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Polish experience in operation of Sludge Treatment Reed Beds

Katarzyna Kołecka[*)], Hanna Obarska-Pempkowiak[**)], Magdalena Gajewska[***)]

[*)] katkolec@pg.gda.pl - corresponding author

[**)] hoba@pg.gda.pl

[***)] mgaj@pg.gda.pl

Gdańsk University of Technology, Faculty of Civil and Environmental Engineering

11/12 Narutowicza St.

80-233 Gdańsk, Poland

Abstract:

Sludge Treatment Reed Beds (STRBs) is the technology of sludge treatment, which is based on natural processes occurring in the environment, in specially designed and operated facilities to achieve benefits for the environment. Integrated dewatering and stabilization occur in reed systems. For economic and environmental reasons it is an attractive solution, especially in rural areas where there are no appropriate facilities.

In the recent years many European countries like Denmark, France or Germany have applied this technology for sewage sludge management. Poland has also some experience in dewatering and stabilization of sewage sludge in STRB systems.

The objective of the paper is to present the current experience and lessons learned from the operation and to assess the quality of sewage sludge from STRBs in Poland.

The analyzed sewage sludge was treated in STRBs located in five wastewater treatment plants: Darżlubie, Swarzewo, Zambrów, Nadole and Gniewino, Poland. Two from the analyzed systems (Darżlubie and Swarzewo) worked only in a pilot scale and three of them (Darżlubie, Swarzewo and Nadole) did not work any longer. In the collected samples of sludge the evaluation of dewatering and stabilization processes, fertilizer properties, as well as heavy metals concentrations were determined.

The average dry matter content in sludge treated in Polish STRBs was from 11.2 to even 53.7%. The degree of mineralization in analyzed systems was from 31.4 to 68.6%. The average nutrient contents was for nitrogen from 1.0 to 10% DM and for phosphors from 0.2 to 1.0% DM.

The conducted research confirms that sludge treated in STRBs is dewatered and stabilized, thus it could be used as a fertilizer in agriculture.

Keywords: sewage sludge; dewatering; stabilization; nutrients; Sludge Treatment Reed Beds (STRBs)

1. Introduction

Sewage sludge is a by-product of wastewater treatment processes. The systematic increase of sludge quantity has been observed for years (CSO, 2013). It is supposed that this trend will be maintained in the coming years due to the increased demand for the improvement of the quality of treated wastewater (NWMP, 2014). In the past in small and medium-sized WWTPs sewage sludge management was mostly limited to its storage. However, since 2016 this kind of management has been forbidden (MoE, 2015b).

In Poland in recent years 13 facilities for thermal utilization of sludge have been built. However, due to very high cost this method is available only for very big WWTPs (approximately 500,000 pe - person equivalent). It is recommended that valuable elements (for example nutrients) from sludge from small and medium-sized WWTPs should be reused in the environment (NWMP, 2014).

One of the methods of sludge utilization is composting. However, this method generates costs (connected with the purchase of structural material) which are often too high for small WWTPs. What is more, the quality of compost is very often not adequate for agricultural application and it can only be used for non-agricultural purposes. Then, the ratio of preparation of the material and the potential cost of the final product is not justified economically.

Another technology to treat sewage sludge is called Sludge Treatment Reed Beds (STRBs). Reed systems for sludge treatment stimulate natural processes occurring in the environment in specially designed and operated facilities to achieve benefits for the environment. Integrated dewatering and stabilization occur in reed systems.

STRBs are typically built as ground facilities with horizontal layers of gravel and sand, mostly planted with reed. It is very important to build the drainage system connected with ventilation chimneys. It prevents the formation of anaerobic conditions and provides proper conditions for dewatering and stabilization of sludge. During the operation of STRBs there are three periods (commissioning, full operation and emptying) (Kołecka & Obarska-Pempkowiak, 2008, 2013; Nielsen, 2003, 2011). During the first period of the operation - commissioning (which lasts for about 2 years), the dose of dry matter of sludge should be lower than the designed values (Nielsen, 2003). During operation reed systems are periodically irrigated with sewage sludge with low dry matter content (from 0.5% to 1.5%). The resting periods (breaks in sludge supply) may take several days, depending on the weather conditions, the age of the system and the dry matter content in sludge, as well as thickness of the accumulated sludge (Nielsen, 2003). Before emptying the bed should not be used for some time (preferably in summer) to increase the content of dry matter and improve its sanitary properties (Kołecka & Obarska-Pempkowiak, 2013; Nielsen, 2003; Troesch et al., 2009).

It is estimated that the maintenance cost of STRBs is only 10% of the cost of the traditional solution used for sludge management (Nielsen, 2015). Additionally, it is environmentally friendly technology which does not need the use of additional chemicals (e.g. coagulants or polyelectrolytes) and is characterized by low emission of gases (Brix et. al., 2001; Kołecka & Obarska-Pempkowiak, 2013; Olsson et al., 2014; Uggetti et. al., 2012). Therefore, it is an attractive solution for economic and environmental reasons, especially in rural areas.

STRBs have been used in many countries, for example about 105 reed systems were built in Denmark and 120 in France. These systems work also in Germany, Italy and Spain (Brix, 2017; Nielsen et al., 2014; Troesch et al., 2009; Uggetti et al., 2010). In Poland there is some experience in dewatering and stabilization of sewage sludge and septage in STRBs (Kołecka et. al, 2017; Karolinczak & Dąbrowski, 2017; Obarska-Pempkowiak et al., 2003, 2015a; 2015b; Pempkowiak & Obarska-Pempkowiak, 2002).

Based on years of research in Denmark, France, Spain, Italy and Poland (Kołecka & Obarska-Pempkowiak, 2008; Kołecka et al., 2017; Nielsen, 2003, 2011; Troesch et al., 2009, Uggetti et al., 2010, 2012) recommendations for the construction of STRBs were established. The main design factor is the sewage sludge loading rate (Uggetti, et al., 2010). This value for secondary sludge is approx. 60 kg DM (dry matter)$\cdot$ $m^{-2}\cdot year^{-1}$. In case of sludge with high content of fat or fermented substances the recommended loading rate is lower and equal to 50 kg DM$\cdot$ $m^{-2}\cdot year^{-1}$. To provide sufficient time for the transformations of accumulated sludge, the system of STRBs should consist of several beds. More beds ensure longer resting period between supplying sludge, which leads to the improvement of efficiency in dewatering and stabilization of sludge. Sludge is supplied until the system reaches its full capacity. The stabilization period is usually from 8 to 12 years.

The aim of the paper is to present the current state and experience of Polish STRBs. The main focus was on the quality of the achieved material and its fertilizing value. The novelty of the paper is presentation of entirety of experiences from Polish STRBs, which has not been elaborate yet. Based on carried out investigations and collected data, as well as experiences lessons learnt have been prepared.

2. Material and methods

The analyzed sewage sludge was dewatered and stabilized in STRBs located in the northern part of Poland. Some of them worked only in pilot scale. The characteristics of this system is presented in Table 1.

Table 1. The characteristics of Polish STRBs

Localization	Swarzewo near Puck	Darżlubie near Puck	Zambrów near Suwałki	Nadole near Wejherowo	Gniewino near Wejherowo
Year of establishing	1994	1995	1997	2001	2011
Time of operation in years	3	5	4*)	9 and 3 years of resting**)	4
Amount of wastewater,	4 000 in winter	140	3500	80	845

m^3/day	6500 in summer				
Total area, m^2	2500	480	5500	150	2400
Number of beds/basins	1	2	1	2	6
Type of facilities	pilot	pilot	full-scale	full-scale	full-scale
Type of sewage sludge	surplus sludge from conventional WWTP	sludge from Imhoff tank at the beginning of local WWTP and from household sedimentation tanks	surplus secondary sludge from conventional WWTP	surplus secondary sludge from conventional WWTP	surplus secondary sludge from conventional WWTP
Average loading of sludge, kgDM/ $m^2 \cdot a$	31	38	62	33	55
Loading	3-4 times a year	8 times a year	in vegetation period[***)]	in vegetation period[***)], every 3-4 weeks	in vegetation period[***)], every 3 weeks
Status	not operating	not operating	in operation	not operating	in operation
Stop of operation	1997	2000	-	2010	-

[*)] the research concerns the first period of operation (first 3 years)
[**)]during the resting period raw sludge was not discharged
[***)] in our latitude from May to October

Three systems (located in Darżlubie, Swarzewo and Nadole) are not in operation any longer. In case of Darżlubie and Nadole the WWTPs were closed due to the modernization of wastewater treatment, namely the connection of the catchment area of the treatment plant to a larger plant. Wastewater from WWTP in Darżlubie was connected to the municipal sewage system and was discharged to the bigger WWTP located in Swarzewo. The same was in case of Nadole, where the wastewater was discharged to WWTP in Gniewino in 2010. In 1997 the layer of sludge of about 4.5 m high in Swarzewo was discharged to the reed system as a result of operation problems in WWTP. This extremely excessive load caused serious damage in reed and destroyed the system. The reed system was not reconstructed. Now sludge in Swarzewo is composted. Zambrów basin with reed is still in operation and this year WWTP is going to remove the sludge residue. The facility in Gniewino is also still in operation and the next new three beds planted with reed will be built to meet the requirements.

In the analyzed facilities the loading of sludge was below the recommended values or exceeded them insignificantly (Zambrów). Some operation problems in the pilot system were probably caused by a low number of beds. Additionally, at least 8-12 years of operation are needed to ensure right dewatering and stabilization. In the pilot systems the time of sludge treatment was much shorter.

In the paper the following properties of sludge were analyzed: dewatering and stabilization process, as well as the fertilizing potential. To estimate the above-mentioned properties, dry and organic matter content, as well as nitrogen, phosphorus and heavy metals concentrations were determined. The whole research was carried out according to Polish Standards (PN-C-04537-14:1998; PN-EN 12879:2004; PN-EN 13657:2006; PN-EN 16169:2012) and APHA (2005). The determinations of the selected heavy metals in the sludge were made by using atomic absorption after their mineralization.

The degree of mineralization was calculated as (Podedworna & Umiejewska, 2008):

$$M = 100 - \left(\frac{m.d.m_0 \cdot o.d.m_s}{o.d.m_0 \cdot m.d.m_s} \right) \quad (\%)$$

where:

o.d.m_0 – organic dry matter at the beginning of the process, % DM

o.d.m_s – organic dry matter after stabilisation, % DM

m.d.m_0 – mineral dry matter at the beginning of the process, % DM

m.d.m_s – mineral dry matter after stabilisation, % DM

The quality of sludge from the three facilities (Darżlubie, Swarzewo, Zambrów) was presented based on the data from literature. Additionally, the quality of sludge treated in STRBs in Nadole and Gniewino was determined in the laboratory of Faculty of Civil and Environmental Engineering at Gdańsk University of Technology.

The samples of sludge from STRBs in Gniewino and Nadole were collected 3 times from the selected bed in six points by using of a special probe (Kołecka & Obarska-Pempkowiak, 2008; 2013). STRB in Gniewino treats sludge all the time while raw sludge was not discharged for 3 years in the facility in Nadole. Then the samples of sludge were averaged for analysis. In Gniewino and Darżlubie the samples of sludge were collected along the vertical profile. The profile was divided into the top and the bottom layer. Sludge from the bottom layer was treated longer than sludge from the top layer.

3. Results and discussion

3.1. Dewatering processes

In Poland, the average summer temperature is between 16°C and 20°C and between -6°C and 0°C in winter. The average annual air temperature is 7 - 9°C (excluding mountain areas). The average rainfall is about 600 mm per year. The rainfall distribution is uneven throughout the year, 2/3 of annual precipitation is in summer (http://www.imgw.pl/). The climate conditions are similar to Denmark and they do not have any negative effect on the dewatering process.

In all analyzed STRBs the discharged sludge had high content of water, which amounted from 95 to 99%. The highest content of the dry matter was found in sludge from Nadole (Table 2). Effective dewatering, higher than from mechanical equipment, which is maximum 40%, has been obtained due to long time of operation. Also the time when sludge was not discharged has an impact on dewatering processes. The highest content of the dry matter (53.7%) was observed in Nadole, which has the longest resting period (3 years). The lower content of dry matter was found in the sludge from Gniewino (11.2%), Swarzewo (14.0%) and Zambrów (17.5%). In Swarzewo the lower content of dry matter was caused by improper operation of the facility while in case of Gniewino and Zambrów STRBs the relatively low content of dry matter is caused by regular discharging of new volume portions of sewage sludge (Table 2). Additionally, in Gniewino there were some maintenance problems connected with wrong aeration and overload of the system. The research conducted in Danish STRBs confirmed the high content of dry matter (from 20.3 to 29.3 %). These STRBs were in operation, however the long-term treatment (10-15 years) resulted in very good dewatering (Kołecka & Obarska-Pempkowiak, 2013). Such effective dewatering is caused, among other things, by plants transpiration.

Table 2. The average dry matter content in sewage sludge treated in STRBs based on own research and literature data (Obarska et al, 2003; Zwara & Obarska-Pempkowiak, 2000)

STRBs	Darżlubie	Zambrów	Swarzewo	Nadole	Gniewino
Time of operation, years	5	4	3	9 and 3 years of resting	4
Dry matter, %	41.6 ±8.6	17.5±1.2	14.0±2.5	53.7±6.4	11.2±6.87

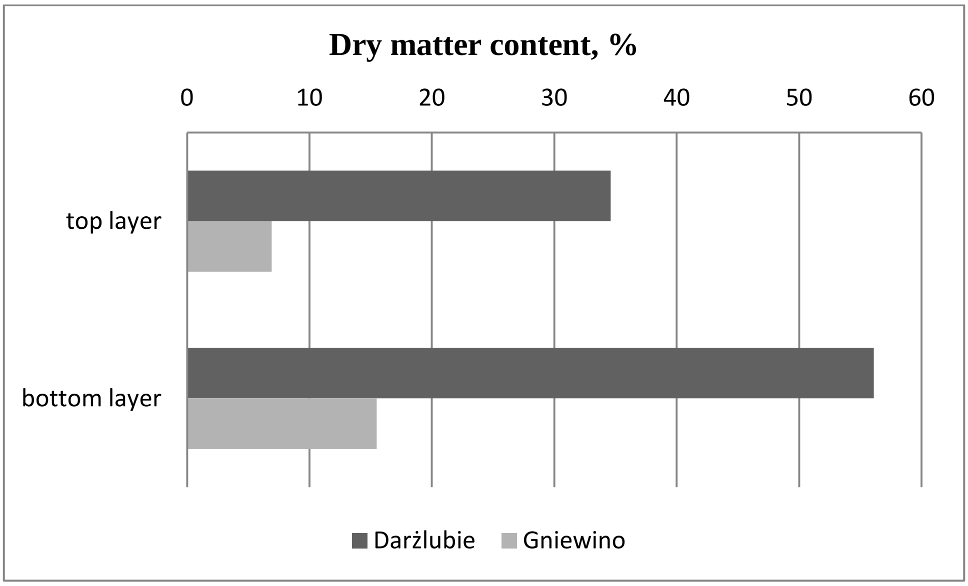

Fig. 1. Changes of dry matter content with depth in sludge treated in STRBs

It was also found out that the dry matter content increased with depth (Fig. 1). The top layer, which was dewatered over a shorter period, had much lower content of dry matter than the bottom layer, which was dewatered much longer. The same results were obtained in Danish STRBs (Kołecka & Obarska-Pempkowiak, 2008, 2013).

Basing on these results it can be concluded that to obtain high dry matter content in sludge removed from STRB it is necessary to provide time without sludge discharging. The data from literature (Kołecka & Obarska-Pempkowiak, 2013; Matamoros et al., 2012; Nielsen, 2013; Stefanakis & Tsihrintzis, 2011) show that the sludge dewatered in STRBs for a long time (10-15 years) can reach the dry matter content of over 30%.

The increase of dry matter content connected with efficient dewatering caused a significant decrease in sludge volume. In Darżlubie the initial volume decreased about 94.3% in 5 years, in Swarzewo 85.7% in 3 years, in Zambrów 91.5% in 4 years and in Gniewino 80% in 4 years (Obarska-Pempkowiak et al. 2003; Zwara & Obarska-Pempkowiak, 2000). In the Danish systems operating for 7-15 years the reduction of initial volume reached 95 % on average.

Due to the high reduction of sludge volume the reed beds can be used for a long time without the removal of sludge residue.

3.2. Stabilization processes

According to the definition, stabilization is a chemical or biological process that stops the natural decomposition of sludge. In STRBs this process occurs in natural conditions and causes the decrease of organic matter. It is estimated that sludge with organic matter of about 50% DM is stable.

In the analyzed STRBS in Nadole and Darżlubie it could be assumed that sludge is stable (Table 3). The organic matter content decreased by about 15% in the sludge from Swarzewo STRB during three years of operation. The average content of organic matter is above 50% DM in Zambrów and Gniewino. It is caused by the regular discharge of raw sludge. However, in Gniewino in the bottom layer (the longest treated) the organic matter content exceeded insignificantly 50% DM (Fig. 2). In comparison to all Danish facilities operating from 7 to 15 years the organic matter content was from 41.1 to 46.6 % DM (Kołecka & Obarska-Pempkowiak, 2013).

The degree of mineralization in the analyzed systems was from 31.4 to 68.6 % (Table 3). The lower stabilization took place in the facilities which were regularly fed with raw sludge (Zambrów and Gniewino).

Table 3. The average organic matter content in sewage sludge treated in STRBs based on own research and literature data (Obarska-Pempkowiak et al. 2003, 2015a; Zwara & Obarska-Pempkowiak, 2000)

STRBs	**Darżlubie** after 5 years	**Zambrów** after 4 years	**Swarzewo** after 3 years	**Nadole** after 12 years	**Gniewino** after 4 years
Organic matter, %DM	45.3±3.2	64.4±7.9	60±5.6	50.1±4.4	62.2±9.8
Degree of mineralization, %	68.6	31.4	43.1	61.9	37.6

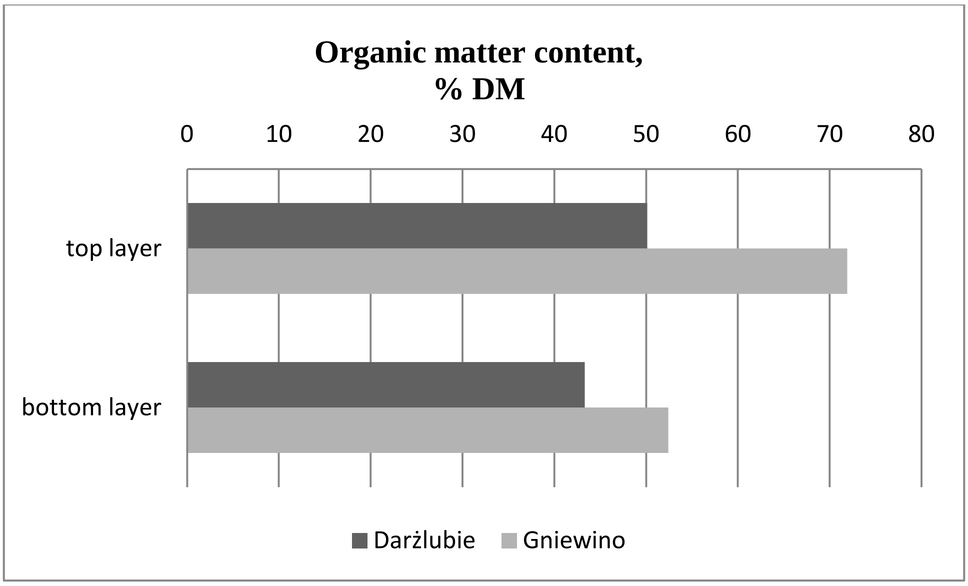

Fig. 2. Organic matter content changes with depth in sludge treated in STRBs

It was found out that the organic matter content decreased with depth of reed beds (Fig.2). In Gniewino in the top layer (shorter processing time) the organic matter content was 62.2 % DM and it decreased to 52.4 % DM in the bottom layer (longer processing time). The same was in Darżlubie where the organic matter content decreased from 50.1 % DM (in the top layer) to 43.3 % DM (in the bottom layer). It indicates that the process of stabilization occurs in the reed systems.Based on literature data (Kołecka & Obarska-Pempkowiak, 2008, 2013; Nielsen, 2007; Peruzzi et al., 2013; 2017) it could be assumed that sewage sludge should be treated in STRB at least for four years to ensure correct stabilization and the right decrease of the organic matter content.

3.3. Fertilizing potential

The analyzed reed systems were characterized by different contents of nitrogen and phosphorus in the sludge which was processed (Table 4). The highest nitrogen content was in Gniewino and on average it amounted to 4.8% DM and in Swarzewo it achieved even 10% DM, while the lowest content was in Nadole and it was 1.3% DM.

In case of phosphorus the highest content was again in Gniewino (3.5 % DM on average) and the lowest was in Darżlubie (0.24% DM on average). Based on these results it can be supposed that the nutrient contents depend on wastewater quality, as well as on the technology of wastewater treatment. In STRBs with the highest content of nitrogen, WWTPs served the area where the food and dairy industry is developed. The influent of industry wastewater with high content of N causes the increase of its concentration in surplus sludge. The high content of phosphorus in sludge from

Gniewino is probably caused by the chemical precipitation of this element from wastewater.

Table 4. The average nutrient contents in sewage sludge treated in STRBs and in natural fertilizer based on own research and literature date (Kołecka & Obarska-Pempkowiak, 2013; Obarska-Pempkowiak et al. 2003, 2015a; Pempkowiak & Obarska-Pempkowiak, 2002).

STRBs	**Darżlubie**	**Zambrów**	**Swarzewo**	**Nadole**	**Gniewino**	**Manure, average**
Nitrogen, % DM	2.35±0.09	3.90±0.7	1-10	1.31±0.40	4.8±1.2	1.5
Phosphorus, % DM	0.24±0.02	0.55±0.06	0.2-1	2.09±0.36	3.50±0.1	0.4

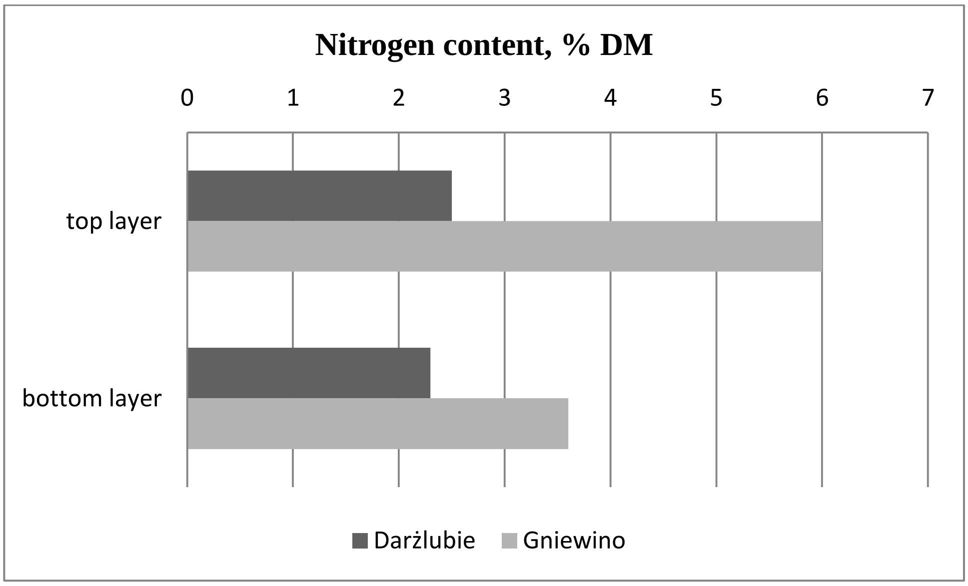

Fig.3. Nitrogen content changes with depth in sludge treated in STRBs

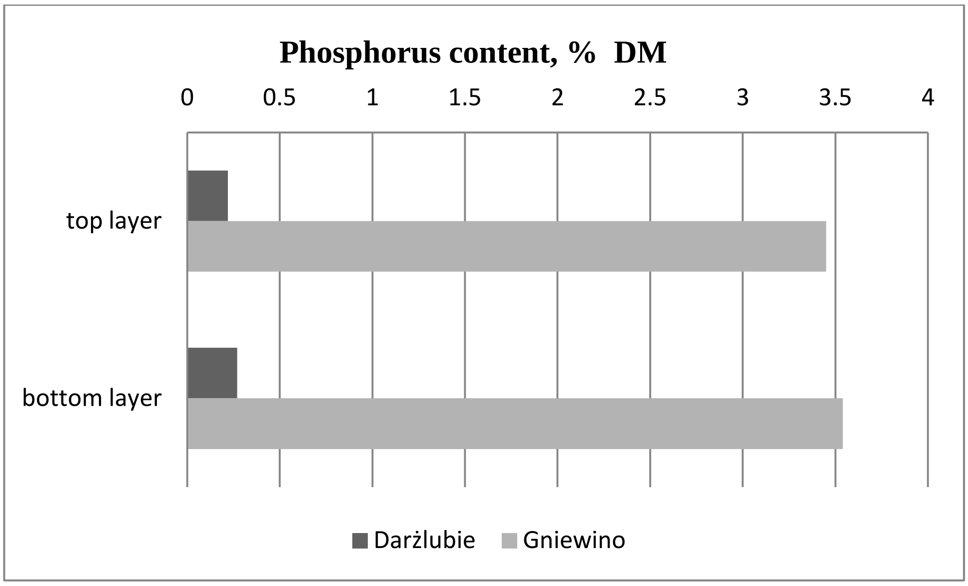

Fig. 4. Phosphorus content changes with depth in sludge treated in STRBs

During the treatment of sludge in STRBs the decrease of nitrogen and the increase of phosphorus content is noticed with depth (Fig. 3 and 4). The changes of nitrogen are caused by nitrification and denitrification, as well as by mineralization processes. The long-term treatment influences the significant decrease of N content. However, its content is higher than in manure, which is a fertilizer. The increase of phosphorus content was probably caused by the decomposition of the organic matter apart from the decrease in the volume of stabilized sewage sludge. The content of P in the majority of the analyzed STRBs is also higher than in manure.

The same dependence was found out in STBRs in Denmark (Kołecka & Obarska-Pempkowiak, 2008, 2013).

The sludge treated in STRBs is dewatered and stabilized, it is also characterized by high contents of nutrients, higher than in manure (natural fertilizer), that is why it can be considered as a potential fertilizer. However, heavy metals concentrations need to meet the requirements of MoE (2015a) in order to use sludge for agricultural purposes. Fig. 5 presents the concentration of heavy metals in sewage sludge from STRBs in Poland.

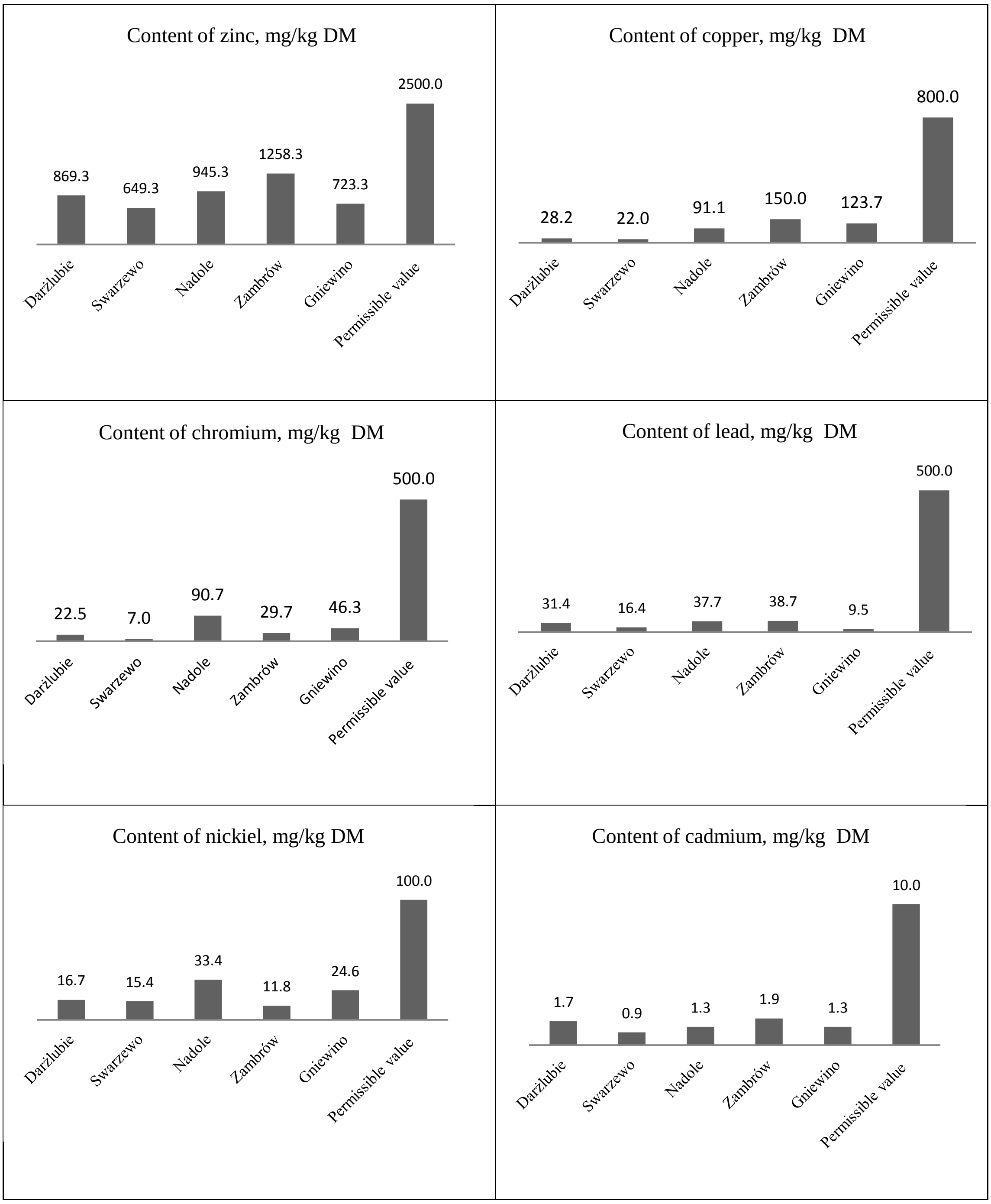

Fig. 5. Selected heavy metals concentration in sewage sludge from STRBs in Poland

The highest concentration of the analyzed heavy metals (except nickel and chromium) was found out in Zambrów. It was probably caused by the small industry developing in the catchment of the analyzed WWTP. The highest chromium concentration was in Nadole, where the sewage system was made of chrome pipes.

Based on the obtained results it can be supposed that the concentration of heavy metals does not depend significantly on the dewatering time and stabilization of sludge but it depends on the quality of wastewater influent. This observation confirms the research conducted by Kołecka & Obarska-Pempkowiak (2008, 2013) and Nielsen (2011) in Danish STRBs. These systems treated sludge for a long time (from 7 to 15 years) and it was found out that the dewatering time and stabilization had an insignificant influence on heavy metals concentration. Although the time of sludge treatment was much longer in Danish systems, heavy metals concentration was similar to Polish ones.

The most important is that the analyzed heavy metals concentrations in sewage sludge from STRBs were significantly below the permissible values for the agricultural use.

Additionally it was found out that during long-term stabilization sewage sludge from STRB is safe in terms of sanitary properties (Nielsen, 2007). Reed in non-vegetation period dries and in this way it becomes the structural material. Thus, in STRBs the natural process of composting takes place. The research conducted by Nielsen (2007) shows that microorganisms in sludge from STRBs are significantly reduced within 3-4 months..

4. Lessons learned

Although Poland has a lower experience in comparison with other European countries some learned lessons can be formulated. The proper design and construction of the reed system is essential for its good operation. Even small mistakes can cause problems with the maintenance of the system. For example, using bad quality gravel for the filtration layer can result in clogging, wrong dewatering and the creation of anaerobic conditions, which, as a consequence, lead to decreasing the efficiency of dewatering and stabilization. Providing the right aeration is also very important. In some Polish facilities aeration was insufficient (for example in Gniewino). It has caused problems with reed, proper dewatering and stabilization. However, the problems connected with wrong aeration appear very often when the layer of sludge storage is rather high (about 50-60 cm). In case of lower height the air is able to diffuse into the depths of the deposited sludge. It is most important not to exceed the permissible value of sludge load, which is 60 kg DM/m^2/annual. If the sludge is of bad quality (high content of fat or low content of oxygen) this value should be lowered. The overload of the system would cause its improper work and even its destruction.

Polish experience shows that even the systems that do not meet the requirements of the amount of beds can work very efficiently. For example, although the reed systems in Nadole and Darżlubie had only 2 beds, the processes of dewatering and stabilization of sludge were very effective. It was caused by the low load of sludge discharged into the systems, as well as by long resting time. However, the solutions with lower numbers of beds can only be used for very small local wastewater treatment plants serving several hundred people.

In Poland there are no Polish companies which design and build STRBs. The offer of foreign companies is very often too expensive for wastewater treatment plants. So, they try to construct reed systems through trial and error, which often leads to faults in design and building and causes the incorrect operation of the systems.

5. Conclusions

Based on the findings and obtained results, as well as the review of the literature the following conclusions can be formulated:

1. In comparison with some European countries, Poland has a lower experience in the use of STRBs.
2. The obtained results indicate that this technology could be an economical and useful solution of the sewage sludge problem in small and medium-sized wastewater treatment plants.
3. The increase of the dry matter and the decrease of the organic matter shows that sewage sludge is dewatered and stabilized simultaneously.
4. The relatively high contents of nutrients and low concentrations of heavy metals cause that sewage sludge utilized in STRBs can be potentially a good fertilizer.
5. The proper work of STRBs requires the right design and maintenance.

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FIRST VERSION OF THE MANUSCRIPT - without correction

Polish experiences with operation of Sludge Treatment Reed Beds

Katarzyna Kołecka[*)], Hanna Obarska-Pempkowiak[**)],Magdalena Gajewska[***)]

[*)] katkolec@pg.gda.pl - corresponding Author

[**)] hoba@pg.gda.pl

[***)] mgaj@pg.gda.pl

Gdansk University of Technology , Faculty of Civil And Environmental Engineering

Narutowicza st. 11/12

80-233 Gdańsk, Poland

Abstract:

Sludge Treatment Reed Beds (STRBs) is technology of sludge treatment, which based on natural processes occurring in the environment in specially designed and operated facilities in order to achieve benefits for the environment. In reed systems integrated dewatering and stabilization occur. For economic and environmental reasons it is an attractive solution, especially on rural areas, where is lack of appropriate facilities.

In the recent years, many European countries like Denmark, France or Germany have applied this technology for sewage sludge management. Also Poland has some experience in dewatering and stabilization of sewage sludge in STRB systems.

The objective of the paper is to present the current experience and lessons learned of the operation as well as asses quality of sewage sludge from STRBs in Poland.

All analyzed sewage sludge was treated in STRBs located in six wastewater treatment plants: Darżlubie, Swarzewo, Zambrów, Nadole, Gniewino in Poland. Two of analyzed system had been working only in a pilot scale. Three from analyzed systems have not worked any longer. In collected samples of sludge the evaluation of dewatering and stabilization processes, fertilizer properties as well as heavy metals concentrations were determined.

Conducted research confirms that sludge treated in STRBs is dewatered and stabilized and could be used as fertilizer in agriculture.

Keywords: sewage sludge; dewatering; stabilization; nutrients; Sludge Treatment Red Beds (STRB)

1. Introduction

Sewage sludge is by-products of wastewater treatment processes. Since many years the systematic increase of sludge quantity is observed (CSO, 2013). It is supposed that this trend will be maintained in the next years (NWMP, 2014) due to still increasing the demand for improvement of treated wastewater quality. In the past in small and medium-sized WWTPs mostly sewage sludge management was limited to it storage. However since 2016 this kind of management is forbidden (Regulation from 2015, item 1277).

In Poland in the last years 13 facilities for thermal utilization of sludge has been built. However, due to very high cost this method is available only for very big WWTPs (approximately 500,000 pe - person equivalent). It is recommended (NWMP, 2014) that valuable elements (for example nutrients) from sludge from small and medium-sized WWTPs should be used in the environment.

c is technology which is used for preparing of sewage sludge for environmental purposes. This method also generates costs (connected with purchase of structural material) which are often too high for small WWTPs. What is more very often the quality of the compost is not adequate for agricultural application only for use in the non-agricultural purposes. And then the ratio for preparation of the material and potential cost of the final product is not economically reasonable.

Other technology which prepare sewage sludge to use it in environment is co-called Sludge Treatment Reed Beds (STRBs). Reed systems for sludge treatment simulate natural processes occurring in the environment in specially designed and operated facilities in order to achieve benefits for the environment. In reed systems integrated dewatering and stabilization occurs.

STRBs are typically built as ground objects with horizontal layers of gravel and sand mostly planted with reed. Very important is to build drainage system connected to the ventilation chimneys. This prevents the formation of anaerobic conditions and ensures properly conditions for dewatering and stabilization of sludge. During the operation of STRBs there are three periods (commissioning, full operation and emptying) (Kołecka & Obarska-Pempkowiak, 2008, 2013; Nielsen, 2003, 2011). During the first period of the operation commissioning one (which lasts about 2 years), dose of dry matter of sludge should be lower than designed values (Nielsen, 2003). During operating reed systems are periodically irrigated with sewage sludge with a low dry matter content (from 0.5% to 1.5%). Resting periods (breaks in sludge supplying) may take several days, depending on weather conditions, the age of a system, and the dry matter content in sludge as well as thickness of accumulated sludge (Nielsen, 2003). Before emptying bed should not be used for some time (preferably in summer) to increase the content of dry matter and also improve sanitary properties (Kołecka & Obarska-Pempkowiak, 2013; Nielsen, 2003; Troesch et al., 2009).

It is estimated that the maintenance cost of STRBs is only 10% of cost traditional solution used for sludge management (Nielsen, 2015). Additionally this is environmentally friendly technology which does not need the use of additional chemicals (e.g. coagulants or polyelectrolytes) and is characterized by low emission of gases (Brix et. al., 2001; Kołecka & Obarska-Pempkowiak, 2013; Olsson et al., 2014; Uggetti et. al., 2012). So, for economic and environmental reasons it is an attractive solution, especially on rural areas.

STRBs have been used in many countries for example in Denmark about 105 and in France 120 reed systems were built. These systems work also in Germany, Italy and Spain (Brix, 2017; Nielsen et al., 2014; Troesch et al., 2009; Uggetti et al., 2010). Poland has some experience in dewatering and stabilization of sewage sludge and septage in STRBs, too (Kołecka et. al, 2017; Karolinczak & Dąbrowski, 2017; Obarska-Pempkowiak et al., 2003, 2015a; 2015b; Pempkowiak & Obarska-Pempkowiak, 2002).

Based on years of research from Denmark, French, Spain, Italy and Poland (Kołecka & Obarska-Pempkowiak, 2008; Kołecka et al., 2017; Nielsen, 2003, 2011; Troesch et al., 2009, Uggetti et al., 2010, 2012) the recommendations for construction of STRBs was established. The main design factor is the sewage sludge loading rate (Uggetti, et al., 2010). This value for secondary sludge is approx. 60 kg DM (dry matter)· m^{-2}·$year^{-1}$. In case of sludge with a high content of fat or fermented substances the recommended loading rate is lower and equal to 50 kg DM$\cdot$ m$^{-2}\cdot$year^{-1}. To provide sufficient time for the transformations of accumulated sludge, the system of STRBs should consist of at least eight beds. More beds ensure longer resting period between supplying of sludge what leads to improving of the efficiency of dewatering and stabilization of the sludge. Sludge is supplied until the system reach the full capacity. The stabilization period is usually from 8 to 12 years.

The aim of the paper is to present the current experience of Polish STRBs. The main focus was on the quality of achieved material and its fertilizer value. Also important was the lesson learned from the period of operation of STRBs in Polish conditions.

2. Material and Methods

All analyzed sewage sludge was dewatered and stabilized in STRBs located in northern part of Poland. Some of them had worked only in pilot scale. The characteristic of these system is presented in Table 1.

Table 1. The characteristic of Polish STRBs

Localization	Swarzewo near Puck	Darżlubie near Puck	Zambrów near Suwałki	Nadole near Wejherowo	Gniewino near Wejherowo
Year of establishing	1994	1995	1997	2001	2011
Time of operation, years	3	5	4*)	9 and 3 years of resting**)	4

Amount of wastewater, m^3/day	4 000 in winter 6500 in summer	140	3500	80	845
Total area, m^2	2500	480	5500	150	2400
Number of beds/basins	1	2	1	2	6
Type of facilities	pilot	pilot	full-scale	full-scale	full-scale
Type of sewage sludge	excess sludge from conventional WWTP	sludge from Imhoff tank at the beginning of local WWTP and from household sedimentation tanks	excess secondary sludge from conventional WWTP	excess secondary sludge from conventional WWTP	excess secondary sludge from conventional WWTP
Average loading of sludge, kgDM/ $m^2 \cdot a$	31	38	62	33	55
Loading	3-4 times a year	8 times a year	in vegetation period	in vegetation period, every 3-4 weeks	in vegetation period, every 3 weeks
Status	not operating	not operating	in operation	not operating	in operation

*) the research concerning first period of operation (first 3 years)
**)during the resting period raw sludge has not been discharged

Three systems (located in Darżlubie, Swarzewo and Nadole) have not worked any longer. In case of Darżlubie and Nadole the WWTPs were closed due to the modernization of wastewater treatment namely connection of the catchment area of the treatment plant to the larger plant. Wastewater from WWTP in Darżlubie was connected to municipal sewage system and was discharged to the bigger WWTP located in

Swarzewo. The same was in case of Nadole where the wastewater was discharged to WWTP in Gniewino in 2010. In 1997 in Swarzewo layer of sludge about 4.5 m height was discharged to reed system as a results of operation problems in WWTP. This extremely excessive load caused serious damage in reed and destroyed the system. Reed system was not reconstructed. Now in Swarzewo sludge is composting. Zambrów basin with reed is still working and in this year it is planned to remove the sludge residue. Also the facility in Gniewino is still in operation and next new three beds planted with reed will be built to meet requirements.

In analyzed facilities the loading of sludge was below recommended values or exceeded them insignificant (Zambrów). Some operation problems in pilot objects was probably caused by low number of beds. Additionally to ensure right dewatering and stabilization at least 8-12 years of operation are needed. In pilot objects time of sludge treated was much shorter.

In paper following properties of sludge was analyzed: dewatering and stabilization process as well as fertilizing potential. To estimate above-mentioned properties dry and organic matter content as well as nitrogen, phosphorus and heavy metals concentrations were determined. All determination were carried out according to Polish Standards (PN-C-04537-14:1998; PN-EN 12879:2004; PN-EN 13657:2006; PN-EN 16169:2012) and APHA (2005). Determinations of selected heavy metals in the sludge were made by using atomic absorption after their mineralization.

Degree of mineralization was calculated as (Podedworna & Umiejewska, 2008):

$$M = 100 - \left(\frac{m.d.m_0 \cdot o.d.m_s}{o.d.m_0 \cdot m.d.m_s} \right) \quad (\%)$$

where:

$o.d.m_0$ – organic dry matter at the beginning of the process

$o.d.m_s$ – organic dry matter after stabilisation

$m.d.m_0$ – mineral dry matter at the beginning of the process

$m.d.m_s$ – mineral dry matter after stabilisation

The quality of sludge from three facilities (Darżlubie, Swarzewo, Zambrów) was presented based on our data from literature. Additionally the quality of sludge treated in STRBs in Nadole and Gniewino was determined in the laboratory of Faculty of Civil and Environmental Engineering in Gdansk University of Technology.

The samples of sludge from STRBs in Gniewino and Nadole were collected 3 times from the selected bed by using of a special probe in six points (Kołecka & Obarska-Pempkowiak, 2008; 2013). STRB from Gniewino all the time treats sludge while to facility in Nadole raw sludge was not discharge for 3 years. Then the samples of sludge was averaged for analyses. In Gniewino and Darżlubie the samples of sludge was collected along the vertical profile. The profile was divided into top and bottom layer. Sludge from bottom layer was treated longer than sludge from top layer.

3. Results and Discussion

3.1. Dewatering processes

In Poland, the average summer temperature is between 16.°C and 20°C, in winter between -6°C and 0°C. Average annual air temperature is 7 - 9°C (excluding mountain areas). Average rainfall is about 600 mm per year. Rainfall distribution is uneven throughout the year, 2/3 of annual precipitation is in summer (http://www.imgw.pl/).

The climate conditions are similar to Danish and they do not have the negative effect on dewatering process.

In all analyzed STRBs discharged sludge had high content of water which amounted from 95 to 99%. The highest content of the dry matter was found in sludge from Nadole (Table 2). Effective dewatering, higher than from mechanical equipment's, which is maximum 40%, has been obtained due to long time of operation. Also time when sludge was not discharged has influence on dewatering processes. The highest content of the dry matter (53.7%) was observed in Nadole which has the longest resting period (3 years). The lower content of dry matter was found in the sludge from Gniewino (11.2%), Swarzewo (14.0%) and Zambrów (17.5%). In Swarzewo the lower content of dry matter was caused by improper operation of object. While in case of Gniewino and Zambrów STRBs the relatively low content of dry matter is caused by regular discharging of new volume portion of sewage sludge (Table 2). Additionally in Gniewino there was some maintenance problems connected with wrong aeration and overload of system. Research conducted in Danish STRBs confirmed the high content of dry matter (from 20.3 to 29.3 %). These STRBs was in operation, however the long-term treatment (10-15 years) results in very good dewatering (Kołecka i Obarska, 2013). So effective dewatered is caused among other things due to plants transpiration.

Table 2. The average dry matter content in sewage sludge treated in STRBs based on own determination and (Obarska et al, 2003; Zwara & Obarska-Pempkowiak, 2000)

STRBs	**Darżlubie**	**Zambrów**	**Swarzewo**	**Nadole**	**Gniewino**
Time of operation, years	5	4	3	9 and 3 years of resting	4

Dry matter, %	41.6 ±8.6	17.5±1.2	14.0±2.5	53.7±6.4	11.2±6.87

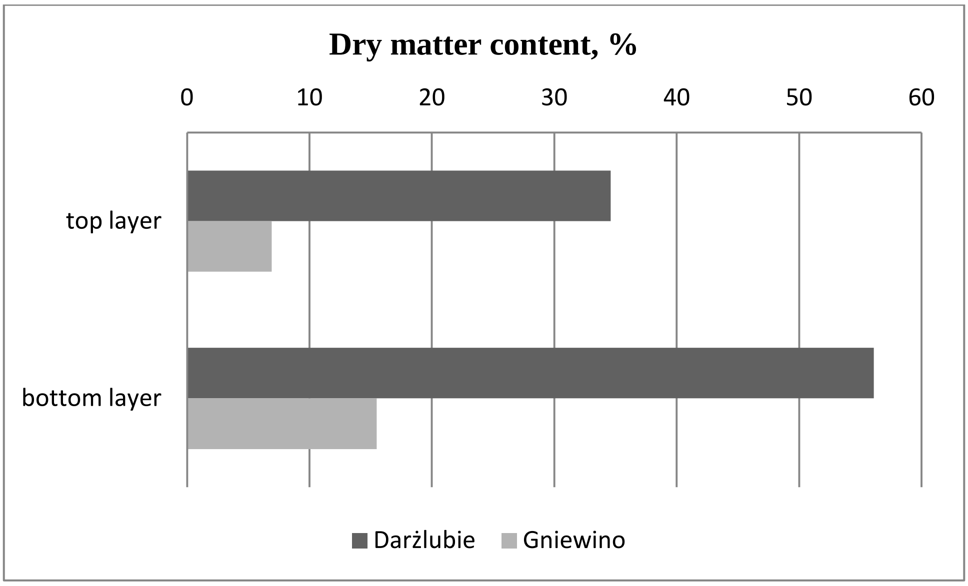

Fig. 1. Changes of dry matter content with depth in sludge treated in STRBs

It was also found that dry matter content increased with depth (Fig. 1). The top layer shorter dewatered had much lower content of dry matter than bottom layer which was dewatered much longer. The same results was obtained in Danish STRBs (Kołecka & Obarska-Pempkowiak, 2008, 2013).

Based on these results it can be concluded that to obtain the high dry matter content in sludge removed from STRB it is necessary to ensure time without discharging of sludge. The data from literature (Kołecka & Obarska-Pempkowiak, 2013; Matamoros et al., 2012; Nielsen, 2013; Stefanakis & Tsihrintzis, 2011) shows that the sludge dewatered in STRBs for a long time (10-15 years) can reach the dry matter content over 30%.

The increase of dry matter content connected with efficient dewatering caused the significant decrease of sludge volume (Fig. 2). In Darżlubie the initial volume decreased about 94.3% during 5 years, in Swarzewo 85.7% during 3 year in Zambrów 91.5% during 4 years and in Gniewino 80% during 4 years (Obarska-Pempkowiak et al. 2003; Zwara & Obarska-Pempkowiak, 2000). In Danish systems operated during 7-15 years the reduction of initial volume average reached 95 % .

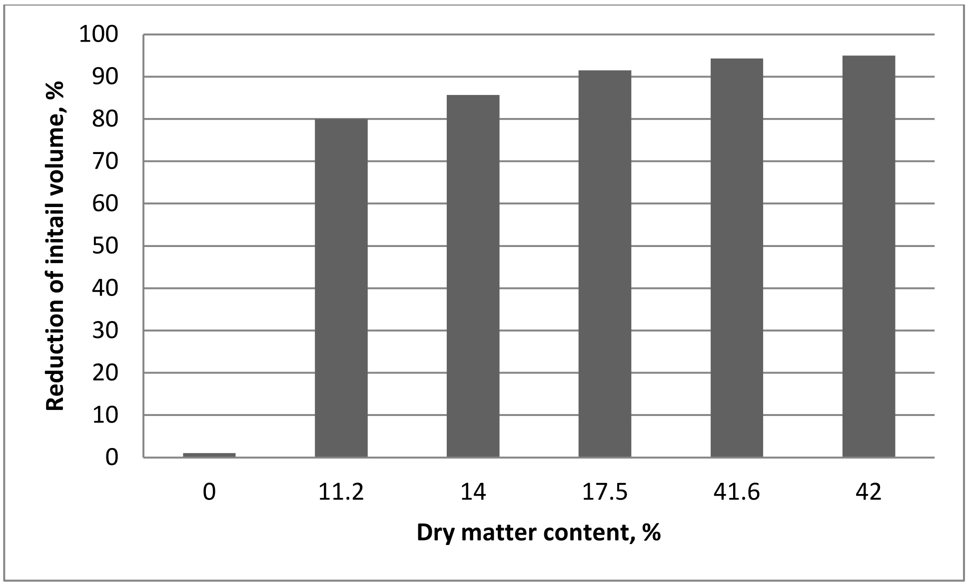

Fig. 2. The reduction of initial sludge volume in comparison to dry matter content in STRBs, worked out on research

Due to high reduction of sludge volume (Fig. 2) the reed beds can be used for a long time without removing of sludge residue.

3.2. Stabilization processes

Stabilization from the definition is a chemical or biological process that stops the natural decomposition of sludge. In STRBs this process occurs in natural condition and causes the decrease of organic matter. It is estimated that sludge with organic matter about 50% DM is stable.

In analyzed STRBS in Nadole and Darżlubie it could be assumed that sludge is stable (Table 3). In the sludge from Swarzewo STRB during three years of operation the organic matter content decreased about 15%. In Zambrów and Gniewino the average content of organic matter is above 50% DM. It is caused by regular discharging of raw sludge. However in Gniewino in bottom layer (the longest treated) organic matter content exceeded insignificantly 50% DM (Fig. 2). In comparison for all Danish facilities operated from 7 to 15 years the organic matter content was from 41.1 to 46.6 % DM (Kołecka & Obarska-Pempkowiak, 2013).

The degree of mineralization in analyzed systems was from 31.4 to 68.6 % (Table 3). The lower stabilization took place in facilities which was regularly fed with raw sludge (Zambrów and Gniewino).

Table 3. The average organic matter content in sewage sludge treated in STRBs based on own determination and references (Obarska-Pempkowiak et al. 2003, 2015a; Zwara & Obarska-Pempkowiak, 2000)

STRBs	**Darżlubie** after 5 years	**Zambrów** after 4 years	**Swarzewo** after 3 years	**Nadole** after 12 years	**Gniewino** after 4 years
Organic matter, %DM	45.3±3.2	64.4±7.9	60±5.6	50.1±4.4	62.2±9.8

Degree of mineralization, %	68.6	31.4	43.1	61.9	37.6

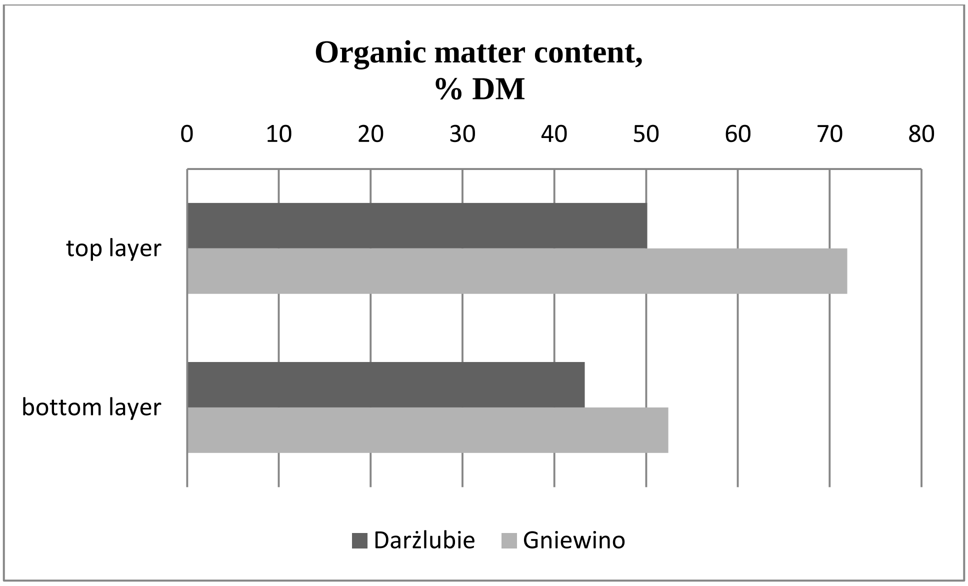

Fig. 3. Changes of organic matter content with depth in sludge treated in STRBs

It was found that the organic matter content decreased with depth of reed beds (Fig.3). In Gniewino in top layer (shorter processing time) the organic matter content was 62.2 % DM and it decreased to 52.4 % DM in bottom layer (the longer processing time). The same was in Darżlubie where the organic matter content decreased from 50.1 % DM (in top layer) to 43.3 % DM (in bottom layer). It indicates that in reed systems the process of stabilization occurs. Based on references (Kołecka & Obarska-Pempkowiak, 2008, 2013; Nielsen, 2007; Peruzzi et al., 2013; 2017) it could be assumed that sewage sludge should be treated in STRB at least for four years to ensure the correct stabilization and the right decrease of the organic matter content.

3.3. Fertilizing potential

The analyzed reed systems were characterized by different concentrations of nitrogen and phosphorus in sludge which underwent the processing (Table 4). The nitrogen concentration was the highest in Gniewino and in average amounted to 4.8% DM and in Swarzewo were it achieved even 10% DM. While the lowest concentration was in Nadole and it was 1.3% DM.

In case of phosphorus the highest concentration was again in Gniewino (average 3.5 % DM) and the lowest was in Darżlubie (average 0.24% DM). Based on results it can be supposed that the nutrients concentration depending on wastewater quality as well as technology of wastewater treatment. In STRBs with the highest concentration of nitrogen, WWTPs served the area where the food and dairy industry occurs. The influent of industry wastewater with high concentration of N causes the increase of it concentration in surplus sludge. The high concentration of phosphorus in sludge from Gniewino is probably caused by chemical precipitation of this element from wastewater.

Table 4. The average nutrients concentrations in sewage sludge treated in STRBs and in natural fertilizer based on own determination and references (Kołecka & Obarska-Pempkowiak, 2013; Obarska-Pempkowiak et al. 2003, 2015a; Pempkowiak& Obarska-Pempkowiak, 2002)

STRBs	Darżlubie	Zambrów	Swarzewo	Nadole	Gniewino	Manure, average
Nitrogen, % DM	2.35±0.09	3.90±0.7	1-10	1.31±0.40	4.8±1.2	1.5

Phosphorus, % DM	0.24±0.02	0.55±0.06	0.2-1	2.09±0.36	3.50±0.1	0.4

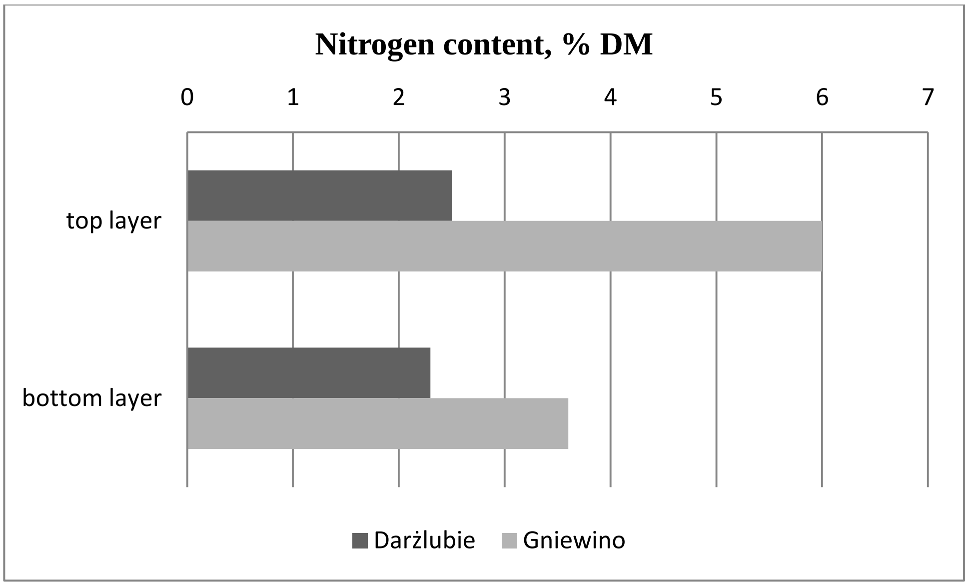

Fig.4. Changes of nitrogen concentration with depth in sludge treated in STRBs

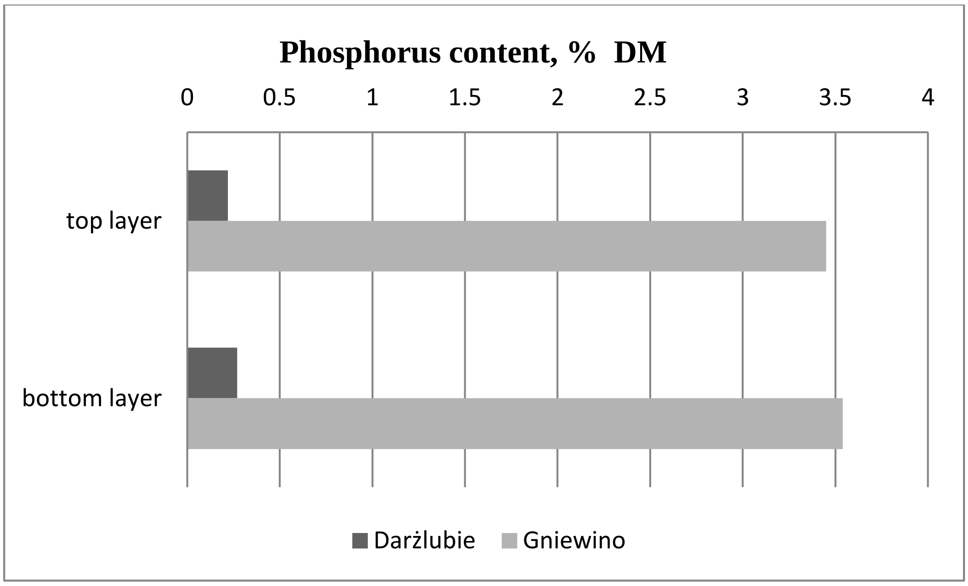

Fig. 5. Changes of phosphorus concentration with depth in sludge treated in STRBs

During treatment of sludge in STRBs the decrease of nitrogen and the increase of phosphorus concentration with depth occurs (Fig. 4 and 5). The changes of nitrogen are caused by nitrification and denitrification as well as mineralization processes. Long term treatment influences on the significant decrease of N concentration. However it concentration is mostly higher than in manure which is natural fertilizer. The increase of phosphorus concentration was probably caused by decomposition of organic matter in addition to a decrease in volume of stabilized sewage sludge. The concentration of P in majority of analyzed STRBs is also higher than in manure.

The same dependence was found in STBRs from Denmark (Kołecka & Obarska-Pempkowiak, 2008, 2013).

The sludge treated in STRBs are dewatered and stabilized as well as it is characterized by high concentration of nutrients, higher than in manure (natural fertilizer), that is why it can be considered as a potential fertilizer. However to use sludge for agriculture purposes the heavy metals concentrations need to meet the requirements of Regulation of the Minister of the Environment on municipal sewage sludge (2015). Fig. 6 presents the concentration of heavy metals in sewage sludge from STRBs in Poland.

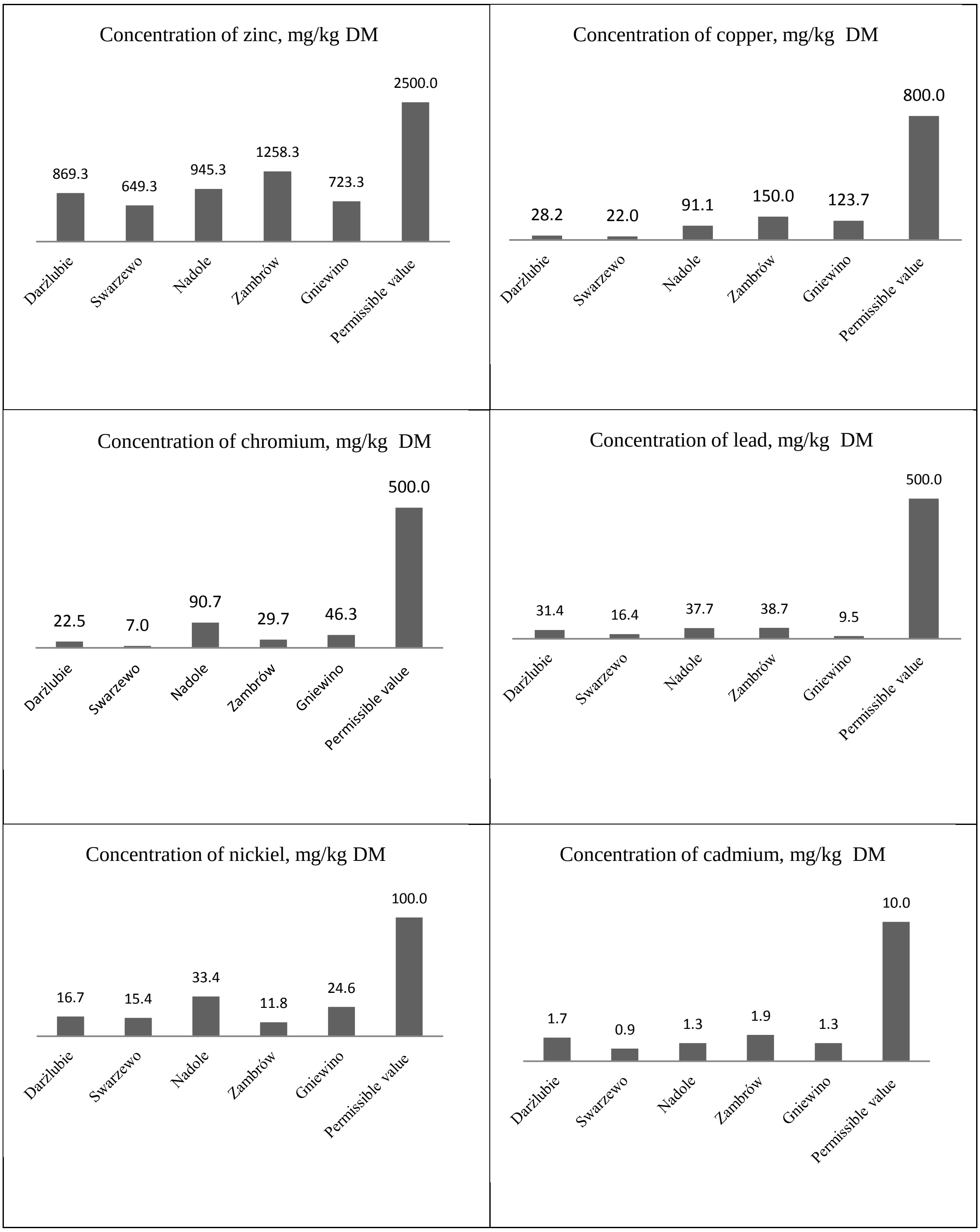

Fig. 6. Selected heavy metals concentration in sewage sludge from STRBs in Poland

The highest concentration of analyzed heavy metals (except nickel and chromium) was found in Zambrów. It was probably cause by small industry occurring in the catchment of the analyzed WWTP. The highest chromium concentration was in Nadole, where the sewage system was made of chrome pipes.

Based on obtained results it can be supposed that the concentration of heavy metals do not significant depend on the time of dewatering and stabilization of sludge and depend on the quality of wastewater influent. This observation confirms the research conducted by Kołecka & Obarska-Pempkowiak (2008, 2013) and Nielsen (2011) in Danish STRBs. These systems treated sludge for long time (from 7 to 15 years) and it was found that the time of dewatering and stabilization had insignificant influence on heavy metals concentration. Although the time of sludge treated was much longer in Danish systems, heavy metals concentration was similar to Polish systems.

The most important that it was indicated that analyzed heavy metals concentrations in sewage sludge from STRBs were significantly below the permissible values for the agricultural use.

Additionally it was found (Nielsen, 2007) that during long-term stabilization sewage sludge from STRB is safe in terms of sanitary. Reed in non-vegetation period dies and in this way supplies a structure material. Thus in STRBs natural process of composing takes place. Research conducted by Nielsen (2007) shows that microorganisms in sludge from STRBs within 3-4 months are significantly reduced.

4. Lesson learned

Although Poland has got insignificant experience in comparison to other European counters some lessons learned can be formulated. The proper design and construction of reed system is essential for it well-working. Even small mistakes caused problems with maintenance of system. For example using bad quality of gravel for filtration layer can results in it clogging, wrong dewatering and a creation of anaerobic condition, what leads in consequence to decreasing of efficiency of dewatering and stabilization. Also assurance of right aeration is very important. In some Polish facilities aeration was insufficient (for example in Gniewino). That has caused problems with reed as well as not proper dewatering and stabilization. However the problems connected with wrong aeration very often appear when the layer of storage sludge is rather high (about 50-60 cm). For lower height the air is able to diffuse into the depths of the deposited sludge. The most important is to not exceed the permissible value of sludge load which is 60 kg DM/m^2/annual. If the sludge is of bad quality (high content of fat or low content of oxygen) this value should be lower. Overload of system would cause it improper work and even it destruction.

Polish experience shows that even objects that do not meet the requirements of the amount of beds can work very efficiently. For example although reed systems in Nadole and Darżlubie had only 2 beds, the processes of dewatering and stabilization of sludge occurred very effective. It was caused by low load of sludge discharged into systems as well as long resting time. However, solutions with lower numbers of beds can only be used for very small local wastewater treatment plants serving several hundred people.

In Poland there is not Polish companies which design and built STRBs. The offer of foreign companies very often is too expensive for wastewater treatment plants. So, they try to construct reed systems by the process of trial and error. This often leads to errors in the design and execution and causes incorrect operation of the systems.

5. Conclusions

Based on carried out determination and obtained results as well as review of the literature following conclusions could be formulated:

1. In comparison with some European countries, Poland has insignificant experience with the use of STRBs.

2. The obtained results indicate that this technology could be economical and useful solution of the sewage sludge problem in small and medium-sized wastewater treatment plants.

3. The increase of dry matter and decrease of organic matter show that sewage sludge is dewatered and stabilized simultaneously.

4. The relatively high concentrations of nutrients and low concentrations of heavy metals cause that sewage sludge utilized in STRBs can be potentially a good fertilizer.

5. Proper work of STRBs requires right design and maintenance.

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