhole in the ring, the space between the ring and the manhole affects the value of the volume flow rate of water entering the measuring tank through this space.
12. There is a gasket between the ring and the manhole to dampen vibrations from the traffic. If the gasket is in poor condition or there is no gasket, the volume of water flowing between the ring and the manhole will increase.
13. Increasing the volume flow of water flowing into the manhole results in increasing the volume flow of water flowing through the manhole to the maximum load of the manhole. Further increase of the volume flow of water flowing into the manhole does not increase the volume flow of water flowing through the manhole.
14. When the TYPE 4 manhole is put, water flows into the manhole through the opening. When the manhole is installed from the end of the manhole, water flows through the space between the ring and the manhole. Due to the design of the manhole, water above the opening must be piled up to a height of more than 4 mm to get through the opening in the manhole.
15. The arrangement of the manhole, the location of the manhole openings in relation to the inflow has an influence on the manhole load. With the transverse arrangement of the holes, or with the hole placed closer to the end of the station, the space between the ring and the manhole is more loaded before the hole in the manhole is loaded than with the axial arrangement of the hole – the hole positioned to the inflow direction.
16. Actual volume flow rates of water flowing through the manhole may differ from those obtained at the test station due to a reduction in the space between the ring and the manhole (backfilling with sand, gravel, pebbles), or by blocking the service opening in the manhole.
17. The smallest value of the volume flowing through the manhole as a function of the height of the water level above the manhole was recorded for a cast iron manhole with concrete filling and two service openings, but with less space between the ring and the manhole. The actual values of the volume flow of water entering through the manhole are closest to the theoretical values for this manhole. This is due to the smallest area of space between the ring and manhole from the manhole tested.

18. The highest value of the volume flowing through the manhole as a function of the height of the water level above the manhole was recorded for the cast iron manhole with four openings above the water level piling up to 20 mm, and for the cast iron manhole with concrete filling and two service openings, but smaller space between the ring and the manhole below the water level piling up to 20 mm. These differences result from the variable load (depending on the stream of water flowing into the manhole) of not only the service openings, but also the space between the ring and the manhole.

12 SUMMARY OF TESTS AT THE TEST STATION

The research has shown that the construction of manholes is the cause of rainwater entering the sanitary sewer system.

The amount of infiltration/inflow entering through the manhole is dependent on the surface of the holes in the manhole, the space between the ring and the manhole, and the height of the water level above the manhole, which depends on the location of the manhole in the catchment area, and the intensity of rain. The curve of dependence of the water flow through the manhole as a function of water level height accumulation above the manhole is an increasing function occurring in the form of a square root.

The actual amounts of stormwater entering the sanitary sewer system through the manhole are illustrated by field tests.

It is impossible to fully eliminate the phenomenon of stormwater entering the sanitary sewer system. In order to minimize the scale of this phenomenon, during construction attention should be paid to detailed execution of street surfaces, installation of manholes. The recommendation for manufacturers is to limit the surface of service openings, and to seal the surface between the ring and the manhole.

Field studies

1 ANALYSIS OF THE CATCHMENT AREA

The manhole is located in Podańsko. Wastewater from this locality is gravitationally transported to the sewage pumping station, and then transported to the sewage pumping station, to which wastewater from Budno, Danowo and leachate from the landfill also flows. Sewage from these catchment areas is transported to the wastewater treatment plant in Goleniów.

The Goleniów wastewater treatment plant's catchment area consists of localities: Goleniów, Podańsko, Budno, Danowo, Białuń, Miękowo, Marszewo, Żółwia Błoć, Żdzary, Łaniewo.

Table 4. Comparison of sewage sales and values read at the flow meter in the Podańsko, Budno, Danowo catchment area and sewage sales in the catchment area of the wastewater treatment plant in Goleniów as well as sewage inflow to this plant in 2018 and 2019.

zlewnia:		Goleniów				Podańsko, Budno, Danowo, składowisko			
rok	miesiąc	dopływ do OCS	sprzedaż	ΔQ [m^3]	ΔQ [%]	przepływomierz	sprzedaż	ΔQ [m^3]	ΔQ [%]
2018	styczeń	260 355	109637	150 718	58	3068	1925	1143	37
	luty	222 985	98233	124 752	56	2468	1562	906	37
	marzec	222 861	106692	116 169	52	2837	1743	1094	39
	kwiecień	213 339	101430	111 909	52	2738	1688	1050	38
	maj	182 868	115223	67 645	37	1968	2287	-319	-16
	czerwiec	164 188	107068	57 120	35	2105	1672	433	21
	lipiec	175 307	111607	63 700	36	2627	1981	646	25
	sierpień	153 610	113056	40 554	26	2240	1813	427	19
	wrzesień	143 997	106168	37 829	26	2222	1745	477	21
	październik	151 472	107599	43 873	29	245	1860	-1615	-659
	listopad	145 311	105977	39 334	27	1929	1961	-32	-2
	grudzień	164 323	104619	59 704	36	2603	1762	841	32
2019	styczeń	192 616	111189	81 427	42	2840	1900	940	33
	luty	172 275	103031	69 244	40	2303	1665	638	28
	marzec	193 326	111345	81 981	42	2710	1882	828	31
	kwiecień	165 555	112321	53 234	32	2710	2001	709	26
	maj	167 201	111772	55 429	33	2088	2035	53	3
	czerwiec	161 669	111116	50 553	31	2007	1595	412	21
	lipiec	151 857	112039	39 818	26	2301	2054	247	11
	sierpień	147 970	111575	36 395	25	1883	1837	46	2
	wrzesień	153 854	112942	40 912	27	2797	1861	936	33
	październik	176 410	113486	62 924	36	2327	1801	526	23
	listopad	176 562	107804	68 758	39	2987	1884	1103	37
	grudzień	177 380	114460	62 920	35	2357	2155	202	9

Note: The color indicates the error of the flow meter

Key:
wys. zwierciadła wody…– height of the water level above the manhole [m]
natężenie przepływu wody…– Water flow rate through the opening in the manhole

styczeń – January	sierpień – August
luty – February	wrzesień – September
marzec – March	październik – October
kwiecień – April	listopad – November
maj – May	grudzień – December
czerwiec – June	
lipiec – July	

1.1 Test station

The test station consists of a manhole mounted on a sewer inspection chamber, a rain gauge installed in a nearby sewage pumping station, and a flow measurement device by Unitechnisc. The device is made of a rotary overflow tank, which after being filled up performs a rotation, pouring out the collected rainwater. The controller counts the number of tank rotations in time. On this basis, it calculates the characteristics of the number of rotations during the measurement.

Fig. 12. Measuring device

1.2 Testing procedure

1) A measuring device was installed in the selected manhole of the sanitary sewer.
2) A rain gauge was installed in a nearby sanitary sewage pumping station.
3) The height of the precipitation level h_{opad} was read at a selected hour, with a constant interval between readings (24 hours).
4) Data from the controller were read out.

5) Based on the data, the amount of infiltration/inflow entering the sanitary sewer system was calculated, as well as the momentary volumetric flow rate of water entering through the manhole.
6) The rainfall intensity was calculated from the Błaszczyk formula.
7) The results were compared with the values obtained during tests performed at the test station.
8) The amount of sewage in the Podańsko catchment area and the catchment area of the wastewater treatment plant in Goleniów was analysed.

Fig. 12. The manhole under examination

Fig. 13. Measuring device installed in a sanitary sewer chamber

2. TECHNICAL DATA OF THE MANHOLE

Manhole type: Cast iron with concrete filling

- Number of holes **n=2 pcs.**
- External diameter of the manhole $_{dz}$ = 68 cm
- Internal diameter of the manhole body $_{dw=67}$ cm
- The surface of the hole: F=898 mm2
- The manhole position in the field:

3. ANALYSIS OF INFILTRATION/INFLOW QUANTITY IN CATCHMENT AREAS

Table 5. Amount of infiltration/inflow entering through the manhole under investigation

month	Quantity of infiltration/inflow entering through the manhole	
January	2064.6 dm^3	2 m^3 were adopted
February	1134,7 dm^3	1.2 m^3 were adopted

Assumptions for infiltration/inflow analysis:

1) The amount of water infiltrating from the ground to the sanitary sewer system calculated on the basis of Kotowski's data was considered in the balance because the calculation of the amount of water infiltrating to the sewer system using PN-92 B-10735 is a great approximation of the average length of the sewage pipes' diameter- and in the report on the length and material of pipes not all pipes have the diameter assigned.
2) In the sewer system in the catchment area of the Goleniów wastewater treatment plant there are sewage collectors made of stoneware, concrete and plastics. Therefore, average values of qinf, qi presented in the tables were assumed.
3) In the calculations, the sanitary fixtures were omitted as they were assumed to be above the ground water level.
4) Due to the high level of groundwater in the Goleniów municipality, it was assumed that all sewage collectors are located in the soil layer, where groundwater is present.
5) In the Podańsko, Budno, Danowo catchment area it has been assumed that stormwater gets through 60% of manholes, while in the Goleniów WWTP catchment area 80% of manholes.

3.1 The catchment area: Podańsko, Budno, Danowo

Table 6. Amount of incidental waters in the catchment area of the Podańsko, Budno, Danowo

Parameter		January	February
flow meter	m^3	2579	2308
sale of wastewater	m^3	2074	1987
Infiltration/inflow	m^3	506	321
	%	20	14
manhole	pcs	417	
Vi	m^3	2	1.2
water infiltrating through manholes + landfill leachate	m^3	500	300
other ifiltration/inflow – leachate from the landfill	m^3	5	20
% of waters infiltrating through the manhole of all infiltration/inflow	%	99	94

3.2 The catchment area: Goleniów

Table 7. Amount of infiltration/inflow in the catchment area of the Goleniów WWTP

Parameter		January	February
Flow meter	m^3	175632	185204
sale of waste water	m^3	113286	110539
Infiltration/inflow	m^3	62347	74665
	%	35	40
manhole	pcs	6050	
V_i	m^3	2.1	1.2
$Q_{inf,właz}$	m^3	10164	5808
% of waters infiltrating through the manhole of all infiltration/inflow	%	16.3	7.8
q_{inf}	m^3/d km	20	20
$Q_{inf,grunt}$	m^3	1653	1653
	m^3/month	51242	47936
% of groundwater infiltrating from the ground of all infiltration/inflow	%	82.2	64.2
Other infiltration/inflow	m^3	941	20922
	%	1.5	28.0

4. CONCLUSIONS AFTER THE FIELD STUDIES

1) The maximum instantaneous water flow through the manhole was 6.70 $\frac{dm^3}{min}$. This corresponds to a water level above the manhole of about 3mm.
2) The average sinking of the manhole under test is 0.4 mm
3) The amount of stormwater entering through the manhole is influenced by the catchment area of the manhole, its run-off coefficient, manhole depression, precipitation height and its duration.
4) The amount of infiltration/inflow entering through manholes may differ from the values obtained by manhole testing. This is influenced by the manhole sunk, the catchment area of each manhole, the type of surface in which it is installed, i.e. a different rate of run-off, the number of service openings, and the space between the body and manhole.
5) Assuming that stormwater gets through 60% of the manholes in the Podańsko, Budno, Danowo catchment area, in the month of January, infiltration/inflow getting through the manhole accounts for 99% of all infiltration/inflow, whereas in the month of February: 94%. In this catchment area a part of infiltration/inflow is leachate from a landfill.
6) Assuming that stormwater in the Podańsko, Budno, Danowo catchment area gets through 100% of the manholes, the obtained value is higher than the amount of infiltration/inflow.
7) The calculated amount of water infiltrating from the ground into the sanitary sewer system is greater than the amount of infiltration/inflow present in this catchment area.
8) The flow meters counting the amount of wastewater from Podańsko and Danów shows incorrect values. The indications of the flow meter counting the amount of sewage from Podańsko, Budno, Danowo and leachate from the landfill are doubtful.
9) Assuming that stormwater gets through 80% of manholes in the catchment area of the Goleniów sewage treatment plant in the month of January, incidental water getting through the manholes constitutes 16.3% of all infiltration/inflow, whereas 7.8% in the month of February.
10) The remaining part of the infiltration/inflow in January is groundwater infiltrating the sewage system. They account for 82.2% of all infiltration/inflow. Whereas in the month of February 64.2%.
11) There was no rainfall on 5 February 2020 in Podańsko. However, in Goleniów the height of rainfall was 5mm. On that day, thanks to stormwater entering the sanitary sewer system, the inflow of sewage to the wastewater treatment plant was increased. The main influence on the inflow to the wastewater treatment plant has the basin of the town of Goleniów. It is influenced by the catchment area, number of manholes, the condition and depth of the channels influencing the groundwater infiltration to the sanitary sewer system.

5. SUMMARY OF FIELD STUDIES

The biggest difference in the amount of infiltration/inflow flowing into the wastewater treatment plant is noticeable when rainfall occurs, and a few hours afterwards when infiltration/inflow from the sewer system reaches the plant. Water infiltrating through manholes constitutes about 16.3% of infiltration/inflow flowing into the wastewater treatment plant in January and 7.8% in February. Ground water should infiltrate the sewer system with a relatively constant flow of infiltrating water depending on the ground water level. Groundwater infiltrating from the ground to the sanitary sewer system accounts for 82.2% of infiltration/inflow flowing into the wastewater treatment plant in January and 64.2% in February.

With the assumed values of infiltration and stormwater inflow to the sanitary sewer system, they account for 98.5% of infiltration/inflow flowing into the wastewater treatment plant in January and 72% in February. Actual values may differ significantly from the assumed values. The assumption of a constant flow through all manholes on the basis of the manhole test is a great simplification. The calculated values of groundwater infiltrating to the sewer system are purely theoretical, as the same amount of groundwater infiltrating to the sewer system is assumed for each kilometer of the sewer system in January and February. The difference in the remaining quantities of infiltration/inflow in the months of January and February may be due to different groundwater levels, rainfall intensities resulting in fluctuating values of water flowing from hardened surfaces by means of manholes and illegal connections of drained areas, therefore illegal connections of roof drainage, hardened areas should not be excluded, and connections to the sewer network should be checked by means of smoking.

In the Podańsko, Budno, Danowo catchment area, the calculated amounts of infiltration/inflow entering through manholes, assuming that stormwater enters through 100% of the manholes, and the calculated amounts of water infiltrating from the ground into the sanitary sewer system are greater than the actual value of infiltration/inflow occurring in this catchment area. The calculated theoretical amount of infiltration/inflow for the catchment area of the Goleniów wastewater treatment plant, despite the fact that it falls within the amount of actual infiltration/inflow, should be smaller than the actual value, as it takes place in the Podańsko, Budno, Danowo catchment area. However, looking at the theoretical calculated values of infiltration/inflow in the catchment area of the Goleniów WWTP one can have doubts about the operation of the sewage flow meter counting the sewage from Budno, Danowo, Podańsko, which can understate the values of the sewage flowing.

The actual value of stormwater entering through manholes and infiltrating waters from the ground to the sanitary sewer system that is smaller than the total amount of infiltration/inflow indicates that the drainage systems of the areas are connected to the sanitary sewer system.

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Chapter 6 NATIONAL SLUDGE HANDLING RULES COMPARISON

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INTRODUCTION

The different countries in EU have different traditions and issues about the use of sludge in agriculture, and the national legislation is also different, although the same EU-directive (86/278/EEC) regulate Limit Values of heavy metals in sludge from Wastewater Treatment Plants (WWTP) when used as fertilizer in agriculture (see table 1 and 3 below).
In the STEP project's deliverable 3.2 it is described and compared the national rules and the issues and barriers to the use of sludge in agriculture, from the perspective of each partner and the specific regulation in their country.

1 COMPARISON OF NATIONAL RULES IN GENERAL

A thorough comparison of limit-values of different compounds in sludge is published in the EU-report: Disposal and recycling routes for sewage sludge, Part 2 - Regulatory report October 2001.

Table 1. Limit values for heavy metals in sludge (mg/kg DM)
(Shaded cells represent limit values below those required by Directive 86/278/EEC)

	Cd	Cr	Cu	Hg	Ni	Pb	Zn	As	Mo	Co
Directive 86/278/EEC	20 – 40	–	1000 –1750	16 – 25	300 –400	750 – 1200	2500 – 4000	–	–	–
Austria	2 [a] 10 [b] 10 [c] 4 [d] 10 [e] 0.7 -2.5 [f]	50 [a] 500 [b] 500 [c] 300 [d] 500 [e] 70 -100 [f]	300 [a] 500 [b] 500 [c] 500 [d] 500 [e] 70 -300 [f]	2 [a] 10 [b] 10 [c] 4 [d] 10 [e] 0.4 -2.5 [f]	25 [a] 100 [b] 100 [c] 100 [d] 100 [e] 25 -80 [f]	100 [a] 400 [b] 500 [c] 150 [d] 500 [e] 45 -150 [f]	1500 [a] 2000 [b] 2000 [c] 1800 [d] 2000 [e] 200 -1800 [f]	20 [e]	20 [e]	10 [a] 100 [e]
Belgium (Flanders)	6	250	375[f]	5	100	300	900[f]	150	–	–
Belgium (Walloon)	10	500	600	10	100	500	2000		–	–
Denmark – dry matter basis – total phosphonus basis	0.8 100	100	1000	0.8 200	30 2500	120 [g] 10 000 [g]	4000	25 [h]	–	–
Finland	3 1.5 [I]	300	600	2 1 [I]	100	150 100 [I]	1500	–	–	–
France	20 [J]	1000	1000	10	200	800	3000	–	–	–
Germany	10	900	800	8	200	900	2500	–	–	–
Greece	20 - 40	500	1000 - 1750	16-25	300 - 400	750 - 1200	2500 - 4000	–	–	–
Ireland	20	–	1000	16	300	750	2500	–	–	–
Italy	20	–	1000	10	300	750	2500	–	–	
Luxembourg	20 - 40	1000 - 1750	1000 - 1750	16-25	300 - 400	750 - 1200	2500 -4000	–	–	–
Netherlands	1.25	75	75	0.75	30	100	300	–	–	
Portugal	20	1000	1000	16	300	750	2500	–	–	
Spain – soil pH < 7 – soil pH > 7	20 40	1000 1750	1000 1750	16 25	300 400	750 1200	2500 4000	–	–	–
Sweden	2	100	600	2.5	50	100	800	–	–	
UK	–	–	–	–	–	–	–	–	–	–
Accession countries										
Estonia	15	1200	800	16	400	900	2900	–	–	–
Latvia	20	2000	1000	16	300	750	2500	–	–	–
Poland	10	500	800	5	100	500	2500	–	–	–

[a] Lower Austria
[b] Upper Austria
[c] Burgenland
[d] Vorarlberg
[e] Steiermark
[f] Carinthia

[f] These values are reduced to 125 (Cu) and 300 (Zn) from 31/12/2007
[g] For private gardening, lead value is reduced to 60 mg/kg DM or 5000 mg/kg P
[h] For private gardening
[i] Target limit values for 1998
[j] 15 mg/kg DM from January 1, 2001 and 10 mg/kg DM from January 1, 2004

Table 3: Limit values for organic compounds in sludge (mg/kg DM)

	Dioxins and Furans (PCDD, PCDF) ng TE/kg DM	PCBs	AOX	LAS[l]	DEHP[p]	NPE[q]	PAH[r]	Toluen
Austria	100 [a, b, d]	0.2 [a, b, d]	500 [a, b, f]	–	–	–	6[f]	
Belgium (Flanders)?	50 [f]							
Denmark – from 1/07/2000 – from 1/07/2002	–	–	–	2600 1300 1300	100 50 50	50 30 10	6 3 3	–
France		0.8 [m]		dc			2 – 5 [n] 1.5 – 4 [o]	
Germany	100	0,2 [s]	500	–	–	–	–	–
Sweden	–	0.4		–	–	100	3	5

[a] Lower Austria
[b] Upper Austria
[c] Burgenland
[d] Vorarlberg
[e] Steiermark
[f] Carinthia

[k] Limit values for approximately 30 organic compounds (see p. 35)
[l] Linear alkyl-benzene sulphonates
[m] Sum of 7 principal PCBs (PCB 28, 52, 101, 118, 138, 153, 180)
[n] Fluoranthen, Benzo(b)fluoranthen, Benzo(a)pyren
[o] When used on pasture land
[p] Di (2-ethylhexyl)phtalate
[n] Includes nonylphenol
[o] Poly aromatic hydrocarbons
[p] For each one of the six congeners

The report states: "*In particular, the limit values for concentrations of heavy metals in sludge are lower than the limit values specified in the Directive in a majority of countries. In five countries (Belgium -Flanders-, Denmark, Finland, the Netherlands and Sweden), the limit values for heavy metals in sludge are even much lower…*

In the majority of Member States, the specific regulations which have been introduced covering the disposal and recycling of sludge mainly concern the use of sludge in agriculture, while the disposal of sludge is addressed by general legislation on landfill and incineration of waste..
In the Directive, very few specific provisions for sludge from septic tanks are included in national regulations."[1]
The STEP project partners have confirmed that the contemporary limit-values are still the same in their countries as shown in the tables above.

2 DENMARK (BORNHOLM)

The national rules about use of sludge in agriculture have essentially been unchanged for many years. In generally the sludge quality I Denmark has improved during the years and the majority of the sludge is used in agriculture (about 75%).
On Bornholm all the sludge from wastewater treatment is used as fertilizer in agriculture. Sludge from WWTPs and septic tanks are treated separately.

[1] http://ec.europa.eu/environment/archives/waste/sludge/pdf/sludge_disposal2.pdf

2.1 Heavy metals

Cadmium – is usually the heavy metal in sludge that might come closest to, or surpass, the limit value in DK. This is not surprising when we take a look at the table comparing Limit Values: Denmark has one of the lowest limits for Cadmium in EU: 0,8 mg/kg DM (or 100 mg/kg P), where the directive operates with 20-40 mg/kg DM.

One of the WWTP's on Bornholm (Boderne) sometimes come close to, and occasionally surpasses, the Danish limit value of Cadmium. It is possible that the large amount of excess water this WWTP receives contributes to this situation.

The low Danish Limit value for Cadmium is generally not a barrier to agricultural use of sludge in Denmark or Bornholm, and it gives us a natural focus on industrial wastewater permissions, where the allowed concentration of Cadmium in wastewater is usually low.

2.2 Organics

Denmark and Sweden are some of the few countries in EU where the national legislation has Limit Values for groups of organic compounds.

2.3 "Psychological barriers"

"The Arla directive": The mayor Danish diary-company, Arla, don't allow their milk suppliers to use sludge on fields where their cows feed. This is related to possible reactions from costumers.

2.4 Sludge from septic tanks

Sludge from septic tanks is also regulated by the same national rules as sludge from WWTPs. On Bornholm the sludge from septic tanks (app. 5000) is composted to reduce the content of organic compounds, e.g. LAS, below the limit values. The sludge is composted with straw cut in bits, and then mixed with burned lime, before it is used as fertilizer in agriculture.

This is a cheap, energy-effective way to handle sludge from septic tanks.

3 SWEDEN (HÖÖR/HÖRBY)

Close to one million tons of sludge derived from wastewater is collected every year in Sweden. Between 25 to 30 % of this sludge is spread on arable land. The remaining part is used as e.g. soil conditioner or for covering landfills.

In Sweden a water utility can be certified by the Revaq-standard. Revaq is a system which aims to reduce the stream of harmful substances to the wastewater treatment plant (WWTP), so that a lot of nutrients can be sustainable redistributed. Obtaining a Revaq-certificate signifies that the operator of a WWTP is working with these issues in an active and structured manner and that there is a continuous strive for self-improvement of the organization.

Revaq is the product of Swedish water (the trade association for Swedish water- and wastewater utilities). It is also linked to the agricultural sector and the food business as well as the Swedish environmental protection agency. Revaq was launched in 2008 and so far 42 WWTP's have been certified (roughly corresponding to 50% of all generated wastewater sludge).
Some of the stipulated criteria for the certification of sludge according to Revaq are:

- The sludge should be hygenized to avoid infections.
- Leachate from landfills cannot be connected to the WWTP.
- Threshold limits for the addition of metals to arable land cannot be exceeded. The limits are calculated based on grams per person, hectare and year. These limits are lower than the national legislation.

The legislation in Sweden concerning the usage and spreading of sludge originating from wastewater was passed in 1994. During the last 15 years, parliament and government have worked out a new proposal for legislation but it has not been passed as of the writing of this report (2019).

3.1 Heavy metals

The elevated concentrations of some of the metals signify a problem; it can be difficult to spread the sludge from Höör and Hörby. For the sludge produced in Höör, the levels of lead, cadmium, copper and mercury have been observed to be above this threshold limit. For Hörby it is only cadmium which exceeded the limit.

Höör and Hörby are situated on top of bedrock rich in lead and cadmium. Since elevated levels of these metals also have been found in the soil layers above, it cannot be ruled out that one source could be infiltration through cracks and other irregularities in the sewer network.

According to Swedish standards, it is necessary for a cadmium-phosphorus quota of 17 up until the year of 2025. The sludge from the Höör and Hörby WWTP's have quotas of 72 and 42 respectively.

In the proposal for new regulation, threshold limits for silver will also be included. This compound is not monitored on a daily basis at Mittskåne water. However, according to available, there should be no problem in fulfilling this new requirement.

If the Swedish threshold limits are compared to the legislation around Europe, it can be seen that the Swedish ones are generally lower. That is to say, the legislation in Sweden puts a tougher demand on sludge quality than most European countries.

3.2 Organics

The substances that are regulated in Swedish law are these: PAH, PCB, Nonylfenol och Toluen. In the table below it can be seen that the levels of organics at the WWTP's in Höör and Hörby are well below the stipulated threshold values.

3.3 "Psychological barriers"

A debate has been ongoing in Sweden about the suitability of fertilizing with sludge originating from WWTP's. In the end of the 90s and in the beginning of the 00s it was prohibited to disperse the sludge in this way. E.g. the milk company Arla did not want their cattle to receive food grown with sludge as a basic nutrient. The Federation of Swedish farmers has for the last decades encouraged their members not to spread sludge on arable land. This is the basic historical foundation for Revaq, to ensure the quality of the sludge.

For over ten years there has been work carried out to elaborate new regulations. The suggestions concern stronger regulations for hygenisation and recirculation of phosphorous to arable land. The threshold limits for metal contents are also considered to be lowered.

A prohibition of the dispersal of sewage sludge should not mean an obstacle for the generation of biogas. The aim is set for both energy and phosphorous to be recovered from the sludge without running the risk of potentially harmful substances reaching the environment.

3.4 Sludge from septic tanks

In Höör and Hörby there exist roughly 6 000 septic tanks. The sludge from these are collected by lorry and driven to the wastewater treatment plant where it is added to the incoming wastewater stream. Thereafter the septic tank sludge is treated according to the same processes as any other wastewater reaching the plant. Investigations have found relatively large quantities of metals in the sludge originating from septic tanks (sometimes more than 50 % of the total metal content).

Within the STEP-project a pilot-plant has been setup. Here the sludge coming from septic tanks will be treated externally.

4 LITHUANIA (KLAIPEDA)

4.1 Legislation review

Directive 86/278/EEC is the main document defining the requirements on sludge management in agriculture in EU level. Well as the other Directives also have significant role on sludge management, this document contains national rules comparison with respect to Directive 86/278/EEC requirements.

Lithuanian legal system has 2 documents regarding wastewater sludge management in agriculture:

1. The main national document regarding transposition of Directive 86/278/EEC requirements into Lithuanian legislation is Environmental Protection Normative document LAND 20-2005: Requirements on the use of Sewage sludge for Fertilization and Reclamation[2] adopted by the Order of the Ministry of Environment.
2. Environmental requirements for composting, anaerobic treatment of biodegradable waste adopted by the Minister of Environment order[3]. Requirements determine the conditions for composting, anaerobic treatment of biodegradable waste, types of composted, anaerobically treated waste, requirements for the quality and use of compost, anaerobic fermentation. The main points, regarding sewage sludge management in agriculture:
    - Composting or anaerobic treatment can be used for sludge I and II categories and A, B classes (according to LAND 20-2005).
    - Compost is considered suitable for usage when the values of heavy metals in the compost made from sludge does not exceed the category II limits (according to LAND 20-2005).

Table 8. Sludge differentiated into categories according to heavy metals concentrations

Sludge category	Heavy metals concentration, mg/kg (LAND 20-2005)						
	Pb	Cd	**Cr**	**Cu**	**Ni**	**Zn**	**Hg**
I	<140	<1,5	<140	<75	<50	<300	<1,0
II	140-750	1,5-20	140-400	75-1000	50-300	300-2500	1,0-8,0
III	>750	>20	>400	>1000	>300	>2500	>8,0
EU Directive 86/278/EEC limit values in sludge(mg/kgDM)	**750-1200**	**20-40**	-	**1000-1750**	**300-400**	**2500-4000**	16-25

New draft version of the Requirements for the use of sewage sludge for fertilization and recultivation[4]

[2] 28/07/2016 Order of the Ministry of Environment with latest amendment No. D1-517: https://www.e-tar.lt/portal/lt/legalAct/TAR.3536A8337E8A/oOjEMmzJtx

[3] 14/03/2016 Order of the Ministry of Environment with the latest amendment No. D1-186 https://www.e-tar.lt/portal/legalAct.html?documentId=63c2f1c0ea7d11e58deaaf0783ebf65b

[4] Draft order of the Ministry of Environment: https://e-seimas.lrs.lt/portal/legalAct/lt/TAP/16d38e20c88c11e8a82fc67610e51066?jfwid=-w4wfq4b9z

The draft document has the main proposals:

- Establishing the criteria for classifying sludge compost and sludge ferment.
- To tighten restrictions for heavy metal values from 2021 (Table No. 3), allowing water management and other companies to prepare for the implementation of this legislation, and to align with the Urban Wastewater Regulation, which requires canceling effluent (including cadmium) of priority hazardous substances by 2020.
- Only sludge of **category I** can be used in agriculture.

Table 10. Sludge differentiated into categories according to heavy metals concentrations (proposal)

Sludge Category	Heavy metals concentration, mg/kg						
	Pb	Cd	Cr	Cu	Ni	Zn	Hg
I	<140	<1,5	<140	<300	<50	<800	<1,0
II	140-750	1,5-20	140-400	300-1000	50-300	800-2500	1,0-8,0
III	>750	>20	>400	>1000	>300	>2500	>8,0
	Heavy metal concentration from 2021, mg/kg						
I	<120	<1,5	<100	<300	<50	<800	<1,0
II	120-150	1,5-5	100-130	300-500	50-70	<800-1500	1-1,5
III	>150	>5	>130	>500	>70	>1500	>1,5

4.2 Sludge management in a national level

In Lithuania we have 23 state projects sludge management facilities funded by EU: 12 sewage sludge digestion-drying plants, 2 drying facilities and 9 composting sites.
According to Environmental Protection Agency statistical data (2017)[5], sludge managed in these ways:

- Used for fertilization and recultivation – 48,3%
- Used for composting – 38,7%
- Incinerated – 0,3%
- At landfills – 7,4%
- Other methods – 5,2%.

4.3 Remarks/conclusions

Sewage sludge treated as a waste in general, not as a product. Therefore, it leads to economic aspects, as e.g. WWTP companies needs to pay "gate fee" in the incineration plant, while producing sludge granules 11-12 MJ. According to the Ministry of Environment, opinion there is no standard for sludge fuel as a product.

5 Source: Environmental Protection Agency: http://vanduo.gamta.lt/files/Visuomen%C4%97s%20informavimo%20 ataskaita_2019.pdf

Still there are companies discharging heavy metals to the city wastewater treatment's plant in amount exceeding the MAC (Maximum Allowable Concentration). Industrial companies are penalized, but from economic point of view for companies better to pay penalty then to install an innovative and effective treatment/equipment on their site.

"Psychological barriers" for sludge usage in agriculture. Even the companies preparing fertilization plans free, giving dried sludge free it is hard to find farmers/companies. Farmers are afraid of the smell as well.

Relatively high sludge compost insertion to the soil cost, as it is necessary to have equipment because sludge should be spread quickly. Fertilizers do not need this condition. Farmers prefer to choose mineral fertilizers that only need to be poured on the fields.

5 POLAND (GOLENIOW)

Municipal sewage sludge is subject to Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste, the so-called Waste Framework Directive, which sets out the principles for the management of waste, including municipal sewage sludge, from the moment it is regarded as waste.

European Union's legal regulations regarding management of sewage sludge include primarily the Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture, the so-called Sewage Sludge Directive, which results in significant restrictions for the agricultural and natural use of sludge.

5.1 Polish Legislation review

Polish national regulations concerning the processing and final management of municipal sewage sludge constituting waste are laid out in the Waste Act of 14 December 2012 and the Regulation of the Minister of the Environment of 6 February 2015 on municipal sewage sludge.

These legal acts specify the conditions, frequencies and types of sediment and soil testing to be carried out before using sludge, as well as the obligations of the landowners and producers of sludge. It is also possible to use stabilized municipal sewage sludge for manufacturing fertilizers or plant cultivation aids, as laid out in the Act on Fertilizers and Fertilization of 10 July 2007 (Dz. U. 2018, item 1259) and the Regulation of the Minister of Agriculture and Rural Development of 18 June 2008 on the implementation of certain provisions of the Act on Fertilizers and Fertilizations (Dz. U. of 2008 No. 129, item 76). These laws lay down the conditions for marketing products manufactured from municipal sewage sludge and explain how to obtain authorizations for placing a product on the market via obtaining independent opinions of the competent research institutes.

The Waste Act defines how to properly classify sewage sludge into appropriate groups, subgroup and types of waste, in accordance with the Regulation of the Minister of the Climate of 2 January 2020 on Waste Index (Dz. U. of 2020 , item 10). The classification is carried out by the waste producer. If a sewage sludge has been subject to stabilization, i.e. biological, chemical, thermal or other treatments aiming to reduce the susceptibility of municipal sewage sludge to mineralization (rotting), such sewage is classified under code 19 08 05 - *stabilized sewage sludge*. Sewage sludge classified as above can be recycled above ground.

The most important parameters determining the suitability of the sludge for use in agriculture is the absence of biological contaminants and concentration of heavy metals not exceeding the maximum values presented in the table 12 below.

Table 12. Maximum permissible content of heavy metals in municipal sewage sludge

No.	Metals	for agriculture and for the rehabilitation of land	for the rehabilitation of land for non-agricultural purposes	for the adaptation of land to specific needs resulting from waste management plans, spatial development plans or decisions on development and land use conditions, for cultivating plants intended for composting, for cultivating of non-food crops and for the production of forage
1	Cadmium (Cd)	20	25	50
2	Copper (Cu)	1000	1200	2000
3	Nickel (Ni)	300	400	500
4	Lead (Pb)	750	1000	1500
5	Zinc (Zn)	2500	3500	5000
6	Mercury (Hg)	16	20	25
7	Chromium (Cr)	500	1000	2500

It must be stressed however, that using sludge classified as waste under code 19 08 05 is not always possible due to strict legal regulations, because it may contain high levels of heavy metals and biogases in quantities that disqualify using it as fertilizer in agriculture. A possible solution for using sewage sludge which does not meet the aforementioned requirements is utilizing composted sludge.

Composting is a microbiological process based on processing of organic waste. The process occurs under aerobic conditions and leads to partial mineralization and humification of organic matter. An important element in the composting process is the composition of the compost mixture, especially in chemical, biological and mechanical terms, in order to obtain a stable and environmentally safe product.

Composting produces fertilizer which meets the criteria for being placed on the market under the laws on fertilizing and fertilization.

The Polish market for fertilizers is regulated by the provisions of the Fertilizers and Fertilization Act of 10 July 2007. (Dz. U. of 2007, No. 147, item 1033), Regulation of the Minister of Agriculture and Rural Development (Dz. U. of 2009, No. 224, item 804) and implementing rules:

- Regulation of the Minister of Agriculture and Rural Development of 18 June 2008 (Dz. U. No. 119, item 765).
- Regulation of the Minister of Agriculture and Rural Development of 8 September 2010 (Dz. U. No. 183, item 1229).

The main aim of the legal regulations is to ensure that fertilizers offered and used for agricultural purposes meet high quality standards and their use is safe for the environment, as well as human and animal health.

Permits for placing on the market are granted in order to protect the interests of the agricultural producers (persons purchasing the fertilizer or agent) and to protect the environment, human and animal health. The following components are subject to assessment:

- quality (chemical and physicochemical properties);
- the fertilizer value of the product;
- the impact of the product on the environment, human and animal health, manufacturing technology and raw materials used, the sanitary condition of the product, the heavy metal content and veterinary requirements.

The criteria for the health status assessment include testing for Salmonella bacteria, live intestinal parasite eggs (*Toxoxoxara sp., Ascaris sp., Trucharis sp.*), Enterobacteriaceae bacterial count (up to 1000 ykt/1g of fertiliser) - in the case of fertilisers containing animal by-products.

The total content of heavy metals together with the requirements for components is strictly defined (Tables no. 15, 16, 17) for organic and organic-mineral fertilizers.

Fertilizer value assessment is carried out experimentally on test plants (agricultural crops) under strict conditions of field or pot experiments. The yield-forming activities, the influence of fertilizer on the quality of yield, and the influence of soil fertility are subject to assessments.
All tests, from fertilizer sampling to testing, are carried out by bodies and laboratories accredited in the EU. On the basis of the results obtained, tests and evaluations, the quality requirements are evaluated and the fertilizer value of the institute is evaluated: -IUNG -PBI, Institute of Pomology and Vegetation, Forest Research Institute. Opinions on the impact on human health, the Institute of Rural Medicine, the impact on animal health - PIW-PIB, the impact on the environment - Instytut Ochrony Środowiska (Institute for Environmental Protection).

After completing the study and collecting all opinions, a complete application must be submitted to the Ministry of Agriculture and Rural Development for a permit to place the fertilizer / agent on the market.

Authorization shall be granted for an unlimited period, may be withdrawn if the fertilizer does not comply with the conditions laid down in the authorization or if it is established on the basis of new facts that it is likely to endanger human or animal health or adversely affect the environment. The quality of marketed products is controlled by the Inspection of Commercial Quality of Agricultural and Food Products.

The processing of municipal sewage sludge constituting waste requires a relevant waste processing permit or an integrated permit covering waste processing. The Waste Act exempts from the obligation to obtain a waste processing permit a person owning the land area on which municipal sewage sludge is used for the following purposes: in agriculture, for the cultivation of plants intended for the production of compost, for the cultivation of plants not intended for consumption and for the production of fodder. The responsibility for the correct use of municipal sewage sludge lies with the producer of the sludge and is therefore obliged to obtain the permit. By transferring stabilized municipal sewage sludge to a natural person for use on the soil, the treatment plant continues to be responsible for the proper use of this waste. Municipal sewage sludge may be transferred to the landowner for use only by the sludge producer.

6 CONCLUSIONS AND RECOMMENDATIONS

Our common understanding among the STEP project partners based on an ecological approach is that sludge from WWTPs:

- is a valuable biomass and as much as possible of the nutrients in the treated waste water should be collected in the sludge/as little as possible of nutrients, organic matter and chemicals in the treated waste water should pass onto the recipients.
- Should, if possible, be used as fertilizer in agriculture, so the valuable nutrients are recycled, and the carbon in the sludge is built into the soil, instead of quickly released as CO_2.
- Should, if possible, be digested to produce biogas /energy, thus replacing fossil fuels.

The EU framework legislation and the national legislations, is generally ensuring a safe and sustainable use of sludge as fertilizer, and based on our work in the STEP – project we want to point out that:

- Accumulated scientific evidence in general points to, that there are no adverse effects of using sludge from WWTP's in agriculture. The fate of certain persistent substances needs to be further clarified, both regarding the amounts in sludge and the fate in the ecosystem, e.g. PFAS.

- Barriers to the use of sludge from WWTP's as fertilizer in agriculture is sometimes psychological.
- Extremely strict National Limit Values can also be a barrier (e.g. copper in Sweden), and could be reviewed.
- Use of heavy metals and persistent chemicals in different products should be further restricted (e.g. cadmium in artists paints).

Chapter 7 ENERGY EFFICIENCY

Torben Jørgensen – Bornholms Energy & Supply

The overall goal with the activities included in work package 4 (WP4) was to study the different possibilities for energy savings in small and medium sized WWTP with special focus on sludge handling

Energy efficiency is crucial in water treatment, because wastewater treatment in general is associated with a high consumption of energy, mainly for the processes: Wastewater aeration, pumping, sludge dewatering and other related processes. But sludge dewatering and handling can also be optimized and new approaches can be proposed, giving outlines for future investments and dewatering improvements.

Within the scope of WP4 different examples and strategies of increasing energy efficiency is presented in this chapter:

Deliverable 4.1, A plan for sludge treatment for wastewater treatment plants of different size, aims to present different variants of sewage sludge treatment for WWTPs of various sizes. It contains an analysis of sludge treatment methods considering recovery of valuable materials and possibility of their reuse, and it also addresses the aspect of energy efficiency. Sewage sludge management however is a broader concept than just processing technology, storage or reuse. When choosing the economy model, three basic criteria are important:

- Environmental impact – emissions to water, soil and air, energy efficiency
- Financial impact – investment and energy costs, life cycle analysis
- Social impact – safety, nuisance (odours, area value loss)

Importantly, when choosing a waste management model, all three criteria must be met simultaneously to ensure its sustainability. The quantity of wastewater sludge produced is expected to increase over the next 25 years as new and upgraded wastewater treatment plants are completed. EU environmental policy tending to eliminate fossil sources and encouraging valuable materials and energy recovery will with high probability promote solutions such as e.g. phosphorus recovery. While organizing sludge management system a huge impact should be put on stream valorisation minding the fact that even with small systems the whole value chain would probably be much more complex as it was for the same circumstances few years before. The gravity of the problem lays now not in solving the waste problem at any cost but at improving already sophisticated designs, simultaneously facing rapid changes in waste legislation.

Deliverable 4.2, Overview of energy efficient sludge dewatering technologies, is a case study drawing on the experiences of the partners in the STEP project: We describe the development of sludge dewatering technologies, with focus on energy efficiency and based on the experiences of the three partners running WWTPs and handling sludge: Bornholm (Denmark), Goleniow (Poland), and Mittskåne Vatten (Sweden). The partners in STEP are currently using much the same sludge dewatering technologies, although the sludge is treated in different ways afterwards: composting, direct use in agriculture, mineralization and combustion. In general the sludge dewatering system of the individual WWTP must be designed according to the local circumstances, needs and possibilities. However we see a clear trend among the partners in STEP project to replace dewatering systems with new systems based on screw presses, and this improves energy efficiency of the sludge dewatering systems with up to app. 85%. A very different, but also highly energy efficient combined dewatering/storage method, is implementation of sludge mineralization, having the disadvantage of large area requirements, and large initial construction costs.

Deliverable 3.2 also gives examples of different strategies for treating sludge from septic tanks, and concludes: In general the systematic collection and handling of sludge from septic tanks must be organized according to the local circumstances, needs and possibilities. However it is clear, that separate handling of sludge from septic tanks is much more energy efficient than treatment in WWTPs. Treatment in WWTPs is of course an easy way to "get rid of" sludge from septic tanks, if you have a WWTP with sufficient capacity, and you only have one sludge fraction in the end.

Furthermore, we have looked into effects on WWTPs of reducing excess water, and means of investigating where excess water enters the sewer systems (see case studies on the homepage). In Bornholm, based on the result of a simulation study, the the benefits of reduced hydraulic loading to Rønne WWTP in terms of improved effluent quality and lower operational costs, was quantified: Excess hydraulic loading accounted for 40% of average daily influent flow, and it was estimated that every 20% step reduction of this excess flow will correspond to:

- 2%, 9% and 10% reduction in effluent BOD, N and P, respectively
- 4% reduction in energy consumption (pumping and aeration)
- 7% reduction in costs (effluent taxes, energy)

1 "A PLAN FOR SLUDGE TREATMENT FOR WASTEWATER TREATMENT PLANTS OF DIFFERENT SIZE"

Dr. Olga Anne – Klaipeda University
Dr. Łukasz Kruszyński

The implementation of the European Council Urban Wastewater Treatment Directive (UWWTD) 97/271/EC (21 May 1991) resulted in significant changes of the approach to sewage sludge management. Banned discharge of sludge to the sea and the limitation of phosphorus and nitrogen release, which forced the creation of more effective treatment methods and modernization of infrastructure as a result of increasing the amount of sediments, had a significant impact here. The sludge storage – oriented economy model is being replaced by an approach in which stabilization and reuse play a major role. The sludge treatment process is designed to ensure efficiency and safety in the event of its disposal or reuse. Sewage sludge has various impurities that determine the disposal method. Some sludge generated in small treatment plants, where the inlet stream of pollutants is relatively homogeneous, and the pollutants are non-toxic and known, can be subject to simple treatment methods such as thickening, dewatering and neutralization. Unfortunately, such opportunities are few, because as the industry develops, the use of increasingly diverse fertilizers, crop protection products, chemicals in the food industry, animal breeding, crops, and the situation with sludge becomes more complicated. Therefore, the treatment and pollution control also becomes crucial if we consider the possibility of sludge reuse. Sewage sludge management however is a broader concept than just processing technology, storage or reuse. When choosing the economy model, three basic criteria are important:

- Environmental impact – emissions to water, soil and air, energy efficiency.
- Financial impact – investment and energy costs, life cycle analysis.
- Social impact – safety, nuisance (odours, area value loss).

Importantly, when choosing a waste management model, all three criteria must be met simultaneously to ensure its sustainability. This study aims to present different variants of sewage sludge treatment proposed for sewage treatment plants of various sizes. The following division of sewage treatment plants was taken size wise:

- Small (PE <10,000).
- Medium (PE 10,000 – 100,000).
- Large (PE> 100,000).

2 KEY OBJECTIVES

Choosing the proper sewage sludge management plan depends on many factors. The sludge management process consists of the way it is produced, processed, transported, reused or utilized. When making the choice, the current legislation and its envisaged changes, should be considered as well as knowledge regarding modern technologies and their applicability in the area. The introduction of a sludge management plan requires public and institutional consultation. Such plan should assume the achievement of the following objectives:

- Avoiding harm to human health or environmental damage.
- Meeting all the requirements of the relevant legislation.
- Choice of an economically effective option.
- Selection of effective methods of treatment, disposal and reuse.
- Maximizing the use of sludge as a source of valuable materials and nutrients within the limits of economic viability.
- Energy recovery while maintaining economic viability.
- Minimization of nuisance related to infrastructure and transport of sludge.

Sewage sludge management should be carried out in accordance with the EU Action Plan for the Circular Economy (2015). Sludge production cannot be prevented, so minimization and effective reuse should be sought. The European Commission considers the nutrients recovered from the sludge to be an important category of secondary raw materials that can return to the soil in the form of fertilizer, as long as it does not pose a threat to the environment and human and animal health.

3 WASTEWATER SLUDGE

Sludge is formed in water purification processes. Depending on the source of the wastewater being treated and the treatment methods, sewage sludge may contain a number of impurities, including heavy metals, pathogens and trace amounts of non-degradable organic matter. On the other hand, sludge can be a source of valuable nutrients such as phosphorus and nitrogen, and can contain organic matter useful in soil fertilization.

Sludge generated in sewage treatment plants is an organic by-product consisting of solid particles separated from treated wastewater. The first stage of sludge separation is gravitational sedimentation, which results in a liquid primary sludge with a dry matter content of 1 – 4%. The remaining wastewater passing through the aeration chamber goes to the secondary settler, from which the activated sludge is obtained, part of which is recycled to the aeration chamber. The remaining sludge – called the excessive sludge – usually contains 0.5 to 1% of dry matter; therefore it must be thickened before further treatment. The concentrated excess sludge together with the primary sludge is stabilized. Sediment stabilization is accomplished for two main reasons: to eliminate putrefying and odour production, and to eliminate pathogens. After stabilization, the sludge undergoes a dewatering process, after which it contains on average 15 to 40% dry matter[1].

[1] Valorization strategies for wastewater treatment sludge. L. Fraikin, A. Leonard (2018)

4 SLUDGE TREATMENT MODELS BASED ON WWT PLANT SIZE

There are many ways to treat and manage sewage sludge in the industry related to wastewater treatment. Due to the size of the treatment plant, typical sludge management models can be distinguished. They may differ in technological details; however the basics of their functioning are similar.

Small and medium treatment plants:

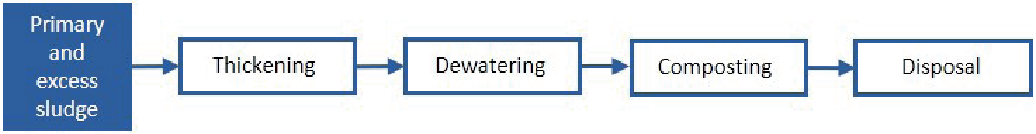

Fig. 1: Typical sludge processing model at small and medium WWT plants.

Medium treatment plants:

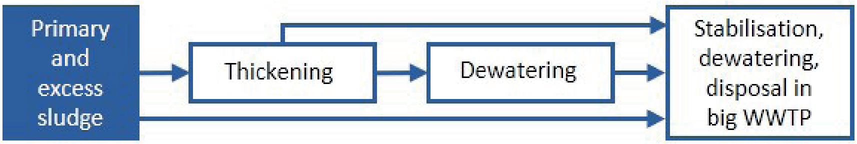

Fig. 2: Typical sludge processing model at medium WWT plants.

Medium and large treatment plants:

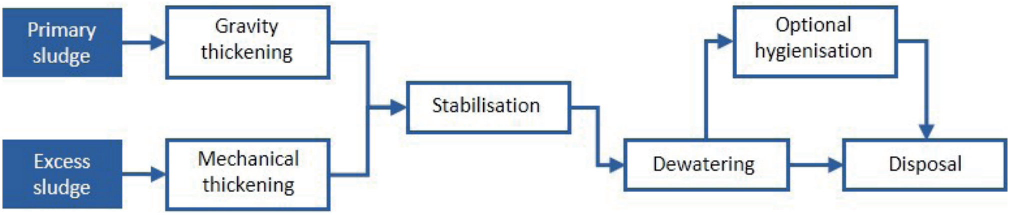

Fig. 3: Typical sludge processing model at medium and big WWT plants.

Large treatment plants:

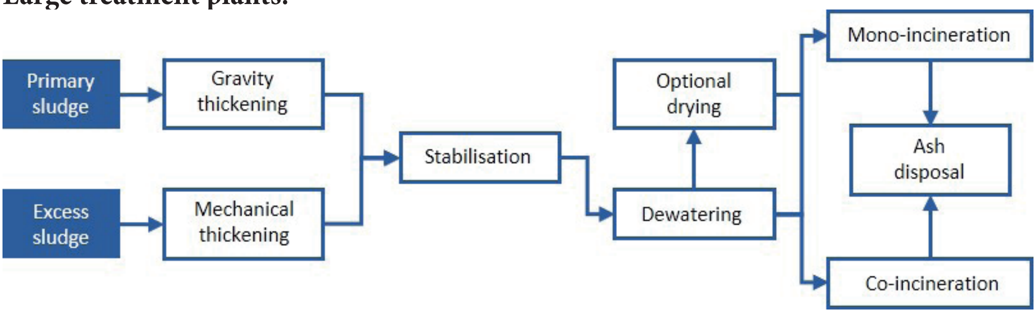

Fig. 4: Typical sludge processing model at big WWT plants.

The above examples indicate the dependence of the choice of the sludge management model on the size of the treatment plant. The larger the treatment plant, the more complex and effective the sludge treatment process. It clearly follows that more complicated models have economic justification only for processing larger volumes of sludge.

5 SLUDGE TREATMENT PROCESSES

The contaminants in the wastewater entering WWT plants vary in their properties depending on their origins (industrial, agricultural, household activities, etc.). Such impurities include, but are not limited to:

- Inorganic substances in the form of various types of salts, phosphates, heavy metals, toxic compounds, etc.
- Organic substances such as pesticides, petroleum derivatives, phenols, etc.
- Various types of bacteria and other biological contaminants.
- The most popular wastewater treatment technologies are:
- biological treatment,
- chemical treatment,
- mechanical treatment,
- combinations of the above.

Each of these technologies causes generation of sewage sludge containing the contaminants mentioned as they migrated from treated wastewater. Purified water is discharged to the environment or re-used in the variety processes according to the actual demand.

Sludge treatment processes should lead to reduction of sludge volume with simultaneous biosolids production and eventual valuable secondary raw materials and / or energy recovery.

- Sludge treatment process can – in general – be divided into three categories:
- Reduction of sludge volume – mainly performed with thickening and dewatering.
- Reduction of sludge quantity.
- Sludge biosolids production – including various digestion types, composting, drying etc.

6 REDUCTION OF SLUDGE VOLUME

Sludge volume is reduced to achieve the reduction of the cost of transport of sewage sludge. Two main groups of volume reduction processes are thickening and dewatering.

Sludge thickening causes slight dehydration. The dry matter content level of 2-7% can be achieved depending technology used. 5-7% dry matter content can be obtained on drum or belt thickeners only with addition of flocculant in polyelectrolyte form. Such sludge is still a slightly concentrated solution and is mainly directed to further treatment, i.e. dewatering process.

Sludge dewatering process is the next step of sludge treatment. The sludge after dewatering contains about 13-40% of dry matter. Such sludge may be directed to further thermal treatment in various temperature conditions to get rid of toxic compounds, both organic and inorganic, or transferred directly to the incineration plant, for combustion at high temperatures resulting in heat and / or electricity recovery.

7 SLUDGE BIOSOLIDS PRODUCTION

7.1 Thermal processes of biosolids production

Sludge thickening and dewatering processes mentioned above are not sufficient for the sludge to be allowed for use e.g. in agriculture or for other useful purposes. These deposits still may include various types of pathogens and dangerous chemical compounds disqualifying them from further use. Several of the thermal sludge treatment processes are listed below (these apply mainly to the dewatered sludge):

- **Mesophilic anaerobic digestion with pre- or post- pasteurization.**
- **Thermophilic anaerobic digestion** requires additional heat input.
- **Thermophilic aerobic digestion** also requires an external energy source.
- **Composting**, one of the most popular methods of thermal sludge treatment.
- **Alkaline stabilization** consists of adding hydrated or burnt lime to the dewatered sludge and mixing the two components.
- **Thermal drying of sludge.**

7.2 Other thermal sludge processing methods

The only generally commercially available combustion – based sludge treatment process today is incineration. The methods are worldwide well known; with the sludge dewatered to a minimum of approx. 30% the combustion is self-sustaining. The benefits are easy to estimate – heat / energy recovery, huge volume reduction, when mono-incinerated – possibility of phosphorus recovery what seems to be more and more attractive topic in the last few years. Incineration has high capital and operating costs, but due to regulations change – especially regarding agricultural use of sewage sludge – this option might appear more and more feasible.

There are several advanced technologies of thermal sludge conversion, for example:

- wet oxidation;
- pyrolysis;
- gasification;
- melting furnace.

8 PHOSPHORUS RECOVERY

Phosphorus is one of the – so called – "elements of life". Given the fact that – except singular cases – there are no phosphorus sources in Europe, and the ore deposits located mostly near the banks of north-western Africa are extensively exploited, European Commission in 2014 has added phosphate rock to the list of 20 Critical Raw Materials, for which supply security is at risk and economic importance is high. The consumption of phosphate-based fertilizers on a global scale is very high, because of the demand from food / agriculture sector.
Examples of well-documented technologies of phosphorus recovery from sewage sludge:

- KREPRO method – Kemira company technology – wet method.
- Biocon technology uses ash generated by sludge incineration at a temperature of approx. 9000C.
- Aqua Reci technology. It is a wet technology because it uses sewage sludge e.g. after thickening.
- Sephos technology uses ash from sludge incineration, containing – among the others – aluminium compounds and heavy metals.
- LOPROX technology based on the oxidation of sewage sludge with pure oxygen.

9 STRUVITE PRODUCTION

Struvite is a hydrated ammonium magnesium phosphate represented by the following formula: MgNH4PO4 x 6H2O. In nature, it occurs as a mineral with a crystalline structure. It can also be obtained synthetically as a result of the following reaction:

$$Mg^{+2} + NH_4^{+} + PO_4^{-3} + 6H_2O = MgNH_4PO_4 \times 6H_2O$$

The above reaction shows that for the formation of struvite, an appropriate molar ratio of individual components is needed, which, according to research, is 1:1:1, respectively.

The most susceptible place of struvite generation is the set of supply pipelines and devices (e.g. pumps located after the fermentation chamber) within sludge process line.

However, this problem was dealt with at sewage treatment plants by controlled formation of struvite for further use as a life-giving compound for fertilizing crops, because it contains life-giving elements such as phosphorus, nitrogen and magnesium. Research centres around the world have faced this problem. As a result a number of technologies of controlled struvite formation were developed. Technologies of controlled struvite production:

- SEABORNE technology, a complex process in which about 95% of phosphorus contained in sewage is recovered and the production of struvite is about 550 kg/day.
- Technology with the „PHOSPHOGREEN" reactor, one of the newer processes of sludge treatment, which ultimately leads to the formation of granulated struvite.

10 OPTIONS ASSESSMENT

To pick the proper version of sludge management plan the three main criteria must be covered:

- Environmental impact – emissions to air, water and land, climate change impact and energy use;
- Financial impact – life cycle costs, energy cost and recovery, reliability of technology;
- Social impact – potential nuisance (e.g. odour, noise, traffic), public perception and food safety;

Since there is a wide range of options available here a summary of processes, their advantages and disadvantages and threats. This may serve as a helping matrix – a tool for preliminary assessment of chosen sludge management plan[2]. Each sludge management method is depicted separately.

Table 1. Sludge management: agriculture

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Use in agriculture	Stabilization using earthworms	Many standards to be met	Possibility of managing all sludge	High organic carbon load
	Composting and stabilization in ponds	A relatively long stabilization time if low-temperature processes are used	Low energy expenditure and reduction in concentrations of heavy metals (if earthworm stabilization is used)	Aromatic hydrocarbons Halogenated organic compounds
	Incineration			Heavy metals
	Phosphorus			
	recovery			

Table 2. Sludge management: plants not for human consumption or feeding animals

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Growing plants not intended for human consumption or feeding animals	Stabilization using earthworms	Limited application	Requirements pertaining to the quality of materials are lower than in the case of other uses connected with growing plants	High organic carbon load
	Composting and stabilization in ponds	A relatively long stabilization time		Aromatic hydrocarbons Halogenated organic compounds
				Heavy metals

[2] Analytical and legislative challenges of sewage sludge processing and management, B.M. Cieślik, L. Świerczek, P. Konieczka (2018)

Table 3. Sludge management: soil remediation

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Remediation and adjustment of soil to specific needs	Stabilization using earthworms	This method is not recommended by the European Union	Broad application	High organic carbon load
	Composting and stabilization in ponds		Possibility of managing all sludge	Aromatic hydrocarbons Halogenated organic compounds
				Heavy metals
				Phosphorus

Table 4. Sludge management: construction industry

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Use in the construction industry	Vitrification	Problems with obtaining high strength	Partial refund of costs	Heavy metals
	Incineration	Very high energy demand in the case of vitrification	Broad application	Phosphorus
	Cementing	Many standards to be met	Possibility of managing all sludge	Chlorinated species
	Drying and pellet production	The possibility of releasing heavy metals or organic pollutants (depending on the process used)		

Table 5. Sludge management: industry

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Use in industry	Drying and pellet production	High investment costs	Partial refund of costs	Heavy metals
	Phosphorus recovery	High costs of unit processes	Recovery of precious materials	Phosphorus
	Recovery of rare metals	Complicated processes		

Table 6. Sludge management: energy recovery

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Recovery of energy	Drying and pellet production	High investment costs	Partial refund of costs	Carbon dioxide
	Anaerobic stabilization with biogas recovery	Processes are cost-efficient with large amounts of excess sludge	Generation of energy from renewable resources	
	Conventional incineration and co-incineration	Anaerobic fermentation susceptible to process inhibitors	Fewer odours	

Table 7. Sludge management: adsorbents and bio-oil

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Sludge-based production of adsorbents and bio-oil	Pyrolytic thermal processing	High energy demand	Partial refund of costs	Aromatic hydrocarbons
		Narrow market	Management of the majority of old residues	Halogenated organic compounds
		Many kinds of waste to be managed		

Table 8. Sludge management: fat recovery

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Fat recovery and processing	Sludge treatment	Incomplete management (only some raw materials)	Partial refund of costs	Aromatic hydrocarbons
		It is necessary to install a fat recovery system	Low investment expenditures	Halogenated organic compounds
				Heavy metals

Table 9. Sludge management: sludge storage

Sludge management method	Excess sludge processing	Disadvantages	Advantages	Main pollutants
Storage at treatment plants and in landfills	Disinfection and chemical stabilization	This method is not recommended by the European Union	Simple methods	High organic carbon load
	Incineration	Incomplete management		Aromatic hydrocarbons
	Vitrification	Incurred management costs are not recovered	Less restrictive standards as compared to other methods	Heavy metals
	Solidification of materials			Phosphorus
				Halogenated organic compounds
				Chlorinated species

11 CONCLUSIONS

The quantity of wastewater sludge produced is expected to increase over the next 25 years as new and upgraded wastewater treatment plants are completed. EU environmental policy tending to eliminate fossil sources and encouraging valuable materials and energy recovery will with high probability promote solutions such as e.g. phosphorus recovery. While organizing sludge management system a huge impact should be put on stream valorisation minding the fact that even with small systems the whole value chain would probably be much more complex as it was for the same circumstances few years before. The gravity of the problem lays now not in solving the waste problem at any cost but at improving already sophisticated designs; simultaneously facing rapid changes in waste legislation. Circular economy nowadays is a must! Although even best ideas can face obstacles. An EU action plan for the circular economy released by European Commission in December 2015 covered almost all economy sectors and related waste but not sewage sludge...[3] Land application is still the main route for sewage sludge recovery: 50% of sewage sludge is spread on agriculture soils[4], but the requirements for higher and higher purity of biosolids across EU might change the picture soon.

[3] Use of biosolids in Europe: possibilities and constraints, G. Mininni, G. Sagnotti, M. Porrega (2019)

[4] Legislation for the Reuse of Biosolids on Agricultural Land in Europe: Overview, M. C. Collivignarelli, A.Abbà, A. Frattarola, M. Carnevale Miino, S. Padovani, I.Katsoyiannis, V. Torretta(2019)

Chapter 8 OVERVIEW OF ENERGY EFFICIENT SLUDGE DEWATERING TECHNOLOGIES

Torben Jørgensen – Bornholms Energy & Supply

1 INTRODUCTION

In the STEP project deliverable 4.2 we describe the development of sludge dewatering technologies, with focus on energy efficiency and based on the experiences of the three partners running WWTPs and handling sludge: Bornholm (Denmark), Goleniow (Poland), and Mittskåne Vatten (Sweden).

Different countries in EU have different traditions and issues about sludge dewatering. The partners in STEP are currently using much the same sludge dewatering technologies, although the sludge is treated in different ways afterwards: composting, direct use in agriculture, mineralization and combustion.

2 SLUDGE FROM SMALL AND MEDIUM WWTPS

The production of sludge is primarily a result of introducing biological WWTPs in the treatment of urban waste water, to meet the demands for adequate water quality in the recipients.

Taking Bornholm as an example, the biological WWTPs was constructed in the beginning of the 1990'ies, with a few minor exceptions, with capacity ranging between 1.000 – 60.000 PE. The original sludge dewatering equipment was sieve presses, centrifuges, and a single sludge mineralization plant (earth basins for evaporation and mineralization, planted with reeds). Most of the original dewatering equipment has been replaced with screw presses in the recent years, which is the technology that seems to be best suited for small and medium WWTPs for now, as will be discussed in the next chapter.

2.1 Screw presses

The following is based on a note from our consultant engineer EnviDan, in the planning process of renewing the sludge dewatering equipment on Rønne WWTP (main WWTP on Bornholm, 60.000 PE).

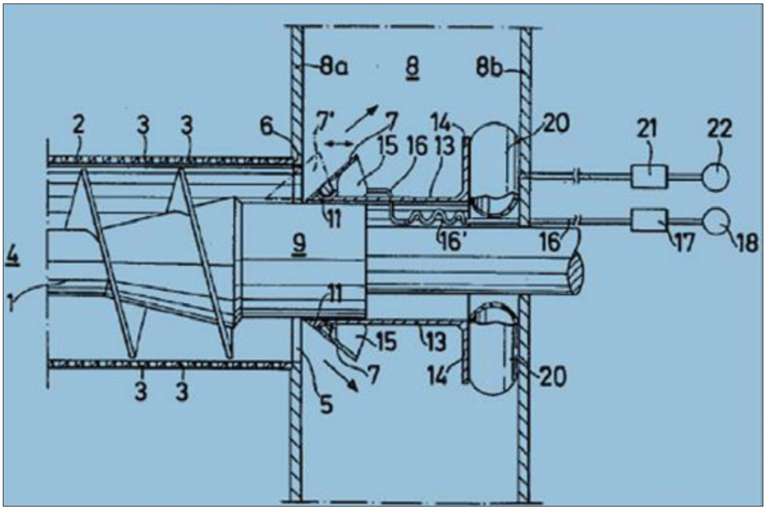

Fig. 1 Screw presses principle scheme

Principles of screw press action (as in Figure 1):
In a screw press incoming suspension is captured by the helix of the screw and advanced towards the annular outlet while being compressed. Compression of the material during its travel along the screw takes place due to the fact that the outlet aperture is relatively small; the water or other liquid pressed from the sludge departs through the perforations in the drum casing. The residual water content of the dewatered pulp discharged through the outlet depends to a very large extent on the size of the outlet.

The total solid content in the dewatered sludge will for biological sludge normally be in the range of 18-22%. The construction of the screw press I hermetically enclosed structure in order to ensure a safe a healthy environment. The structure is mechanically ventilated. Number of manpower days for daily service and maintenance is at a minimum. The screw press is designed for continuously operation 24/7 and no service personal is required during the operation.

Table 1, below shows the estimated consumption of water, polymer and energy compared to the amount of dewatered sludge. The values shown are all based on previously investigation of dewatering equipment installed.

*Table 1 * Energy consumption only refers to the direct power uptake from the screw press.*

Sludge dewatering methods	Energy consumption*	Compressed air consumption	Polymer consumption (active polymer)	Water consumption
	kWh/ton TS		kg/ton TS	m3/ton TS
Screw press	5-8	Compressed air for control and pressure in screw press	10-12	Water consumption only for wash of press during operation 2-5
Centrifuge	11-17	No consumption	9-11	Only water consumption for wash of press shut down

Based on the above comparison of sludge dewatering systems a solution based on a screw press will in general result in the lowest operation cost, mainly caused by low energy consumption for the screw press. Suspended Solid (SS) in the reject water from the sludge dewatering process often varies based on the efficiency of the dewatering equipment. Reject water from screw presses will in general be in the range of 800-1.200 mg SS/l, which is slightly higher than reject water from centrifuges. However, it is often seen that the SS in the reject water from screw presses is well below the range of 800-1.200 mg SS/l when the collide particles in the sludge are low.

Economy – estimate for implementing screw press dewatering on Rønne WWTP. A total estimated budget for changing the existing dewatering plant is as follows in the table 2 below.

Table 2. Estimated budget for changing the existing dewatering plant.

	DKK	€ approx.
Item 1. Design-and tendering of contractor:		
Construction cost	700.000	93.000
Mechanical equipment and installation	3.100.000	413.000
Electrical equipment, installation and SCADA system	500.000	67.000
Unforeseen cost	400.000	53.000
Design and tendering documents	600.000	80.000
Item 2. Evaluation of offers and contracting:		
Evaluation, contracting and follow up on installation	200.000	27.000
Total estimated investment:	**5.500.000**	**733.000**

The above mentioned investment cost will result in following savings (in Danish crones DKK) per year:

- Estimated yearly saving of cost for polymer will be approx. DKK 175.000, – based on a yearly consumption of approx. 5 ton active polymer.
- Estimated yearly savings for stopping use of burned lime powder, approx. DKK 500.000-700.000, –
- Energy savings approx. DKK 50.000- 100.000, –
- Total estimated yearly savings, approx. DKK 725.000-975.000,-

The above investment costs must be seen in the context of stopping the addition of burned lime to the dewatered sludge, an operating savings of DKK 500-700.000, – per year, and that a reduced polymer consumption can be expected, since polymer is only added at one point in the process. It is estimated that the annually savings approx. 5 ton of active polymer, of approx. 35 kr. / kg corresponding to approx. DKK 175.000 per year.

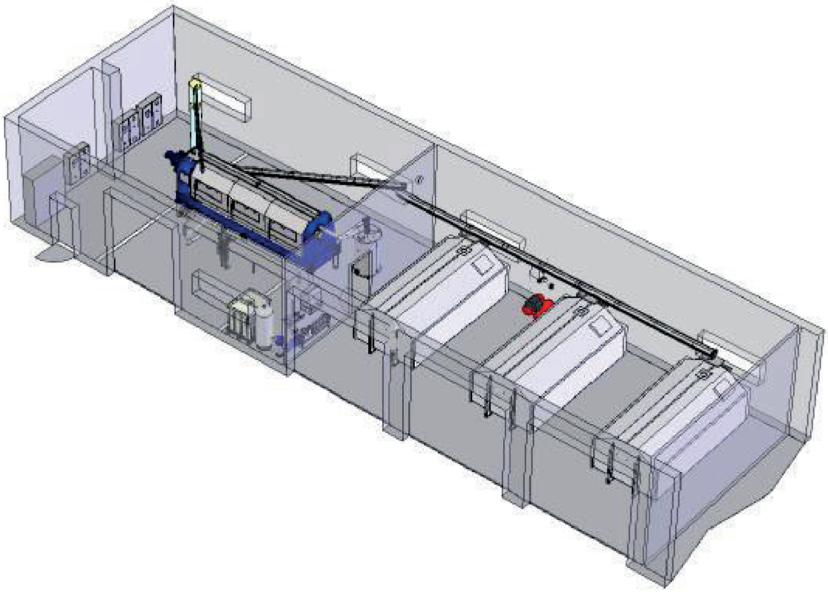

Fig. 2. Screw press dewatering system in Rønne WWTP

Tendering for implementing of screw press dewatering system on Rønne WWTP (see sketch Figure 2 above), was done in the autumn of 2019. The best offer was given from a Danish supplier dealing with an Austrian build screw presses, to a price of a little less than 4.000.000 DKK, or approx. 530.000 €. The new dewatering system will be installed in 2020.

Today we use 48.000 kWh per year for sludge dewatering on Rønne WWTP, this is equivalent to 48 kWh per ton Dry Matter, because the sludge production from is approx. 1.000 ton Dry Matter per year. The expected power consumption for the new system is 6 kWh per ton Dry Matter, and thus the power consumption for dewatering is expected to be reduced with more than 85 %.

From a similar installation on Nexø WWTP (10.000 PE), made a few years ago, we have experienced a reduction in power consumption in this range (more than 85%). Screw press for sludge dewatering at Nexø WWTP, Bornholm (Figure 3). The dewatered sludge falls directly down a container that is transported to an external storage when full.

Fig. 3 Screw press for sludge dewatering at Nexø WWTP, Bornholm

2.2 Sludge mineralization plants

A sludge mineralization plant is beds/basins planted with reeds for drainage and further sludge stabilization. In addition, the aerobic conditions in the plant enable the sludge to reduce the content of environmentally harmful substances.

Sludge mineralization plants are suitable for the treatment of biological sludge, and the thin sludge (with, for example, 0.5-1% TS) is pumped directly to the plant.

The plant is constructed as a concrete or soil pool with a waterproof membrane at the bottom and an effective drainage system in a porous filter layer. On top of the filter, a growth layer is established and planted with reeds, to increase the evaporation of water from the sludge. The drainage system collects the filtered water and returns it to the inlet of the treatment plant. The drainage system and the plant roots help to ensure aerobic conditions in the plant.

Sludge mineralization plants are typically sized to accommodate 10 years of sludge production. However, the experience from several existing plants is that in practice the capacity is not as great as previously assumed. The dry matter content of the sludge is increased to a final solids content of approx. 20-30% TS, and by mineralization the content of organic matter is reduced by up to 25%. The experience from a number of plants has shown that it is difficult to obtain the dry matter content as required for the sizing and establishment of the plants.

The sludge residue is usually used for agricultural purposes, but if the quality requirements cannot be met, it may be necessary to dispose of it in another way, e.g. by incineration or landfill.

Advantages: Highly energy efficient – and cost efficient. Requires very little maintenance. Reducing quantity and volume of sludge.
Disadvantages: Large area requirements (up to 0,5 m^2/PE) – and large initial investments. Nutrients are lost in the mineralization process, especially N.

The mineralization plant at Boderne WWTP, Bornholm

The WWTP (4.000 PE) and mineralization plant was established in the late 1980'ties, to accommodate the sludge from the WWTP for a least 10 years (Figure 4). However the evaporation and mineralization has been very effective, so the plant has been running for more than 30 years now, without been emptied. In 2019 the ground around and between the basins was raised ½ meter to create more volume.

Fig.4 Sludge mineralization plant at Boderne WWTP, Bornholm

2.3 Conclusions

In general the sludge dewatering system of the individual WWTP must be designed according to the local circumstances, needs and possibilities. However we see a clear trend among the partners in STEP project to replace dewatering systems with new systems based on screw presses, and this improves energy efficiency of the sludge dewatering systems with up to app. 85%. A very different, but also highly energy efficient combined dewatering/ storage method, is implementation of sludge mineralization – usually designed from the start of the WWTP, and having the disadvantage of large area requirements, which is not always available, and large initial construction costs.

3 SLUDGE FROM SEPTIC TANKS

This part of the report consists of different approaches in Denmark and Sweden:
Denmark – Bornholm:

- Collecting and dewatering sludge.
- Composting and use in agriculture.
- Energy efficiency and economy, nutrients and carbon.

Sweden – Höör and Hörby:

- Collecting and dewatering sludge
- Use in agriculture.
- Energy efficiency and economy; nutrients and carbon.

4 GENERAL BACKGROUND

Many wastewater companies handle the collection, transport, treatment, and disposal of sludge from the septic tanks in the local areas. There are different approaches to solve the challenges in this work. In this case study we compare the different approaches in relation to energy-efficiency, but also reuse of nutrients and carbon and overall economy.

5 DENMARK – BORNHOLM APPROACH

In Bornholm the systematic collection and handling of sludge from septic tanks started in 1992, in Nexø municipality. When the five municipalities were merged in 2003, all the app. 5.000 septic tanks on Bornholm were included in the systematic collection and handling of sludge.

The most common way to handle sludge from septic tanks in Denmark is to treat the sludge in larger Wastewater Treatment Plants (WWTP's).

On Bornholm we have from the start chosen to treat sludge from septic tanks separately, based on concern about capacity and energy consumption of WWTP's. The sludge from septic tanks is used in agriculture after separate treatment, according to the Danish rules (see chapter on rules/legislation in the partners countries).

5.1 Collecting and dewatering sludge

The sludge from emptying septic tanks are collected and dewatered in a special vehicle (called KSA) that manage to empty app. 30-40 septic tanks before it must be discharge the dewatered sludge. Dewatering is mechanical with use of polymer.

In this way the septic sludge is effectively dewatered to app. 30% Dry Matter (DM).

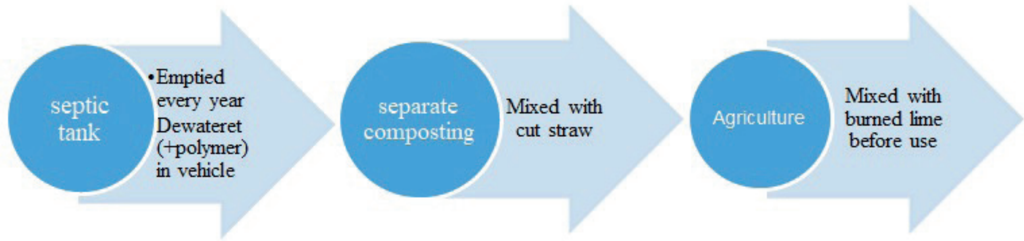

Fig. 5.

5.2 Composting and use in agriculture

The dewatered sludge is composted in a barn by the same farmer that uses the sludge as fertilizer in agriculture. The sludge is mixed with cut straw, and the piles turned regularly. Once a year, usually in august, the composted sludge is mixed with app. 8% burned lime and used as fertilizer in agriculture.
Denmark has the strictest limit value for Cd in EU – 0,8 mg/kg DM – but there is also a limit value in relation to phosphorus – 100 mg/kg P – and it is enough that the content is below one of the limit values. The limit value for Cd in the EU-directive is 20-40 mg/kg DM.

Table 3. Comparison of heavy metals and organics in sludge from septic tanks and WWTP (Rønne)

	Analysis of composted sludge from septic tanks (mean)	Analysis of sludge from WWTP (Rønne – mean)	Limit values
	mg/kg DM	mg/kg DM	mg/kg DM
Pb	26	12	120
Cd	1,4	0,8	0,8
Cu	258	168	1.000
Cr	13	10	100

	Analysis of composted sludge from septic tanks (mean)	Analysis of sludge from WWTP (Rønne – mean)	Limit values
	mg/kg DM	mg/kg DM	mg/kg DM
Hg	0,7	0,3	0,8
Ni	17	10	30
Zn	1.070	495	4.000
Cd/P (mg/kg P)	76	35	100
Hg/P (mg/kg P)	38	14	200
Tot N (g/kg DM)	29,5	48,3	
Tot P (g/kg DM)	18,5	22,8	
LAS	423	< 108	1.300
Sum PAH	1,7	0,6	3
Sum NPE	3,4	1,5	10
DEPH	2,5	5,5	50

Table 3 show that the content of heavy metals and organics is generally lowest in the sludge from WWTP.The initial content of organics in the sludge from septic tanks is very high, and often exceeds the limit values, but composting is effectively reducing these compounds.

5.3 Energy efficiency, nutrients, carbon and economy in this approach

Energy efficiency – qualitatively assessed

- Transport: because the sludge is dewatered in the transport vehicle, and reject water is put into the next emptied septic tank, the energy use for transportation is reduced app. 50%.
- Dewatering: dewatering is mechanical in the transportation vehicle, with addition of polymer, and hence the energy consumption is minimal.
- Composting: involves turning the piles and mixing with straw and lime – low energy consumption.
- Spreading the compost: mostly energy for transport, like other organic fertilizers – low energy consumption.

Nutrient recycling – qualitatively assessed

- The composting process involves a small loss of nitrogen – evaporation off ammonium.
- Agricultural use ensures an effective recycling of the nutrients in the composted sludge.

Carbon storage – qualitatively assessed

- The composting process involves a small loss of easily degradable organic carbon (as CO_2 emission).
- Agricultural use ensures recycling/storage of most of the carbon in the composted sludge, including the added straw.

Economy

In 2020 the owners of septic tanks on Bornholm pay: **523 kr. or app. 70 Euro** (25% VAT included) for the yearly emptying of a septic tank – all expenses included.
Bornholm's Wastewater A/S pays our current contractor: **400 kr. or app. 54 Euro** (25% VAT included) per emptied septic tank, all included.

Administration of costumer payment, handling of complains etc., analysis of sludge; dialog with authorities etc. is done by the Wastewater Company. These administrative tasks accounts for the difference between costumer payment and contractor payment.

6 SWEDEN – HÖÖR AND HÖRBY APPROACH

6.1 Collecting and dewatering sludge – Existing handling

In Sweden, external sludge from septic tanks is collected from individual properties once a year, usually through trucks operated by the municipality. In Höör and Hörby, trucks with the capacity to dewater the sludge on-site are being used. The dewatering on site is achieved by letting the larger particles settle in the tank carried by the truck. The water is then returned to the septic tank on the property.The truck then transports the sludge to the wastewater treatment plant (WWTP) where it is released into the incoming wastewater stream.

The cost for a truck to empty the content from septic tanks at the wastewater treatment plant is roughly 25 €. The cost for Mittskåne Water to ensure a safe collection of the treated sludge is about 28 €/ton.

Fig. 6

Advantages

Nutrients are recovered and spread on arable land.

Disadvantages

The external sludge usually has a relatively high content of heavy metals in relation to nutrients, and hence deteriorates the sludge quality. Further, the external sludge has relatively low levels of oxygen and therefore needs to be aerated, which in turn consumes larger quantities of energy.

6.2 External treatment of sludge – Pilot plant

Höör and Hörby wastewater treatment plants have relatively high levels of metals in the processed sludge; this has been a problem for many years. According to internal analyses, the reason for these levels is most likely due to the sludge from the septic tanks (Table 4).

Table 4. Comparison of the mean values for dewatered external sludge to the processed sludge at the wastewater treatment plant (WWTP) in Hörby (mg/kg dry matter).

	Dewatered external sludge	Processed sludge at the WWTP	Threshold limits
Pb	10,97	8	100
Cd	0,70	0,71	2
Cu	624	389	600
Cr	9,94	19,75	100
Hg	0,32	0,22	2,5
Ni	9,75	10,56	50
Zn	873	469	800
Cd/P	103	36	

6.3 Use in agriculture

Table 5. Comparison of legislation thresholds for metal content with the content at Hörby WWTP after the pilot plant evaluation (mg/kg dry matter)

	Threshold current legislation	Threshold proposed legislation (2030)	Metal content dewatered external sludge (pilot plant)
Pb	100	25	11
Cd	2	0,8	0,70
Cu	600	475	624
Cr	100	35	9,94
Hg	2,5	0,6	0,32
Ni	50	30	9,75
Zn	800	700	873
NH_4-N	-	-	4,7
N-tot	-	-	32,7
P-tot	-	-	6,7
TS	-	-	33

6.4 Energy, nutrients, carbon and economy in this approach

It is difficult to compare the current handling with an external handling of sludge since there exist very little data and the result will be heavily influenced by site characteristics (Table 6).

Table 6. Summary of the alternatives.

	Current handling	External handling of sludge
Energy	Amount of energy per cubic meter external sludge that is treated at the WWTP (12,5 kWh/m3 – Danish EPA 1991)	Energy consumption is estimated to 2,12 kWh/m3 external sludge to increase the level of dry matter from 1 to 27% (Municipality of Östersund facility). To this it must be added the energy consumption for treatment of the supernatant.
Conclusion	Separate handling of external sludge is much more energy efficient than current handling (treatment in WWTP).	
Nutrients	The nutrients are recovered and recirculated by dispersal on arable land.	Since the dewatered external sludge contains high levels of metals it cannot be dispersed on arable land. However the outgoing sludge from the WWTP will be better suited for dispersal on arable land.
Conclusion	Both manners of handling can increase or decrease the use of sludge on arable land.	
Carbon	All carbon in sludge is applied on arable land. The easy degradable carbon is mineralized to CO_2	The external sludge will most likely be combusted and then the carbon will be transformed to carbon dioxide instead of stored in the soil.
Conclusion	Both manners can increase or decrease the carbon storage in the soil of arable land.	
Transport	By returning the liquid to the septic tanks the energy costs for transports is reduced. There is also another type of dewatering where polymer is used to generates a higher dry matter level and therefore increased return of liquid, which in turn generates a lower demand for transports.	
Economy	Very hard to estimate the cost for treating 1 m3 of external sludge.	
User economy	The cost for emptying a septic tank at the treatment plant is roughly 25 € per septic tank. The owner of the septic tank pays about 90 € to have the tank emptied.	

7 SUMMARY AND CONCLUSIONS

The experiences described in this study from Bornholm and Höör – Hörby can hopefully be of interest for other Wastewater companies there in the future have to implement a systematic collection and handling of sludge from septic tanks in their local area. A few quantitative conclusions can be drawn:

Energy for transport:

- It is important that the vehicle used for emptying and transport of sludge from septic tanks is able to perform a good dewatering of the sludge, so as much reject water as possible can be returned to the septic tanks, this reduces both the transported load and the number of times the vehicle must return to unload sludge.

Energy for treatment of the sludge in WWTP or separate sludge handling:

- It is very energy demanding to treat sludge from septic tanks in WWTPs – specially for supplying air to the aerobic processes in the WWTPs – the Danish EPA has estimated an energy consumption of app. 12,5 kWh/m^3. Whereas the separate dewatering described by the Swedish partner is only 2,12 kWh/m^3 (treatment of reject water not included)

In general the systematic collection and handling of sludge from septic tanks must be organized according to the local circumstances, needs and possibilities. However it is clear, that separate handling of sludge from septic tanks is much more energy efficient than treatment in WWTPs.

Chapter 9 COMPOSTING PROCESS

Dariusz Kozak

A major indicators of soil fertility are biogenic elements such as nitrogen, phosphorus and organic carbon. All these elements are found in the municipal sewage sludge however the agricultural use of sludge requires converting it into compost. Recovered organic matter from separately collected biodegradable waste or sewage sludge can alternatively replace manure in regions with lack of animal production. Composting allows conversion sludge into organic fertilisers or soil improvers and it is in line with circular waste management. Appropriate selection of composting substrate and composting technology enable production of good quality soil amendments. The application of sludge-based compost to soil gives also an opportunity to recover so critical nutrients as phosphorus that has already been listed as critical raw material.

Effects of soil application of composts produced on a basis of sewage sludge and straw were tested in the field experiments in 2018 – 2020 period. The experiments revealed that the use of the tested compost did not result in soil contamination. Compost were characterised by low content of heavy metals. Therefore compost application enabled production of high quality barley grain. The investigations have not demonstrated any risk for the environment and the quality of food and feed associated with trace elements. Compost generally increase soil biological activity. It was also revealed that the appropriate use of compost does not pose a greater risk of nitrogen leaching to groundwater than the use of mineral fertilisers. Compost application increases yields of cereals, especially in dry years, which should be associated with their positive effects on soil water retention and soil biological activity, supporting the growth and resistance of plants to stress conditions. The use of compost ensures that the soil carbon level is kept constant despite the removal of all straw from the plots.

1 INTRODUCTION

The change in the way of sewage sludge management towards agricultural use, observed in recent years, is a result of the implementation of the Circular Economy strategy in the European Union assuming the transition of the economy from a linear to circular model in which waste becomes a raw material. This strategy assumes a model of economic development in which the following assumptions are met while maintaining the condition of efficiency:

1) the added value of raw materials / resources, materials and products is maximized or
2) the amount of generated waste is minimized and the waste generated is managed in accordance with the hierarchy of waste management methods, i.e .:
    1. Waste prevention
    2. Preparing for re-use
    3. Recycling
    4. Other ways of recovery
    5. Neutralization

This means that the processing of sewage sludge using the composting process, which significantly changes the properties of the sludge allows, (i) change the classification of sewage sludge from waste to product, (ii) enables the production of compost which after meeting certain requirements, can be qualified as a soil improver. The processing of sewage sludge for agricultural use is consistent with the Circular Economy strategy, the implementation of which results in:

- reducing the consumption of raw materials (in this case of artificial fertilizers),
- limitation of the amount of landfilled waste,
- an increase in the amount of waste used as part of recovery.

Sewage sludge, generated in the process of wastewater treatment, is municipal waste containing biogenic substances with a high fertilizing potential. The possibility of using sewage sludge is determined by the Council Directive of June 12, 1986 on the protection of the environment, in particular the soil, when sewage sludge is used in agriculture (86/278 / EEC). On the other hand, the rules for the use of sewage sludge as a soil improver are sanctioned by Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on making EU fertilising products available on the market. The new regulation replaces the older regulation of the European Parliament (2003) and of the Council EU on fertilizers and covers all types of fertilizers (mineral, organic) and other fertilising products: soil improvers, growing media, growth promoters, etc. The regulation is part of the EU's Circular Economy Action Plan. It harmonises the standards for fertilizers obtained from organic or secondary raw materials in the EU and creates new opportunities for their production and sale on a large scale, where waste is turned into fertilizer material.

Under the regulation, EU fertilising products bearing the *CE* marking will have to meet certain requirements in order to have access to the EU internal market. They concern, inter alia: mandatory maximum levels of pollutants, the use of specific categories of ingredients and labeling.Using the fertilizing potential of sewage sludge is difficult due to the potential threat to the environment. The processing of sewage sludge in the composting process fundamentally changes the properties of the manufactured product and qualifies it for agricultural use. Composting sewage sludge is practically the only biological treatment method resulting in a product that can be used for agricultural purposes.

2 FIELD STUDIES – COMPOSTING

The aim of the research started at the beginning of 2018 was to determine the influence of the proportion between the amount of components making up a mixture of organic materials on the course of the sewage sludge composting process. The high content of the total nitrogen in mechanically dewatered sludge generally in the range of 2÷7% dry mass causes a low value of the C/N ratio. As a result, composting sewage sludge requires the use of additional material (supplement) with a high concentration of organic carbon and low nitrogen content during formating of compost mixture. formation. Practically, a component that modified the C/N ratio in the batch and decided to meet the basic criterion conditioning the correct course of composting was a straw. Because straw is hard to access material research in the context of reducing the share of straw in the batch which determines the correct course of composting should be considered as necessary and expected by companies using this technology for municipal sewage sludge management.

The research was carried out in two parts.

Part I.
Four series have been planned during field research. Each series lasted about 5 months and consisting in monitoring the composting process carried out in windrows of approx. 50 m^3 each. In both series a different proportion between components was used. The basic components were: mechanically dewatered sewage sludge, barley straw, wood chips and mature compost (inoculum). In the first stage two series have been done. In the series no 1 the mass ratio between components forming the compost mixture was respectively 4:1:(0.5+0.5), as described later in the report as 4:1:1. In the series no 2, the mass ratio between the components was respectively 8:1:(1+1), as described later in the report as 8:1:2. Each series was repeated in stage no II.

The research was carried out on an industrial scale using the technology of roofed windrow with a length of approx. 70 m and the dimensions of the trapezoidal cross-section: 3 m – width of the lower base and 1.5 m – height, periodically turned. The research was carried out at the sewage treatment plant in Goleniów. The total area of the concrete composting place with roofing is 2.400 m^2. The parameters of the formed windrows (pictures 1÷3) were as follows:

- working plate length 60 m
- width of the working plate 40 m
- the maximum length of the windrow is 54 m
- width of the windrow base 3 m

- initial windrow height 1.6 m
- height of the windrow with the ready preparation 0.9÷1.1 m.

The produced composts were used in field studies involving the cultivation of selected plant varieties and the assessment of various indicators describing the obtained yields and the impact of compost on soil conditions.

Picture 1. Preparing of compost windrow.

Picture 2. Preparing of compost windrow.

Picture 3. Mixing of compost windrow.

During field tests, compost samples for laboratory tests were systematically taken from each windrow. Laboratory tests consisted of qualitative and quantitative analysis of selected parameters forming four groups, including: basic physicochemical indicators, heavy metals, chemical fractions of heavy metals and humic compounds. The type of indicators that were analyzed corresponds to the requirements set out in national regulations regulating the principles of agricultural use of compost produced on the basis of municipal sewage sludge, having the status of organic fertilizer or plant conditioner. The national and EU regulations regarding the rules of direct use of sewage sludge on agricultural land were also taken into account.

The research showed that the composting process of the sludge proceeds correctly even at the initial C/N ratio equal 10. It is much lower than the recommended value, i.e. 15÷25. It turned out that if there is more sludge than straw in the charge then the temperatures inside the compost windrows are higher and the duration of the thermophilic phase is longer (Fig. 1).

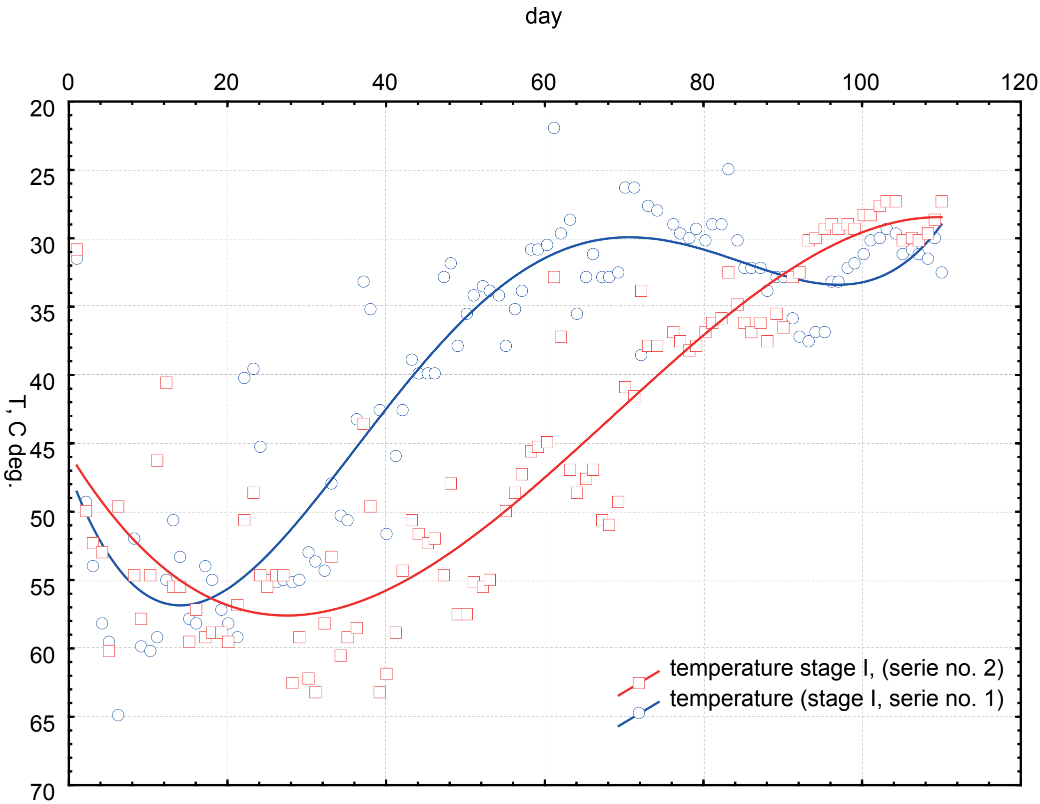

Figure 1. Temperature changes in both compost samples during composting, stage no.I., first part.

In all four conducted compost tests, there were changes in the concentration of organic carbon and nitrogen as expected. The process of mineralization of the organic substance caused a constant loss of total organic carbon. At the same time the nitrogen content in the first phase of composting decreased and then gradually increased. The initial drop in nitrogen concentration was related to the release of NH_4^+ ions and the emission of ammonia in the gas form (NH_3) which could increase odor nuisance. The slow increase in nitrogen concentration in the compost during the maturity phase should be considered favorable due to the fertilizer values of this element.

The transformation of organic matter in the composting phase leads to the formation of macromolecular compounds with the character of organic polymers. This process is called humification and the resulting substance with an extremely complex molecular structure is called humium. The precursor of humic compounds are mainly lignin, cellulose and hemicellulose. From these ones various products are formed i.a. amino acids and phenol. Phenol constituting a basic component of formed humic acids as a result of complex enzymatic reactions. In the initial phase of transformation of organic matter during the humification process, fulvic acids (FA) predominate which over time transform themselves into humic acids (HA). Change in organic carbon forms occurring in the form of so-called nonspecific and specific humic compounds during composting is the basis for determining indices that allow to evaluate the progress of the humification process defined as HA/FA and HA/Corg. The first index is described by the ratio of the carbon of humic acids to carbon of fulvic acids and this is expressed by the abbreviation PI (Polymerisation Index). The second index represents the percentage of carbon of humic acids in relation to the total organic carbon and is referred to as HI (Humification Index).

During the composting, large changes in the content of humic substance were observed. In the first series the 60% decrease of the FA content in relation to the value of this parameter from the beginning of composting was found. In series no.2 this decline was more pronounced and amounted to nearly 50%. At the same time, an increase in the HA content in both series was found. In the case of series no.2 the increase was around 13%. The conversion of fulvic acids into humic acids is one of the determinants of the progress of the humification process. Humic acids could be additionally generated from other humus substances available in the compost. A similar tendency was observed in the series no.2 of second stage where the concentration of KF dropped by 48% and KH increased by 3%. However, in the series no.1 the changes in HA and FA content deviated from the expected.

PI and HI coefficients are commonly used to describe the transformation of humic substance during composting. The values of both humification indices, in the tested windrows during 2nd stage grew but not uniformly. In the series no.1, the PI index increased by nearly 66% and in the second series by 228%. The average initial values of the discussed index were similar for both windrows and amounted to 2.13 and 2.38 respectively. These data indicate that in the initial phase of composting low molecular weight fractions of fulvic acids dominated in both heaps. In the series no.2 of the 2nd stage, the increase in the PI index value amounted to 213%. Assuming that the value of the PI index in the range of 3.6÷6.2 is characterized by mature compost. The moment in which the compost produced during research reached maturity corresponds to about 70 days for the series no.1 and about 40 days for the series no.2 of 1st stage. At the same time, the humification process during the series no.2 was proceeding more stable as evidenced by the dynamics of changes in the PI index value. Therefore, it can be concluded that the duration of the thermophilic phase, which was much longer in the series no.2, has a significant influence on the speed of the humification process. Similar conclusion regarding changes in the PI index during the two series in 2nd stage was not so unambiguous. Generated linear regression lines describing changes in the PI index value in 2nd stage (Fig. 3) compared to 1st stage (Fig. 2), indicate small changes in this parameter over time. At the same time, a large spread of results is visible resulting in a low value of the determination coefficient expressing the quality of the fit of the model to the actual data.

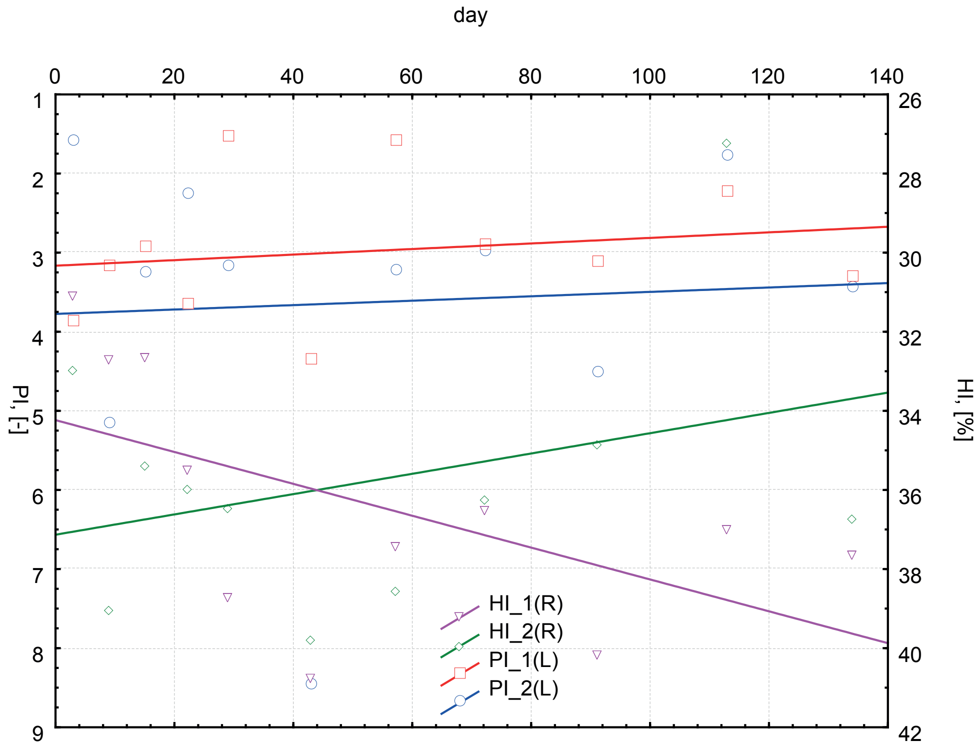

Figure 2. Changes in the values of humification indices PI and HI during composting, stage no.I. first part.

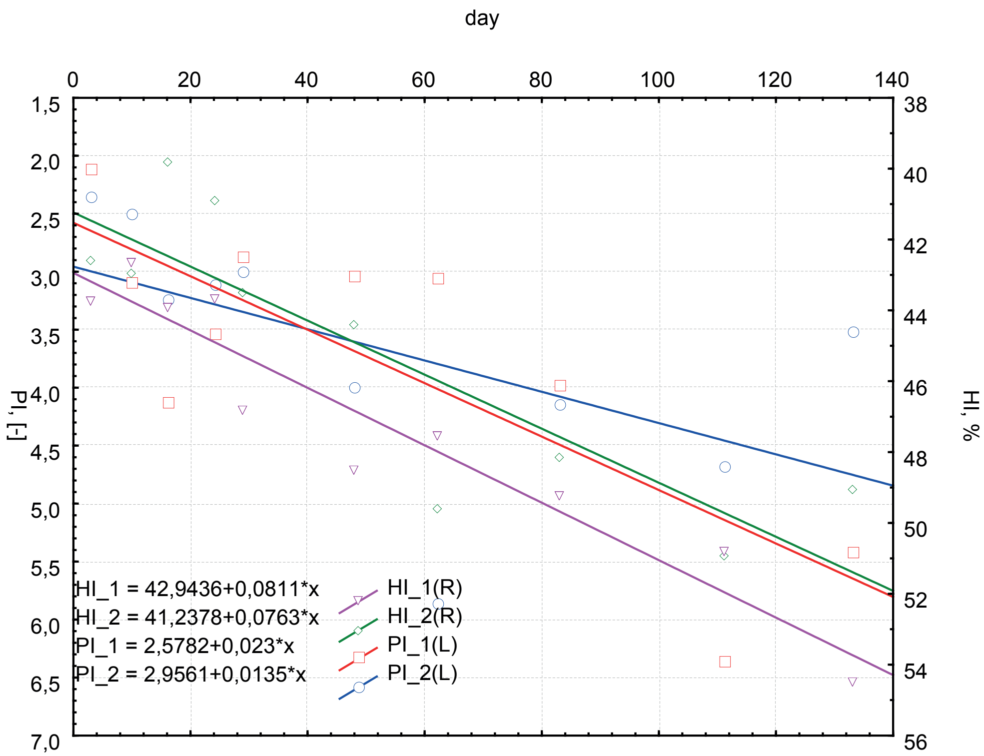

Figure 3. Changes in the values of humification indices PI and HI during composting, stage no.II., first part.

The content of heavy metals in sewage sludge clearly determines the possibility of their agricultural use. In this regard, the national regulations apply – the Regulation of the Minister of the Environment of February 6, 2015 on municipal sewage sludge (Journal of Laws of 2015, item 257)[1] and the Council Directive of June 12, 1986 on the protection of the environment, in particular soil when sewage sludge is used in agriculture (86/278/EEC) (EU[2]). The use of sewage sludge as a soil improver is sanctioned by Regulation 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on making EU fertilising products available on the market (EU[3]).

When assessing the results of laboratory analyzes concerning the content of heavy metals in sewage sludge and compost samples in both test stages, it should be stated that in no case exceeded the limit values set out in separate regulations[1,2,3].

In general, concentrations of heavy metals during composting in all four series grew. The observed increases were related to the successive loss of organic matter content causing a drop in dry matter. In an environment similar to neutral ($pH \approx 7$) heavy metals practically do not form soluble compounds. The total content of heavy metals does not change significantly but in terms of the dry mass the concentration increases.

Speciation analysis allows to mark the chemical forms of a given element in the same sample of compost. The content of heavy metals that have been bounded in the form of various compounds is the result of the natural balance being established depending on environmental conditions. The partial objective of this analysis was to estimate the risk associated with the presence of mobile forms of heavy metals i.e.: nickel, copper and zinc constituting real threats to the environment. It is believed that the binding of heavy metals in the solid phase during the composting process e.g. in the structure of humic compounds and clay minerals, is extremely strong compared to other chemical forms. Thus, the risk of release of heavy metals to the soil medium and their bioaccumulation in crops is reduced.

Separation (fractionation) of heavy metal to different chemical groups characterized by specific properties was carried out in accordance with the Tessier method. According to this method, five groups are identified, i.e.: exchangeable metals (fraction I), metals associated with carbonates (fraction II), metals associated with hydrated iron and manganese oxides (fraction III), metals bound to organic matter (fraction IV) and metals associated with silicates (fraction V). Fractions I and II are treated as unstable. It mean that heavy metals connected with these fractions can be released to the environment. However, in fractions IV and V metals are permanently connected.

Results of the speciation analysis of the compost samples collected in both stages showed that during the composting large changes occur as to the allocation of Ni, Zn and Cu in all fractions. Lines of trend depicting the directions of transformation of chemical forms of the elements determined during composting, in both stages, generally show that the share of metals in the fractions I and II decreases and increases in fractions IV and V. Average nickel content in fraction IV and V in the mature compost obtained in each series accounted for over 97% of the total content. This means that the risk of toxic effects of nickel in the case of agricultural use of compost is practically non-existent. A similar trend was found in the case of copper. Zinc accumulated to a lesser extent in fraction IV and V where the average percentage observed was c.a. 50%.

Part II.

The research was carried out in static composting conditions with forced aeration, running under a cover with a semi-permeable membrane of the GORECover type (pictures 4÷6). In accordance with the composting technology recommended by the manufacturer, one compost test was carried out without the addition of straw, using the mass ratio between sludge and wood chips of 1:1 and additionally one test with addition of barley straw to the mixture of sludge with chips, in a proportion of 2:1:1, respectively.

Picture 4. Composting plant with forced aeration.

Picture 5. Covering the compost reactor with a semi-permeable membrane.

Picture 6. Reactor after completion of the composting process.

In part of the field studies, two independent series (no. 1.2 and no.2.2.) were planned. Both series lasted about 9 weeks. The first compost test started on November 24, 2020 and ended on January 26, 2021. The second attempt lasted from December 16, 2020 to February 8, 2021. The raw material for composting was dewatered, partially stabilized sewage sludge from the municipal sewage treatment plant in Goleniów. About 50% of the weight of mechanically dewatered sewage sludge was used as a structure-forming material.

Composting was carried out under a cover with a semi-permeable GORECover® membrane, in conditions of intensive aeration by forcing air through channels located in the concrete floor of the reactor. The second compost test was carried out using the same process conditions. The difference was that barley straw was used in addition to the sediments and chips to prepare the charge in a mass proportion between the individual components, respectively 2/1/1. The mass of formed compost windrows in both series amounted to approx. 200 tons each.

The composting process in the second part was tested using a new installation in which no additional carbon source is to be used. According to this technology, the dewatered sludge is mixed with wood chips only, which is supposed to improve the porosity of the mixture and increase the air flow efficiency. The process takes place under the cover of a semi-permeable membrane in conditions of intense air flow forced by the work of radial fans. In these circumstances, the use of straw in series no 2.2 was to test the effect of supplementation on the quality of the compost obtained after 9 weeks of composting. The observed organoleptic properties smell, moisture and consistency of the mixture of sludge with wood chips and straw, which were found during series no.2.2, indicated an unfavorable effect of supplementation. This could be due to the increased water retention associated with the presence of straw. Consequently, the increasing air flow resistance resulted in lower oxygenation and local anaerobic zones. Contrary to series no.1.2, where a 22% loss of om was found, in series no.2.2, the content of this parameter practically did not change after 9 weeks of composting. In bouth series, there were changes in the concentration of organic carbon and nitrogen as expected (Fig. 4).

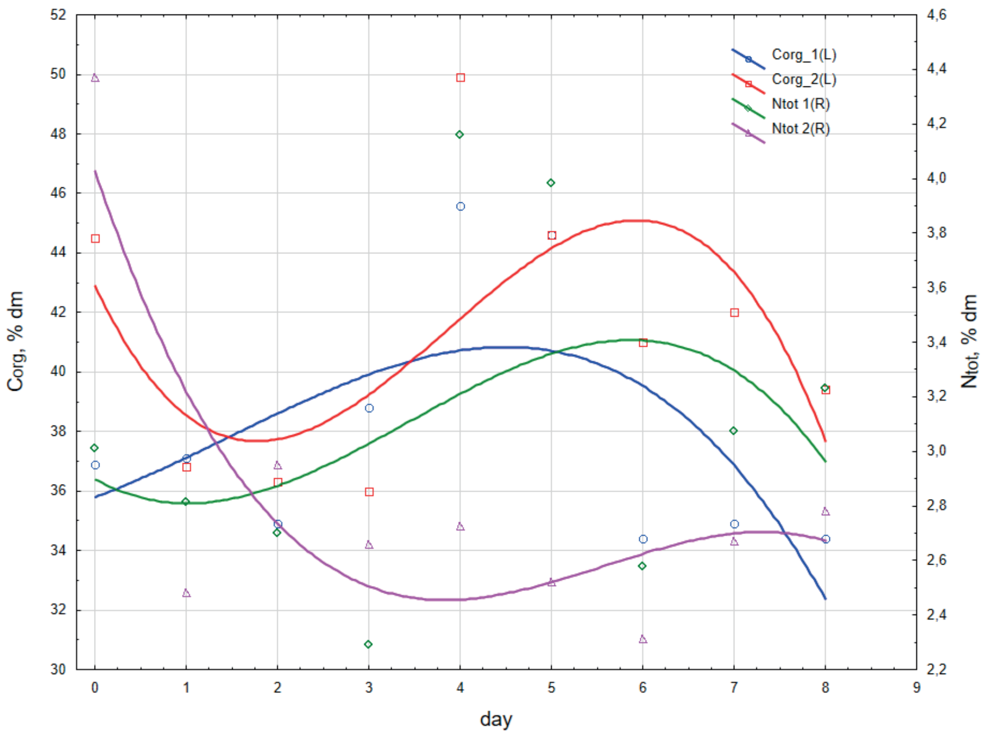

Figure 4. Changes in the concentration of organic carbon and total nitrogen during composting, series 1st and 2nd, second part.

The process of mineralization of the organic matter caused the loss of total organic carbon, while the nitrogen content in the first phase of composting decreased and then increased. The initial decrease in nitrogen concentration was related to the condensate outflow, saturated with NH_4^+ ions released as a result of ammonification. Conducting periodic measurements of NH_3 content in the post-process air, no presence of this gas was found.

Process conditions mainly slightly acidic in the initial phase of composting are not conducive to shifting the equilibrium in the system: $NH_4^+ \leftrightarrow NH_3$, towards ammonia gas. In series no.2.2, the decrease in the concentration of organic carbon (11%) and total nitrogen (10%) was similar, which consequently did not change the value of the C/N parameter. However, in series no.1.2 the increase in this parameter was approximately 33%.

The research results showed that the contents of the tested heavy metals in mature compost used as a soil improver are below the permissible values, except for nickel. In series no.1.2, the concentration of Ni exceeded the limit value by 53%. As in the used sewage sludge the average nickel concentration in both series was 13.25 mg/kg dm, the increase in Ni content in the compost was the result of secondary contamination which could have been the result of the chipping method used or the contamination of the biomass used. In this situation, the research on the content of chemical forms of heavy metals occurrence becomes practical. In the case of nickel, over 98% is bound in fractions IV and V treated as immobile. Nickel present in these fractions is permanently bound in the solid phase of the multiphase medium- compost, which guarantees it is not bioavailable. Generally, it was observed that during composting, the shares of the remaining elements Zn and Cu, related to fractions IV and V, systematically increased.

Laboratory tests, as in part no I, included determination of the content of humic acids resulting from the humification process of organic matter. To evaluate the course of humification, PI and HI indices were used, calculated on the basis of the carbon content in aqueous solutions obtained as a result of extraction of the determined forms of humic acids. It was found that the PI index is the appropriate indicator to describe the effectiveness of humification the value of which increased in the case of series no.1.2 from 0.7 to 1.0 (Fig.5)

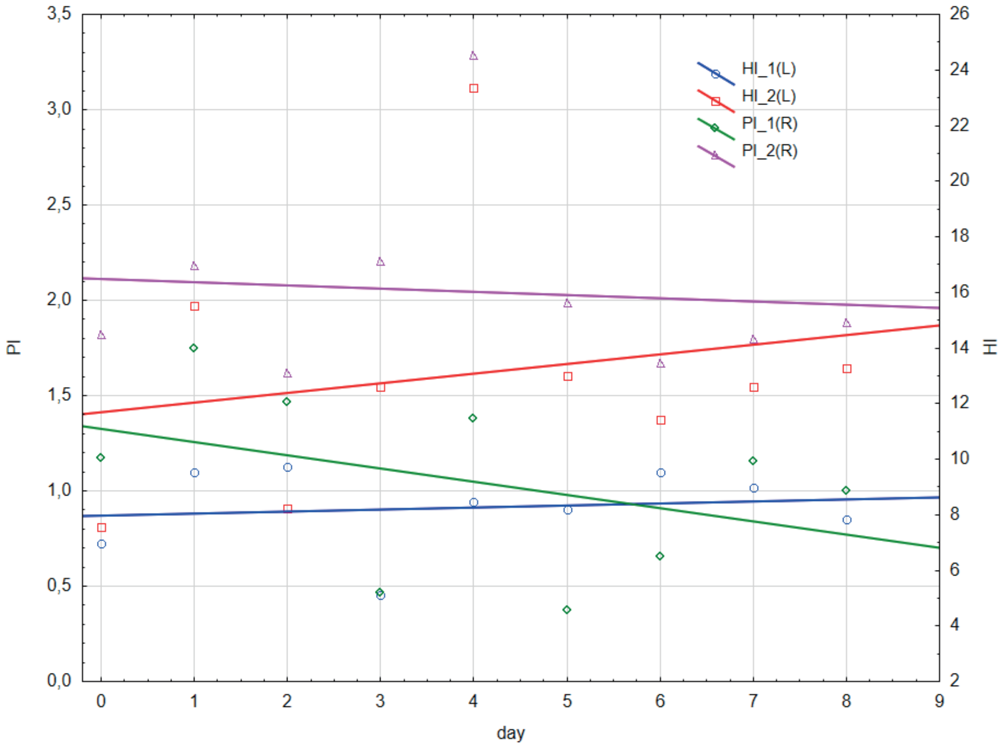

Figure 5. Change of values of humification indexes PI and HI during composting, series 1st and 2nd,second part.

Relatively low values of this index suggest a short time of the composting process. The currently used technology eliminates or limits the compost maturation phase which as a rule takes place in the conditions of periodically turned windrows. As a consequence, the produced compost can reach the level qualifying it as a biologically stable material, but not mature. It should be emphasized that the temperature inside the piles monitored during both series, even after 9 weeks of composting, indicates a high value. Thus, the assessment of the degree of biological stability of the produced compost should be confirmed by performing a self-heating test carried out with the use of a Dewar's vessel.

3 FIELD STUDIES – AGRICULTURAL USE OF COMPOST

The composts produced in part I were used in field studies involving the cultivation of selected plant varieties and the assessment of various indicators describing the yields obtained and the impact of compost on soil conditions. As part of these activities, control field tests were carried out, involving the use of compost as an organic fertilizer in agricultural crops (sowing spring wheat or spring barley). In each year of the experiment, collective soil samples were collected from each plot from a depth of

0-25 cm for laboratory analyzes. Samples for the determination of the content of mineral nitrogen were taken from layers 0-30 and 30-60 before the application of composts and 3 weeks after application from a depth of 0-90 after the plants were harvested. The main objective of the study was to evaluate the effects of agricultural use of various composts produced in the GWIK wastewater treatment plant in Goleniów. The specific objectives were as follows:

- evaluation of the effects of using composts produced in a sewage treatment plant based on sewage sludge and straw on the properties and functions of soil,
- evaluation of the effects of using composts produced from sewage sludge and straw on plant yield and quality,
- evaluation of the possibility of agricultural use of compost,
- risk assessment of agricultural use of composts produced from sewage sludge and straw,
- comparison of composts effects obtained from different composting technologies,
- developing recommendations for the agricultural use of compost produced from sewage sludge and straw.

In the experiment 8 composts characterized by different C/N ratio and maturation time were tested. All types of the compost were produced from the same sludge (municipal sewage treatment plant in Goleniów) and cereal straw.

Schedule and technological details of the analyzed compost types:

Compost no. 1

produced- autumn 2018,
carbon to nitrogen (C/N) ratio = 20,
the time of establishing the compost prism: spring 2018
maturing time: 4 months in the spring-summer season

Compost no. 2

produced – autumn 2018,
carbon to nitrogen (C/N) ratio = 15,
the time of establishing the compost prism: spring 2018
maturing time: 4 months in the spring-summer season

Compost no. 3

produced – spring 2019
carbon to nitrogen (C/N) ratio = 20,
the time of establishing the compost prism: spring 2018
maturing time: 8 months in the spring-summer-autumn-winter season

Compost no. 4

produced – spring 2019
carbon to nitrogen (C/N) ratio = 15,
the time of establishing the compost prism: spring 2018
maturing time: 8 months in the spring-summer-autumn-winter season

Compost no. 5

produced – spring 2019
carbon to nitrogen (C/N) ratio = 20,
the time of establishing the compost prism: autumn 2018
maturing time: 4 months in the autumn-winter season

Compost no. 6

produced – spring 2019
carbon to nitrogen (C/N) ratio = 15,
the time of establishing the compost prism: autumn 2018
maturing time: 4 months in the autumn-winter season

Compost no. 7

produced – autumn 2019
carbon to nitrogen (C/N) ratio =20,
the time of establishing the compost prism: autumn 2018
maturing time: 8 months in the autumn-winter-spring-summer season

Compost no. 8

produced – autumn 2019
carbon to nitrogen (C/N) ratio = 15,
the time of establishing the compost prism: autumn 2018
maturing time: 8 months in the autumn-winter-spring-summer season

3.1 Methodology

The field studies were conducted from autumn 2018 to autumn 2020 in the fields of the Agricultural Experimental Station in Baborówko (RZD Baborówko), belonging to the Institute of Soil Science and Plant Cultivation – State Research Institute (IUNG-PIB). The RZD Baborówko, located in the Wielkopolskie Voivodship, is specialised in crop production especially winter wheat, spring barley, winter rape and maize. It has the equipment for measuring the plant growth, a plotter harvester, a field harvester with a yield meter, and an experienced team of employees.

The total field experiment area was 0.07 ha, covering 30 fields of 21 m^2 (6 x 3.5 m). The plots formed a compact block with uniform soil cover. The experiment was carried out on soil with texture of sand and loamy sand , slightly acidic reaction (pH 5.7 – 6.3 in 1M KCl) and low organic carbon content (0.6 – 0.7%). During the experiment the precipitation was quite low, in all years significantly below the long-term average. The same treatments were applied on all plots. Compost and straw were mixed with the soil by means of a soil ripper connected to the tractor. The control treatments were the plots with straw left for ploughing (control 1) and straw left for ploughing with RSM (control 2). All experimental treatments had 3 repetitions (Table 1) and the location of particular variants was chosen at random.

Table 1. Scheme of plot experiments in the AES IUNG-PIB in Baborkówko

C_2018_III 25	K4_W_2019_II 26	K7_J_2019_II 27	K6_W_2019_I 28	C_2018_I 29	K8_J_2019_I 30
K1_2018_II 19	K8_J_2019_III 20	K3_W_2019_II 21	K2_2018_III 22	K5_W_2019_I 23	K6_W_2019_II 24
C_RSM_2018_I 13	K2_2018_I 14	C_RSM_2018_III 15	K1_2018_III 16	K3_W_2019_III 17	K1_2018_I 18
K6_W_2019_III 7	K5_W_2019_II 8	K4_W_2019_III 9	K8_J_2019_II 10	K2_2018_II 11	C_RSM_2018_II 12
K7_J_2019_I 1	K3_W_2019_I 2	K5_W_2019_III 3	C_2018_II 4	K7_J_2019_III 5	K4_W_2019_I 6

Explanation of the symbols and abbreviations used in the table (Roman numerals indicate the successive replications of the variant concerned):

K1_2018 – compost 1 – application autumn 2018
K2_2018 – compost 2 – application autumn 2018
K3_W_2019 – compost 3 – application spring 2019
K4_W_2019 – compost 4 – application spring 2019
K5_W_2019 – compost 5 – application spring 2019
K6_W_2019 – compost 6 – application spring 2019
K7_J_2019 – compost 7 – application autumn 2019
K8_J_2019 – compost 8 – application autumn 2019
C_2018 – control straw (since 2018)
C_RSM_2018 – control straw + RSM (since 2018)

3.2 Simplified timetable of field works

Year 2018

Autumn 2018 – delineation of experimental plots with the size of 21 m^2. Soil sampling for determination of the initial physico-chemical properties. Leaving straw on control treatments and cleaning straw from treatments dedicated to compost application. Application of composts No. 1 and 2, produced in early October 2018. Soil sampling 3 weeks after application of the composts.

Year 2019

Spring 2019 – application of composts No. 3, 4, 5 and 6. Soil sampling 3 weeks after application of composts and sowing of spring barley on all plots.

Autumn 2019 plant harvest; after plant harvest, application of composts No. 7 and 8. Soil sampling 3 weeks after application of composts. Leaving straw to be mixed with soil on control treatments and other plots.

Year 2020

Spring 2020 – sowing of spring wheat on all plots.

Autumn 2020 plant harvest. Soil sampling for final condition assessment.

Picture 7. Application of compost on experimental plots.

Chemical composition of plants reflected the data obtained for soils, indicating the consistency of the obtained results. There were no statistically significant differences in the content of trace elements in straw and grain. The current legislation (Commission Regulation (EC) No 1881/2006 of 19 December 2006) only sets limits for cadmium (0.1 mg·kg^{-1}) and lead (0.2 mg·kg^{-1}) in cereal grains. Their contents in barley grains in the post-field experiment were several times lower than the permitted contents. Therefore, the fertilization of the soils with the composts under study allows for the production of uncontaminated high quality grain, not deviating in this respect from the grain produced by mineral fertilization. The study did not show any risk to the environment and the quality of food and feed from the use of the applied composts based on sewage sludge and straw.

It can be assumed that the output of metals with high yields fully balances the small amounts of metals introduced into the soil with the composts.

3.3 The impact of composts on yield and quality of crops

The primary purpose of soil fertilization is to achieve an adequate plant yield. The most reliable for the assessment of the impact of composts on barley yields are the yield measurements of 2020, as they reflect the impact of composts at a similar level of soil transformation (at least one year after application). The effect of composts on plant yield may be direct, resulting from the activation of compost fertilizer components, but also indirect – by modifying water retention in soil or activity of microorganisms in the root zone.

Composts K3-K8 significantly increased the yield of straw and spring barley grain in 2020 compared to objects with tilled straw (Fig. 6 and 7). Composts K1 and K2 did not provide such an effect. Due to the fact that the individual objects did not differ significantly in terms of pH and abundance of available fertilizer components, the positive effect of the compost is most likely to be associated with their positive effect on soil water retention and soil biological processes, supporting the development and resistance of plants to stress conditions. Both 2019 and 2020 were characterized by low level of precipitation, compared to the multi-annual average.

Among the composts, the highest yields were obtained for composts K7 and K8 with a long ripening period and applied in autumn 2019. This effect, in turn, can be attributed to the nature of the individual fractions of organic matter derived from the compost and the shorter time after the application of the compost into the soil.

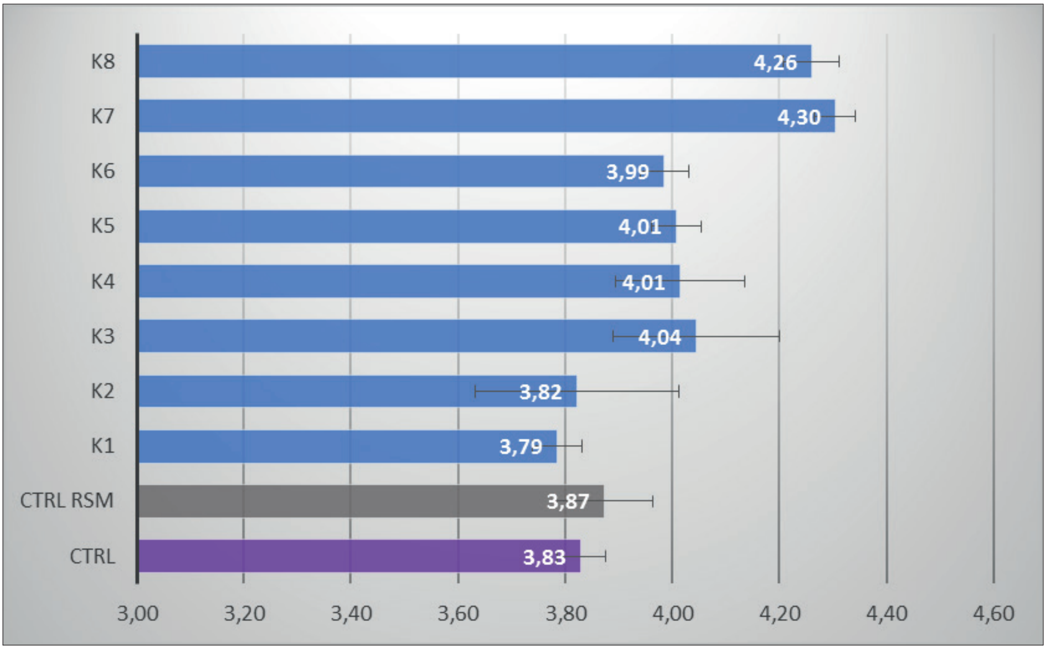

Figure 6. Spring barley straw yield (t·ha-1) in autumn 2020. (the whiskers in the graph indicate the standard deviation from the replication of the variant)

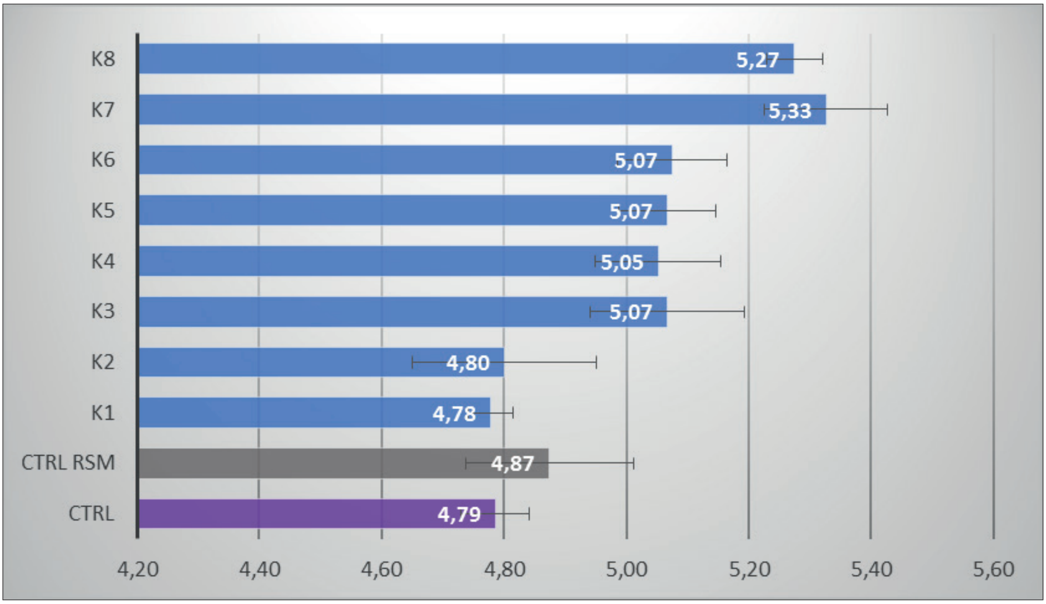

Figure 7. Spring barley grain yield (t·ha-1) in autumn 2020. (the whiskers in the graph indicate the standard deviation from the replication of the variant)

The quality of the crop is evidenced by the content of individual elements (macro and microelements) which determine the balance of nutrients in food or feed. Their content may also explain the differences in yield, in case of deficiency of individual elements. The straw and grains did not show statistically significant differences in the content of nitrogen, potassium, magnesium and micronutrient e.g. manganese (Tab. 2). Therefore, the use of compost does not cause deficiencies of essential elements compared to mineral fertilization.

Table 2. Macro and micronutrient content of spring barley straw and grains in autumn 2020.

Combination	Straw				Grain			
	N	Mn	Mg	K	N	Mn	Mg	K
	%	mg/kg			%	mg/kg		
CTRL	0,87	17,0	1241	20518	1,72	16,5	1661	7091
CTRL RSM	0,68	14,3	1072	18824	1,72	19,3	1652	7619
K1	0,70	18,1	1145	17982	1,72	20,6	1771	8044
K2	0,82	18,7	1153	18527	1,74	18,4	1664	7377
K3	0,85	17,4	1237	18451	1,64	17,9	1679	7522
K4	0,83	20,0	1183	18615	1,74	17,6	1590	6913
K5	0,70	17,5	1256	24245	1,61	18,5	1674	7680
K6	0,79	22,3	1223	19176	1,87	18,7	1679	6977
K7	0,64	15,9	995	19153	1,74	15,2	1511	6705
K8	0,71	18,3	1185	18930	1,71	16,9	1701	7521

Picture 8. Comparison of plant growth in 2020 with insufficient rainfall – left: control with straw ploughing, right: compost K7.

4 RECOMMENDATIONS

4.1 Composting process

Based on the conducted studies on composting sewage sludge aimed at assessing the impact of reduced or completely eliminated supplementation in conditions of periodically turned windrows without aeration – Part I, as well as windrows with forced aeration isolated from the atmosphere with a synthetic membrane – Part II, the following conclusions can be formulated:

Part I

1. The mass ratio between raw materials, forming a batch for the composting process, in the form of: dewatered sewage sludge and barley straw, constituting the basic (balanced) source of organic carbon and nitrogen, structural material and inoculum in the form of wood chips and mature compost, amounting to 8/1/1/1 guaranteeing the value of the C/N≈10, enables the right course of the composting process.
2. There was no inhibitory effect of increased concentration of total nitrogen in the compost associated with high concentrations of this element in sewage sludge (7.48% and 7.54% d.m. in both stages) on the course of the composting process through the

interaction of toxic nitrogen species e.g. in the form of ammonia, which is formed as a result of decay of protein substances which indicates the proper oxygenation of the prism thus preventing the formation of anaerobic conditions.

3. The content of heavy metals in sewage sludge did not exceed the limit values allowing for their agricultural use and thus it is possible to use sludge for processing in the biological process under aerobic conditions for the production of certified compost as organic fertilizer in accordance with the requirements of the Act on fertilizers and fertilization.
4. The results of the speciation analysis related to the determination of heavy metal concentrations i.e.: Zn, Cu and Ni in sequentially separated chemical forms isolated from compost samples, characterized by different levels of bioavailability, showed that composting time has a favorable influence to the allocation of heavy metals by systematic increasing the share of heavy metals bound in stable fractions at the expense of fractions which reliably release elements attached to them.
5. The humification process evaluated on the basis of changes in fulvic acid concentrations transformed into more complex chemical structures including humic acids considered the final effect of these transformations, had a significant impact on the formation of mature compost with a high concentration of humic compounds giving characteristic organoleptic properties i.e. color, aroma and crumbly structure.
6. A reliable indicator describing the effectiveness of the humification process occurring during composting of sewage sludge is the PI index whose value above 3.6 can be considered proper for mature compost provided that the temperature inside the compost windrow within a few days after the last transfer does not rise above the ambient temperature.

Part II

1. In the case of the sewage sludge composting technology with the use of a Gore-Tex membrane cover, it is not recommended to supplement the mixture with mechanically dewatered sewage sludge and wood chips.
2. The high nitrogen content in sewage sludge and a relatively low value of the C / N ratio in the mixture of sludge and wood chips, which is the input for the composting process using intensive aeration and isolation of the windrow with a Gore-Tex membrane, does not pose a threat of gas ammonia emission to the atmosphere
3. The results of the speciation analysis related to the determination of the concentrations of Zn, Cu and Ni in the sequentially separated chemical forms extracted from compost samples, characterized by different levels of bioavailability, showed that with the composting time favorable changes in the allocation of the determined heavy metals consisting in a systematic increase in their share in non-available fractions occurred.
4. During the 12-week composting period, the PI index value did not reach the level of 3.6 considered appropriate for mature compost which suggests the need for further composting in conditions of periodically turned windrows over a period of at least 2 months.

4.2 Agricultural use of compost

In conclusion, the research has provided the following observations:

1. Almost all compost variants promoted an increase in soil phosphorus availability compared to straw ploughing facilities, and this effect lasted long after the compost was applied
2. In the case of available potassium and magnesium, there was a rapid increase in their availability to plants after application, but in the long term, no differences were observed between fertilization variants.
3. The application of RSM before ploughing the straw resulted in a significant decrease in soil pH, similar to composts 1 and 2. Despite dynamic changes in pH shortly after application of some composts, the pH stabilized in the long term and remained in the neutral range, the most favourable for plants.
4. The nitrate nitrogen content was much higher than in the ammonium form, which is typical for processes occurring in soil.
5. Shortly after compost application only in case of one compost, the amount of nitrates in the soil profile was higher than that of recorded for RSM added to ploughed straw. Also in the long term, the amount of nitrates in the soil was lower after application of compost than after ploughing straw or straw with RSM. Most of the nitrates were located in the topsoil layer.
6. The application of the compost did not cause an excessive concentration of ammonium nitrogen, which can be toxic to plants in excessive amounts.
7. After 1 – 2 years from the application of the compost, the organic carbon content remained at the same level, and no differences were observed between the individual plants.
8. In the majority of compost variants, the activity of microorganisms was higher than in the control variant with straw ploughing.
9. K3-K8 composts used in 2019 stimulated bacterial counts more than composts introduced into the soil in 2018, which may indicate the influence of the time factor since the application of the compost.
10. Some composts stimulated the growth of phosphate dissolving bacteria.
11. The K3-K8 composts significantly increased the yield of straw and spring barley grain in 2020 compared to facilities with ploughed straw. Among the composts, the highest yields were obtained for K7 and K8 composts with long ripening period applied in autumn 2019.
12. The use of composts did not cause shortages of essential elements in comparison with mineral fertilization.
13. No changes were found in the content of potentially toxic elements (cadmium, lead, chromium, mercury) in the soil after the composts application, regardless of the technological variant. These contents were at a level significantly lower than the acceptable limits in the national regulations.
14. Cadmium and lead contents in barley grains in the post-treatment experiment were several times lower than the permissible limits.

15. The comparison of the effects of individual composts provided ambiguous information. Composts K1 and K2 stimulated the increase in the assimilability of phosphorus, potassium and magnesium, especially observed in the short term after their application. The same composts acidified the soil, but this effect was short and subsided in the long term. Composts K7 and K8 caused the lowest content of mineral nitrogen 3 weeks after application, and in the long run these effects were less visible. The effect of stimulating the activity and the number of soil microorganisms does not allow the selection of individual variants of the compost – this effect was different for diversified biological parameters. The highest barley yields in 2020 were provided by composts K7 and K8. Also composts K3, K4, K5, K6 caused an increase in yield in comparison with objects with ploughed straw. In terms of grain quality, there were no differences in the effects of individual composts.

5 CONCLUSIONS

1. The use of the composts tested, produced in the process of windrow composting sewage sludge and cereal straw, does not enrich the soil with undesirable elements. This is due to their low content in the feedstock used to produce the composts as well as application of balanced doses of compost.
2. Fertilization of the soils with the composts tested allows the production of uncontaminated grains, which do not differ in quality from grains produced by mineral fertilization.
3. The tests have not demonstrated any risk for the environment and the quality of food and feed associated with trace elements such as cadmium, lead or mercury.
4. High doses of compost may cause a temporary decrease in soil pH, a phenomenon often observed after application of organic fertilization, associated with mineralization of organic matter.
5. Composts generally increase soil biological activity.
6. When applying the recommended doses, the use of compost does not pose a greater risk of excessive leaching of nitrates to water than the use of mineral fertilisation and straw ploughing.
7. The use of composts increases the yielding of straw and barley grain, especially in dry years, which should be associated most closely with their positive effects on soil water retention and soil biological life, supporting the development and resistance of plants to stress conditions.
8. The use of compost ensures that the soil carbon level is kept constant despite the removal of all straw from the plots.
9. The data obtained do not indicate unequivocally which of the tested compost production technologies gives the best results in terms of fertiliser product quality. Composts K1 and K2 with a short ripening period increased the assimilability of fertiliser components for plants to the greatest extent, but they also caused a decrease in soil pH. On the other hand, composts with a long 8-month ripening period, ripened

in spring and summer (K7 and K8) caused the highest increase in straw and grain yield, regardless of the initial carbon/nitrogen ratio. Such a technological process would therefore be most recommended.

6 FINAL RECOMMENDATIONS

Tested composts may be used in agricultural production, including the production of plants for food, without risk. They should be used to the greatest extent for cereal crops as an alternative source of organic matter in the absence of manure. For cereal crops, a rate of 10-15 tonnes of compost per hectare every 2 years is recommended (higher doses on heavier soils), as the most beneficial effect of compost application is observed in the 2nd year after application. It is most recommended to apply the compost in autumn. It should not be used on frozen, snow-covered or flooded soil or during rainfall.

Since high doses of organic matter can cause soil acidification processes, especially on sandy soils with poor buffering properties, the soil should be limed every 3-4 years in order to prevent the pH drop in the soil, in the doses resulting from the analytically determined liming needs.

Chapter 10 EFFICIENCY OF NON-THERMAL PLASMA REACTOR DESIGNED TO REDUCE THE EMISSION OF VOLATILE CHEMICALS RELEASED FROM COMPOSTING WINDROWS

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inż. Noel Anguel Armas Marquez

Advanced oxidation processes (AOP) are used in a large variety of applications, starting with water quality improvement [1], food decontamination, medical applications [2] but also for exhaust gas treatment [3 – 7]. As many cases and literature studies point out plasma and / or UV based systems can be effective in removal of compounds with limited inlet concentration. Further research is needed to provide application possibilities in different fields [4]. Regarding the plasma reactor constructions DBD (electrodes separated by a dielectric barrier) and CD (corona discharge – separated electrodes with no dielectric barrier) reactors are most widely used for atmospheric pressure, cold plasma discharge generation. Different properties of both constructions are an important factor in choosing a certain one for industrial applications and have a strong influence on power supply system design.

Non – thermal plasma is ionized gas between at least two electrodes. Typically the energy connected with atmospheric pressure, non – thermal plasma reactors is between 5 – 15 eV [8]. Two most common discharge types include corona discharge (no dielectric barrier between electrode) and dielectric barrier discharge – DBDs. Typical reactor constructions for both discharge types are depicted in Fig. 1,2.

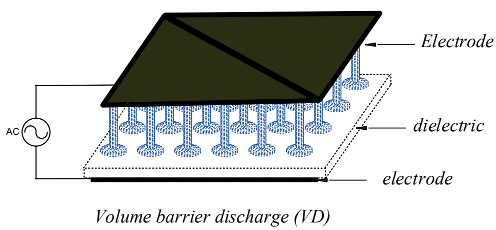


Fig. 1. Principal DBD reactor construction.

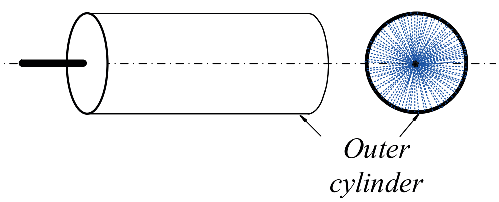


Fig. 2. Principal corona discharge (CD) reactor construction.

As can be noted the DC reactor construction is simpler, however higher complexity of the HV power supply is necessary to avoid spark or even arc discharge in the chamber. Typical view of both reactor constructions during operation is presented in Fig. 3.

a) b)

Fig. 3. Operation of a) DBD reactor b) CD reactor.

This chapter summarizes the description of the applied test procedure and obtained results, which may be the basis for the evaluation of the efficiency of the plasma reactor used to remove volatile compounds from gas streams released from compost windrows during their maturation carried out in the sewage treatment plant in Goleniów. The research has been carried out as part of the implementation of the STEP project (Sludge Technological Ecological Progress), the aim of which is to analyse and refine effective methods of sludge utilization, taking into account the energy efficiency of processes, and reducing the nuisance to the environment. Direct treatment method was used with a prototype of a single, corona discharge tube – Fig. 4.

Fig. 4. Prototype of a single – tube corona discharge unit.

The determination of the effectiveness of various solutions enabling the reduction of volatile odorants emission requires the use of appropriate measurement techniques allowing qualitative and quantitative analysis of odorants. The most popular group of techniques used for this purpose are chromatographic techniques, including the technique of gas chromatography coupled with a mass spectrometer (GC-MS) [9]. This solution is in some cases insufficient, as it does not allow for separating the components present in complex matrices (e.g. gas samples) [10]. An alternative to this case is the use of the two-dimensional gas chromatography (GCxGC) technique, which guarantees a higher degree of separation of analytes present in the tested samples, thanks to the use of a system of two chromatographic columns with different degrees of polarity. The GCxGC technique is increasingly used in various areas of research, mainly food and environmental analysis [11–13].

An alternative to chromatographic techniques, especially in the case of quantitative determinations may be direct measurement techniques in the field of mass spectrometry enabling performing analyses without the need of prior sample preparation [14]. One such technique, developed in the 1980s, is Proton Transfer Reaction Mass Spectrometry (PTR-MS). During the determinations, the tested compounds undergo a reaction of exchanging the proton with hydronium ions generated inside the device. This solution in comparison to chromatographic techniques, in addition to the lack of sample preparation for analysis, is characterized by a shorter time of a single analysis and the possibility of conducting real-time analyses [15, 16].

The gas sampling for testing was carried out in a municipal wastewater treatment plant located in Goleniów (West Pomeranian Voivodeship). In order to carry out the planned tests, 2 compost heaps from the plant were prepared, differing in the ratio of sewage sludge to the added straw. Both piles were located on the indoor compost ripening area; during the gas sampling stage, the given pile was covered in order to limit the exchange of gas stream released from the heap with atmospheric air. The gas sampling took place:

- November 8, 2018 – the first measurement series;
- November 29, 2018 – the second measurement series;
- January 25, 2019 – the third measurement series.

Fig. 5 gives an example of a typical composting windrow.

Fig. 5. Typical compost windrow in the composting facility (Goleniów, Poland).

Gas samples were taken both before the gas entered the reactor and after leaving it. In total, 10 gas samples were taken in Tedlar bags and 10 air samples using solid sorbent packed tubes. The diagram of the applied research methodology described in the further part of the report is shown in Fig. 6.

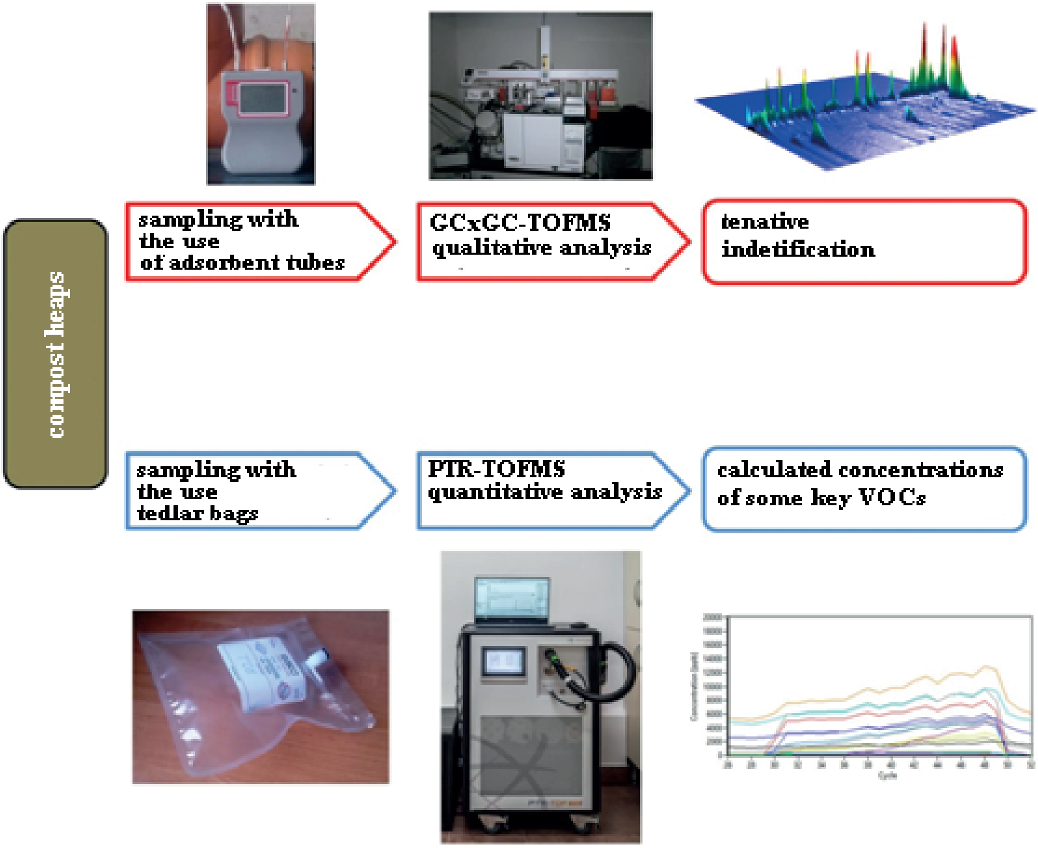


Fig. 6. Diagram of the applied research procedure.

Many different chemical compounds were measured and evaluated including ammonia, hexane, 1-methoxy-2-propanol, toluene.

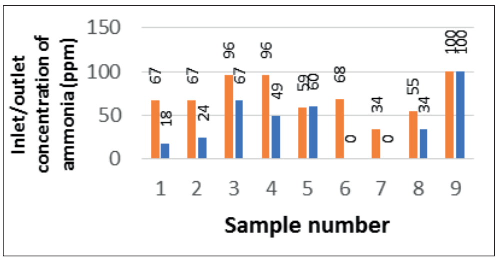
Most important pollutants detected in the exhaust are summarized in Table 1.

Table 1. Measured, main odour compounds.

Compound	Chemical Symbol	Hazards
Ammonia	NH_3	Toxic while inhaled
Hydrogen Sulfide	H_2S	Highly toxic
Hexane	C_6H_{14}	Toxic while inhaled, pulmonary oedema, pneumonitis, death
Dimethyl disulfide	CH_3SCH_3	Toxic while inhaled
1-Methoxy-2-propanol	$C_4H_{10}O_2$	May damage fertility and the unborn child
Toulene	$C_6H_5CH_3$	Headache, Diziness
Pentatane	C_5H_{12}	Drowsiness, diziness
Methanethiol	CH4S	Very toxic
2-methylbutanal	$C_5H_{10}O$	Toxic while inhaled
Benzaldehyde	C_6H_5CHO	Toxic when inhaled
Benzene	C_6H_6	cancirogen
Dichloromethane	CH_2Cl_2	Organs damage through repeated exposure

Exemplary removal efficiencies for high and low input concentrations (first and second measurement series) of ammonia is depicted in Fig. 7. As can be noticed the average removal efficiency for high inlet concentrations was 50% and for low inlet concentrations it reached 80%.

a)



b)

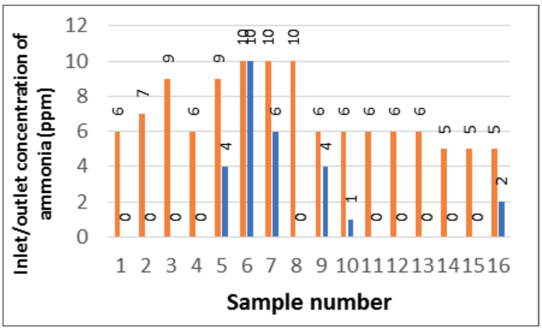
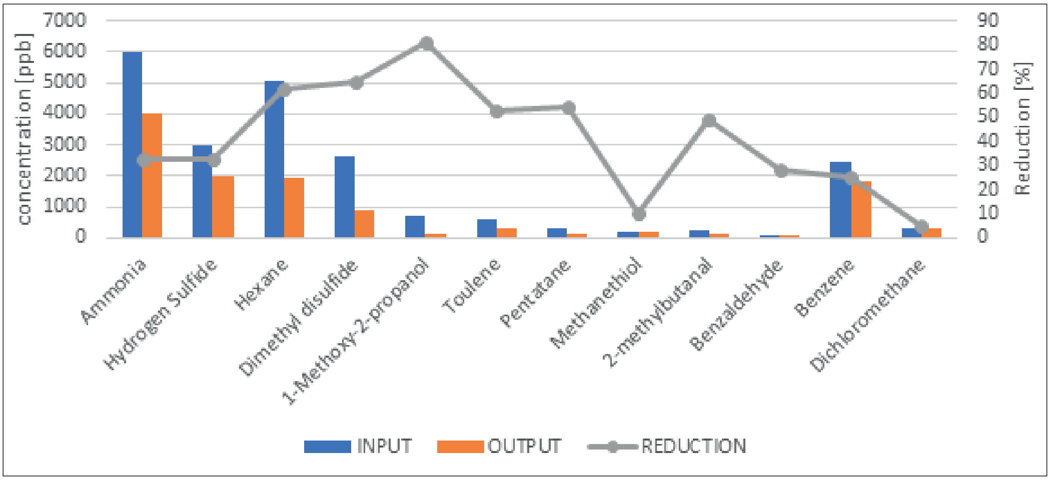


Fig. 7. Removal efficiency for ammonia for direct plasma treatment and a) high inlet concentrations (1,4 Wh/Nm3), b) low inlet concentrations (0,9 Wh/Nm3).

Summarized efficiency for various compounds is depicted in Fig. 8.



The average reduction reached 25% (of all compounds) in the first phase and 40% (of all reductive compounds) in the second phase: 40%. It should be noticed however that synthesis is also possible, benzene was detected in higher concentration on the outlet of the plasma reactor then on the inlet.

SUMMARY

Plasma treatment can be cost – effective in air treatment solutions for low concentration of exhaust pollutants and for deodorization. In case of sludge composting satisfactory results were obtained however the plasma device should be extended with another technology to remove a wider variety of compounds. Main advantages of this technology includes:

- Low operating and investment costs,
- Waste – free processing,
- Relatively small size of necessary equipment,
- Low pressure drop in case of CD and UV units,
- Additional disinfection of treated gases.
- Reasonable efficiency.

Main disadvantages include:

- Risk of corrosion of installation parts
- Presence of strongly oxidizing agents
- Possible ozone presence after treatment
- Efficient only for compounds which are susceptible to oxidation
- Possible synthesis of undesired by – products.

Non – thermal plasma systems offer a larger variety of reduction mechanisms. In industrial conditions often a hybrid treatment plant will offer best performance.

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