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## ANALYSIS OF AEROBIC AND ANAEROBIC SEWAGE SLUDGE DISPOSAL CONCEPTS

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**ABSTRACT:** The article aimed to analyze the concept of modernisation of sludge management prepared for an exemplary sewage sludge treatment plant. Four variants of solutions, based on different processes, aerobic (oxygenic), anaerobic or – aerobic – anaerobic, were discussed. The article presents the characteristics of essential elements of the proposed solutions. The technical and technological parameters of each of the variants are exposed. The expected capital expenditure and basic operating costs are presented. A cost-effectiveness analysis of the options has also been carried out. The analysed technological processes ensure obtaining hygienically and sanitary safe end products. They contribute significantly to minimising the amount of sewage sludge. The most economically efficient, with the lowest average annual costs, is the variant with the application of anaerobic thermophilic-mesophilic sludge stabilisation. The highest average annual costs were obtained for the variant with drying and incineration of sludge.

**KEYWORDS:** sewage sludge, sewage sludge treatment, sewage sludge management, capital expenditure, operating costs

## Introduction

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A by-product of a municipal wastewater treatment plant is the sludge that arises at different stages of its treatment. Almost the entire pollutant load entering the treatment plant is processed into biomass, which is subject to the Directive of the European Parliament and of the Council of 19 November 2008. 2008/98/EC on waste (the so-called Waste Framework Directive). In accordance with the principles of sustainable development, the sludge produced should be treated as a source of recovery, recycling of the main plant nutrients and not as waste. Municipal sewage sludge is slowly beginning to be appreciated by specialists as a raw material that can be successfully returned to the natural circulation in the form of organic fertiliser. They are considered to be one of the best soil additive fertilisers and are also a source of slowly releasing into the environment biogenic compounds and microelements. However, before they are used, they must be properly rendered harmless. Effective solutions for the management of sludge treatment plants should ensure the stabilisation of sludge and its hygienization while reducing its quantity.

In order to maintain the waste treatment hierarchy, when planning the construction or modernisation of wastewater treatment plants, consideration should be given to the use of appropriate technologies that reduce the quantity and ensure the quality of municipal sewage sludge produced. In addition, the processing of municipal sewage sludge understood as its final disposal, depends to a large extent on previous treatment processes. Therefore, the technical and organisational capacity of individual sewage treatment plants significantly influences the quality of municipal sewage sludge and, consequently, the ways it is treated. It should be stressed that in the case of newly built or modernised wastewater treatment plants, these possibilities should be determined as early as the stage of determining the directions of development of investments in water and wastewater management. Incorrect determination of direction, or incorrect assumption at this stage, may result in the sludge generated on the site of a treatment plant being unsuitable for use on the ground or for thermal conversion due to non-compliance with the required parameters. According to the regulations in force in Poland, the criteria for storing municipal sewage sludge in landfills and storage yards practically exclude such a possibility.

The aim of this article was to analyse selected concepts of sludge management and to indicate ways of handling municipal sewage sludge in accordance with the current legislation. It is also important to emphasise the possibility of using the biogenic substances contained in the sludge while meeting all the requirements concerning sanitary, chemical and environmental safety.

## Research methods

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For the purpose of this paper, a concept of sludge management in a municipal wastewater treatment plant was developed. Technical and technological calculations of the installation in all variants were made based on the following parameters:

- excess sludge mass of 11000 kg of dry matter per day;
- 1% concentration of dry matter in excess sludge;
- concentration of dry matter in the sludge after mechanical thickening 4-5%;
- organic matter content in the sludge is 80-85%.

The concept was performed in four variants.

## Characteristics of selected concepts

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Four variants of sewage sludge treatment were presented in the concept. Variant one provided for the use of autothermal thermophilic sludge stabilisation (ATAD). Variant two used an anaerobic stabilisation process. Variant three was developed using aerobic-anaerobic stabilisation. Variant four was prepared for a drying process with combustion.

### Variant I ATAD

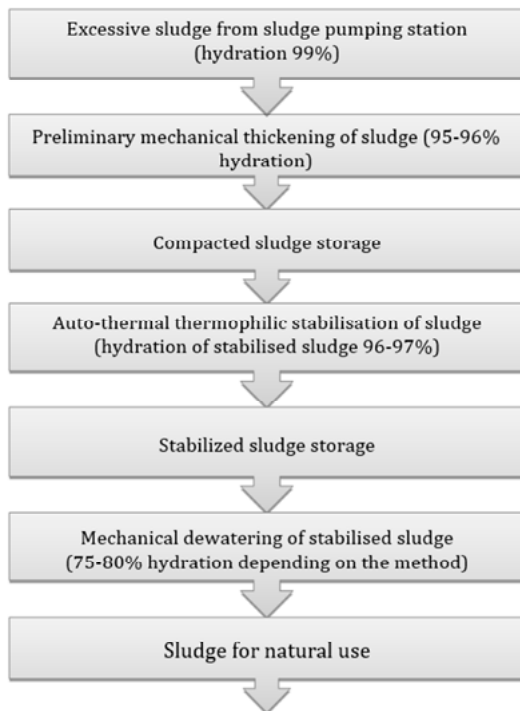
In the sludge mineralization system of the ATAD process, two first and second stage tanks are to be built in two process lines. The reactors are thermally insulated and closed to minimise the heat loss. Excess sludge from the pumping station will be directed directly to mechanical compaction. With the tanks connected in series, the temperature in the first stage of the installation is obtained in the lower thermophilic decomposition range, with maximum disinfection and the highest temperature in the last step. Daily discharge of inactivated sludge will take place only from second stage reactors. At the end of the next release, raw sludge will be fed to the first stage when the partially treated sludge is moved to the next reactor. The reactors will be equipped with aerators that provide a specific flow and control the amount of foam produced. In order to limit the temperature rise in the second stage reactors, heat exchangers will be installed, which will allow the excess energy to be used for the plant's own needs. The air discharged from the ATAD chambers will be purified in an installation consisting of a scrubber, a dryer and a photocatalytic oxidation module. Sludge stabilised after dehydration will be used for natural purposes. The scheme of sediment management is shown in

**Figure 1.** The primary technical and technological parameters of reactors in this variant of sludge management are presented in Table 1.

**Table 1.** Technical and technological parameters of ATAD reactors

Number of reactors	2 reactors of the first stage and 2 second stage reactors	Number of reactors
Reactor dimensions	First stage	Reactor dimensions
Length	25.2 m	Length
Width	12.6 m	Width
Total height	3.1 m	Total height
Height of filling with sludge	2.4 m	Height of filling with sludge
Active volume	1,524 m <sup>3</sup>	Active volume
The total dwell time of sludge in the installation	about 8.3 day	
Daily portion of sludge	275 m <sup>3</sup> /day	

Source: authors' work.



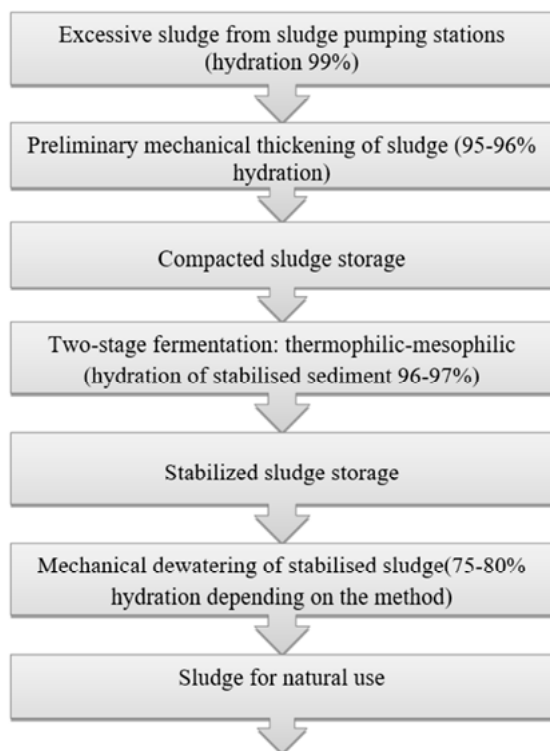
**Figure 1.** Scheme of sludge management using the ATAD process

Source: authors' work.

The odour deactivation installation envisaged in this installation variant will have a capacity of 4,200 m<sup>3</sup>/h.

### Variant II fermentation

In the anaerobic thermophilic-mesophilic sludge stabilisation system, two first- and second-stage digesters in two process lines are planned. Excess sludge from the pumping station will be directly sent to mechanical thickening. The thickened sludge will go to two thermophilic digesters in the first stage. After the process, the sludge will be directed through a sludge-sludge heat exchanger (recuperator) to two more second-stage mesophilic digesters. The first and second stage chambers will be equipped with circulation pumps and external heat exchangers; in the first case, the sludge will be heated to a temperature of approximately 55°C in the exchanger, while the exchanger of the second stage chamber will only be designed to maintain a temperature of 35°C. Stabilized sludge from the digesters will be dewatered.



**Figure 2.** Scheme of sludge management using the fermentation process

Source: authors' work.

The biogas produced in the fermentation process after desulphurisation will be collected in a diaphragm biogas tank, from where it will be directed to a boiler room equipped with a gas boiler and a cogenerator. Excess biogas will be burned in a flare. A diagram of sludge management for variant II is presented in Figure 2.

The basic technical and technological parameters of thermophilic-mesophilic fermentation reactors are presented in Table 2.

**Table 2.** Technical and technological parameters of thermophilic-mesophilic-fermentation reactors

Number of reactors	2 first stage reactors and 2 second stage reactors	
Reactor dimensions	First stage	Second stage
Diameter	10 m	15 m
Total height	12 m	16 m
Sludge filling height	9 m	13.3 m
Active volume	1,413 m <sup>3</sup>	4,698 m <sup>3</sup>
Total dwell time of sludge in the installation	5 days	17 days
Daily portion of sludge	275 m <sup>3</sup> /day	

Source: authors' work.

This variant of sludge management additionally requires the construction of a technological building with rooms for heat exchangers, a pumping station for sludge recirculation, and a fermentation gas installation and a power unit. It was also necessary to build a 1,000 m<sup>3</sup> biogas tank and a torch with a capacity of 180 m<sup>3</sup>/h.

### Variant III aerobic-anaerobic

In the aerobic-anaerobic sludge stabilisation system, four first-stage ATAD tanks and two second-stage mesophilic fermentation tanks are planned. Excess sludge from the pumping station will be directed straight to mechanical compaction. The thickened sludge will go through a recuperator (sludge-sludge heat exchanger) into four ATAD chambers. Each of the ATAD reactors will be equipped with an internal exchanger to be supplied with the heating medium. After the process, the sludge will be directed through a recuperator to the following two mesophilic fermentation chambers. Fermentation chambers will be equipped with circulation pumps and an external heat exchanger. Internal heat exchangers of ATAD chambers will be designed to replenish the heat necessary to obtain a sludge temperature of 60°C. The second stage chamber heat exchanger will serve to maintain the temperature of 35°C. Sta-

bilized sludge will be directed to the dewatering station. The biogas produced in the fermentation process, after possible desulphurisation, will be stored in a diaphragm gas tank, from where it will be directed to a boiler room equipped with a gas boiler and cogenerator. Excess biogas will be burned in a torch. The diagram of sludge management for variant III is shown in Figure 3.

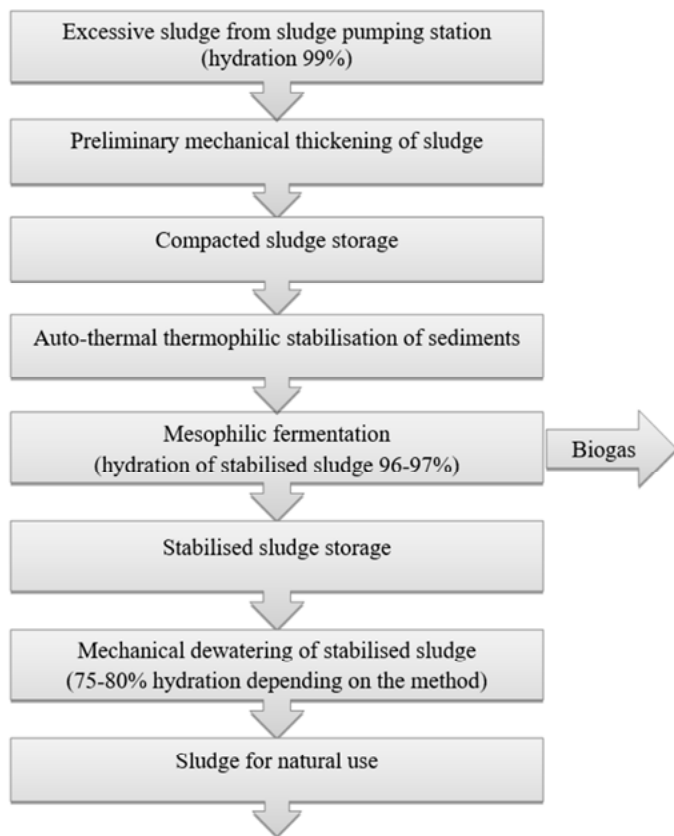


Figure 3. Scheme of sludge management with the use of the aerobic-anaerobic process

Source: authors' work.

The basic technical and technological parameters of the reactors foreseen in this option are presented in Table 3.

This variant includes the installation of odour deactivation from ATAD reactors with a capacity of 700 m<sup>3</sup>/h.

As in variant II of sludge management, the construction of a technological building with rooms for heat exchangers, a pumping station for sludge recirculation, a fermentation gas installation and a power unit is required. It is

necessary to build a biogas tank with a capacity of 1,000 m<sup>3</sup> and a flare with a capacity of 180 m<sup>3</sup>/h.

**Table 3.** Technical and technological parameters of aerobic-anaerobic reactors

Number of reactors	4 reactors of the first stage	2 reactors of the second stage
Reactor dimensions	First stage	Second stage
Diameter	6 m	14 m
Total height	3.3 m	16 m
Sludge filling height	2.5 m	13.7 m
Active volume	283 m <sup>3</sup>	4,216 m <sup>3</sup>
Total dwell time of sludge in the installation	1 day	15 days
Daily portion of sludge	275 m <sup>3</sup> /d	

Source: authors' work.

### Variant IV\_combustion

The system provides for constructing a common building for a sludge drying and combustion plant and a flue gas cleaning station. Excess sludge from the pumping station will be directed directly to mechanical thickening and dewatering. Thickened and dehydrated sludge will be directed to a medium-temperature dryer. The dried sludge will be transported to the next storage tank with a sliding bottom, from where it will be fed to the furnace with a screw conveyor. The burnt sludge in the form of slag will be collected in a tank, from where it will go to a waste dump. The diagram of variant IV sludge management is shown in Figure 4.

For the drying process, a belt dryer is provided, in which effective drying of sludge takes place thanks to the flow of process air heated in heat exchangers. The installation will be equipped with an exhaust air cleaning system consisting of a scrubber and biofilter. Sludge dried by means of a screw conveyor will be fed to the thermal mineralisation system. Flue gas treatment is provided in a scrubber and fluidised bed column. The sludge drying and mineralisation processes will be carried out in a 30 m x 18 m x 8 m building.



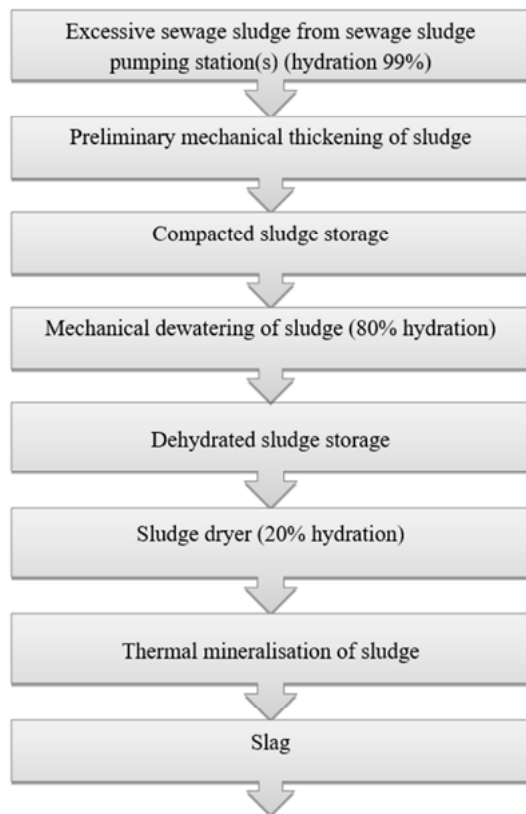


Figure 4. Scheme of sludge management using drying and combustion processes

Source: authors' work.

## Results of the research

When analysing concepts of modernisation or expansion of sewage treatment plant sludge management, it is challenging to neglect the structure of investment outlays or operating costs. Each of the presented variants, apart from technological effects, is characterised by different costs resulting from its implementation. Each variant also expresses different operating expenses. Table 4 presents the investment and annual operating expenses of the proposed sludge management solutions. The outlays are expressed in percent in relation to variant I. The capital expenditures were calculated for the conceptual design based on the costs of the facilities, equipment, installations, or construction and engineering works assumed in each alternative. Operating expenditures were calculated based on the price of electricity and its consumption, as well as the total power of the designed equipment and its oper-

ation time. The expenditures were expressed as a percentage with respect to Variant I.

**Table 4.** Basic investment and operating expenditures of the analysed technological solutions

Proposed variant	Capital expenditures (%)	Operating expenditures (%)
Variant I	100	100
Variant II	220	16
Variant III	204	27
Variant IV	386	151

Source: authors' work.

The highest investment costs are related to the implementation of variant IV. Also the operating expenses will be the highest in case of this variant. The lowest capital expenditure in the case of variant I is associated with high operating costs.

An important part of the operating expenses are the costs of electricity consumption. It is possible to assess individual variants on the basis of technical indicators giving the amount of electricity consumption in relation to the utility effect. Calculation values of indicators are given in Table 5.

The values of indexes have been established on the basis of measured actual values in other sewage treatment plants which operate the analysed technologies and on the basis of many years' experience of the authors. The quantities of sewage sludge processed in these treatment plants, expressed in kilograms of dry mass and volume of sludge, were taken as the useful effect.

**Table 5.** Electricity consumption indicators for the analysed variants of sludge management

Proposed variant	Energy consumption rate in relation to kilogram of dry matter of sludge (kWh/kg)	Energy consumption rate in relation to kilogram of dry matter of sludge (kWh/m <sup>3</sup> )
Variant I	0.565	22.582
Variant II	0.089	3.578
Variant III	0.092	3.680
Variant IV	0.589	23.564

Source: authors' work.

On the basis of the presented indicators, the technologies used in variant IV and variant I turned out to be the most energy-consuming solution.

Each of the proposed variants of sludge management of wastewater treatment plants should be supported by a multidirectional analysis, taking into account its impact on the local environment. Of particular importance here are methods of economic efficiency assessment, which are essential tools in the decision-making process for capital investments (Hunter et al., 2009; Molinos-Senante et al., 2010; Rashid & Hayes, 2011). In addition to determining the investment and operating costs, a Cost-Effectiveness Analysis (CEA) was carried out. In this method, costs are measured in monetary units, and effects are not subject to evaluation. The index of the average annual cost of sewage sludge processing was used to assess the cost-effectiveness of the analysed solutions. It depends on the size of capital expenditures and operating costs of the WWTP and the assumed helpful life of the WWTP, and the discount rate, which are taken into account in the value of the capital recovery factor. In accordance with the assumptions of the cost-effectiveness analysis, it was carried out assuming the same utilisation effect in all cases, which was taken to be the volume of sludge treated. This analysis ignores sludge quality criteria as well as other investment effects. The average annual cost of sewage sludge disposal can then be presented as the sum of the capital interest, depreciation and annual operating costs. Calculations are performed by taking into account the investment outlay and annual operational costs, the discount rate and the depreciation rate, taking into account the imputed lifetime (Karolinczak et al., 2015; Karolinczak & Miłaszewski, 2016).

The total average annual cost of sewage sludge treatment is calculated from the formula:

$$K_r = I\alpha + K_e, \quad (1)$$

where:

- $K_r$  – the function of the total average annual cost of sewage sludge treatment, which is expressed in PLN/year,
- $I$  – the function of investment outlays defined in PLN,
- $\alpha$  – the function of the capital return factor expressed in year<sup>-1</sup>,
- $K_e$  – the function of operating costs without taking depreciation into account in PLN/year.

The capital return factor is calculated from the formula:

$$R = \frac{r(1+r)^n}{(1+r)^n - 1}, \quad (2)$$

where:

- $r$  – the function of discount rate expressed in %,
- $n$  – the function of imputed lifetime expressed in years.

The assumed lifetime for all alternatives is  $n = 30$  years. The discount rate was assumed at  $r = 5\%$ . The value of capital and operating expenditure is explained in the commentary to the table (Miłaszewski, 2003). The calculation results for the concepts discussed are shown in Table 6.

**Table 6.** Summary of expected average annual costs of sludge processing in the analysed solutions of sludge management

Proposed variant	Average annual cost per kilogram of dry matter of sludge (PLN/kg)	Average annual cost in relation to sludge volume (PLN/m <sup>3</sup> )
Variant I	0.515	20.613
Variant II	0.385	15.385
Variant III	0.398	15.930
Variant IV	1.124	44.935

Source: authors' work.

The most economically efficient, with the lowest average annual costs, is variant II. The highest average annual costs will be obtained in the case of variant IV. For variant III, the average annual costs are similar to variant II.

## Results of application of the analysed solutions

The objectives of sewage sludge management are primarily to prevent the generation of sludge or, if this is not possible, to reduce its quantity. The aim should be to eliminate the generation of sewage sludge as waste, which due to its quality, poses problems with its management in accordance with the regulations, through thermal processing, application on the ground, production of fertilisers or plant growing aids, or other. Therefore, the solution of sludge management of wastewater treatment plants should aim at increasing the amount of sewage sludge processed before it is released into the environment and increasing the amount of sewage sludge subjected to thermal transformation. We should also strive to maximise the utilisation of nutrients contained in the sludge while meeting all sanitary, chemical and environmental safety requirements.

The analysed sludge management solutions are in line with the strategic objectives of sewage sludge management. The process of autermic trimophilic stabilisation makes it possible to obtain sludge that does not rot and is free of pathogenic microorganisms, parasites and fungi (Bartkowska, 2014; Bartkowska, 2015). It significantly contributes to minimising the amount of sewage sludge and allows the production of organic fertiliser instead of waste

(Bartkowska et al., 2019; Bartkowska & Dzienis, 2019). The spontaneous acquisition of high temperatures also allows for recovery and manage excess thermal energy.

The anaerobic mineralisation of sewage sludge proposed as a two-stage thermophilic-mesophilic process also fits with the recommended management objectives. Subjecting sewage sludge to anaerobic stabilisation under thermophilic conditions allows for sludge stabilisation and hygienization. Fermentation under thermophilic conditions is faster than under mesophilic conditions, which is associated with a reduction in process time (Zawieja et al., 2016). The thermophilic step represents the acidic fermentation stage in which the complex organic substances that constitute biomass are hydrolysed and converted to volatile fatty acids. In contrast, the mesophilic stage is adapted to the methanogenic phase, where volatile fatty acids are converted to methane and carbon dioxide, leading to effective sludge stabilisation (Grübel et al., 2014). The advantages of thermophilic methane fermentation are a higher degree of organic matter reduction, generation of more easily dewatered sludge, increase in pathogen destruction. The decrease in organic matter content and biogas production is also higher when raw sludge's dry matter content increases (Wang et al., 2014). Under thermophilic conditions, biogas production is intensified, with a simultaneous decrease in methane content observed (Zawieja et al., 2016; Shin et al., 2019). The two-stage anaerobic digestion process gives the possibility to obtain good quality parameters of digested sludge, and it is characterised by an increase in biogas production efficiency, a higher degree of sludge dry matter reduction and stability of the methanogenesis course.

The use of autothermal thermophilic stabilisation with mesophilic fermentation is a much less known method. However, this arrangement of the stabilisation process offers many advantages. First of all, it provides hygienization of the sludge, which is not possible with conventional mesophilic fermentation and increases its susceptibility to anaerobic stabilisation.

The proposed autothermal thermophilic stabilisation takes 24 hours in this configuration. Additional heating of the sludge to 60°C deactivates pathogenic organisms, parasite eggs and other microorganisms (Kato et al., 2003).

In the ATAD process, relatively rapid degradation of organic matter is achieved, active sludge cells are ruptured very efficiently because thermophilic organisms release enzymes that are particularly active in this regard (Cheng et al., 2016). In the first 24 hours of the ATAD process, there is mainly hydrolysis of complex organic compounds and partial decomposition, which results in a reduction of the organic dry matter content, but not more than 10-15%. During this time, substances released from activated sludge cells reach concentrations higher than those used for consumption by thermophilic microorganisms. An increase in chemical oxygen demand and organic

carbon content is observed. However, the important products of this stage are volatile fatty acids, which are mainly formed from the decomposition of carbohydrates and proteins. The partially processed sludge, rich in acetic acid and other forms of bioavailable organic carbon, is a good substrate for methane bacteria. This allows the anaerobic stabilisation time to be reduced to 15 days. The advantage of combining the two processes is the increased degradation of dry organic matter compared to the classical fermentation process (Pagilla et al., 2000). Changes in the amount and dynamics of biogas release are also obtained.

Pagilla et al. (2000), in their study of two-stage autothermal-thermophilic-anaerobic stabilisation, obtained a decrease in the organic matter content of sludge dry matter from 59 to 63%. Borowski and Szopa (2007) report that the two-stage system of autothermal stabilisation and fermentation results in a decrease in organic matter content of 44.2% on average. The loss of organic matter from combined ATAD and fermentation processes, according to Zupančič and Roš (2008), averages 53.5%. In other studies, the decrease in organic matter content due to combined ATAD and fermentation processes was shown to be 60-65% (Novak et al., 2011). Also, Novak et al. (2011) and Jang et al. (2013) obtained a decrease in organic matter content of 57-58%.

In parallel with the decrease in organic matter resulting from the dual stabilisation process, a decrease in chemical oxygen demand values was confirmed in the study. Jang et al. (2013; 2014), in their research, obtained a decrease in COD values of 65% on average after two stabilisation steps. With respect to the control sample, in which the sludge was only subjected to digestion, this decrease was greater by 15%. Pagilla et al. (2000) obtained a decrease in COD values in a two-stage mixed system of 67% on average. Zupančič and Roš (2008) reported an average decrease in COD values of 55.4%.

Microbiological studies of the sludge showed that the ATAD reactor was dominated by bacterial species that contribute to the hydrolysis of complex organic compounds, causing a significant increase in the methanogenic bacterial population in the digester. This interdependent activity of microorganisms leads to a significant increase in methane production (Jang et al., 2013; Jang et al., 2014). In their study, Jang et al. showed an increase in methane production by 40%. This is also supported by a study by Pagilla et al. (2000), which resulted in a 64% increase in methane production in a two-stage ATAD and fermentation system compared to a single-stage fermentation process. A similar increase in biogas production was observed by Borowski and Szopa (2007). In addition, Pagilla et al. (2000), in their study, found that biogas produced by fermentation following a prior ATAD process contains lower amounts of hydrogen sulfide. By preceding the fermentation with the ATAD

process, the retention time in the digester can be reduced by 30% (Borowski & Szopa, 2007).

Thermal transformation of sewage sludge allows the removal of organic components of sludge and pathogenic organisms and reducing sludge weight by up to 90% (Hudziak et al., 2012; Gawdzik & Latosińska, 2014; Payá et al., 2019; Sall et al., 2020). Harmful and hazardous substances are disintegrated into environmentally inert substances or transformed into more stable forms, minimising the risk of ecological hazards. However, the presence of heavy metals precludes natural utilisation. Meanwhile, ongoing studies show that the predominant form of heavy metals (copper, cadmium, chromium, nickel, lead and zinc) are their immobile combinations with aluminosilicates. Thus, the presence of heavy metals in sewage sludge is not an objective criterion for assessing the threat to the environment. Bearing this in mind, it should be mentioned that the metals immobilised in sewage sludge ashes do not pose a significant threat to the environment in the toxicological aspect (Gawdzik & Latosińska, 2014).

Although there are many installations for the thermal conversion of sewage sludge, the main problem of using ash as a by-product of the process is still unresolved. Under domestic conditions, the ash generated in the installations is mainly landfilled as hazardous waste. However, studies indicate the possibilities of ash utilisation. One of the directions is to use it in the production of cement, concrete or ceramics (Payá et al., 2019; Sall et al., 2020; Chin et al., 2016). The studied ashes in terms of silicon, aluminium, iron, calcium or phosphorus oxides content show great similarities to the cement composition (Sall et al., 2020). In another study, the authors showed that the addition of ash from sewage sludge incineration to cement mortar improves the compressive strength of the material (Chin et al., 2016).

Due to their phosphorus content, sewage sludge ash can be an alternative source of this element (Hudziak et al., 2012; Herzel et al., 2016; Hartmann et al., 2020). However, ongoing studies show that the bioavailability of phosphorus in sewage sludge ash is low (Herzel et al., 2016; Hartmann et al., 2020). However, researchers have developed a novel thermochemical treatment process for sewage sludge ash that converts the ash into marketable fertiliser products. Sewage sludge ash was thermochemically treated with sodium and potassium additives under reducing conditions, resulting in the conversion of phosphate-containing mineral phases to plant-available phosphates with high bioavailability of phosphorus (Herzel et al., 2016). Other studies indicate that ash from sewage sludge can be used to produce superphosphate fertilisers (Hartmann et al., 2020). It should be emphasised that obtaining phosphorus compounds from process waste remaining after sludge incineration is possible only in mono-combustion plants.

## Conclusions

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Good practice in municipal sewage sludge management can be defined as a set of methods for handling sewage sludge that effectively address the problem of sewage sludge treatment and management. At the same time, good effects of sewage treatment processes must be ensured. Sustainable development in the area of sewage sludge management should also be provided while maintaining the existing legal standards.

According to current legal standards, municipal sewage sludge can be recycled by using it in agriculture to grow crops and for fodder production. It is also recommended that sludge be used to grow crops intended to produce compost or plants not intended for food or feed production. Another recommended direction of their use is for land reclamation or land adjustment to specific needs resulting from waste management plans, spatial development plans or decisions on land development conditions.

The analysed sludge management concepts for the sample wastewater treatment plant fit into the canons dictated by legal standards. They are also consistent with the National Waste Management Plan 2022, which was adopted by the Council of Ministers on July 1, 2016. It should also be emphasised that they are modern and innovative solutions. Taking into account the location of the sewage treatment plant, there must be many willing potential customers for processed sewage sludge in the area. They declare to grow crops on which fertilisation with municipal sewage sludge is allowed. They have the appropriate equipment to spread and mix the sludge with the soil. They base their activities on the code of good agricultural practice. Restoring the nutrients accumulated in sewage sludge to the soil is not only economically appropriate but also necessary to maintain and repair the ecological balance. The examples discussed indicate just such a way of managing sewage sludge.

The conducted economic analysis showed that the investor would incur the lowest investment outlays when choosing variant I. However, it has to reckon with high exploitation costs. The highest investment and exploitation outlays are connected with picking variant IV. Despite that, it may turn out that the drying and burning method will be the final solution to the problem of organic waste.

Electricity consumption rates are lower with Options II and III. In this regard, Options I and IV are less favourable and will generate higher costs. The annual average costs of sewage sludge treatment will also be lower for variants II and III. On the other hand, the highest prices are expected for variant IV.



The proposed technological processes ensure obtaining hygienically and sanitary safe end products. They significantly contribute to minimising the amount of sewage sludge, particularly the variant with drying and incineration.

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## The contribution of the authors

Izabela Bartkowska – conception, literature review, acquisition of data, analysis and interpretation of data – 33,3%.

Dariusz Wawrentowicz – conception, literature review, acquisition of data, analysis and interpretation of data – 33,3%.

Lech Dzieńis – conception, literature review, acquisition of data, analysis and interpretation of data – 33,3%.

## References

- Bartkowska, I. (2015). Drop in dry mass and organic substance content in autothermal thermophilic aerobic digestion. *Process Safety and Environmental Protection*, 98, 170–175.
- Bartkowska, I. (2014). Influence of the sewage sludge stabilisation process on its oxidation-reduction potential value. *Environmental Technology*, 35(17), 2160–2166.
- Bartkowska, I., Biedka, P., & Tałałaj, I. A. (2019). Analysis of the quality of stabilised municipal sewage sludge. *Journal of Ecological Engineering*, 20(2), 200–208. <https://doi.org/10.12911/22998993/99306>
- Bartkowska, I., & Dzieńis, L. (2019). Utilization of sewage sludge after the process of autothermal digestion. *Journal of Ecological Engineering*, 20(8), 44–49. <https://doi.org/10.12911/22998993/110840>
- Borowski, S., & Szopa, J. S. (2007). Experiences with the dual digestion of municipal sewage sludge. *Bioresource Technology*, 98, 1199–1207.
- Cheng, J., Liu, Y., & Kong, F. (2016). Effects of cell lysis in gas yield and sludge stabilization by combined process of thermophilic aerobic and anaerobic digestion. *Procedia Environmental Sciences*, 31, 50–58. <https://doi.org/10.1016/j.proenv.2016.02.007>
- Chin, S. C., Ing, D. S., Kusbiantoro, A., Wong, J. K., & Ahmad, S. W. (2016). Characterization of sewage sludge ash (SSA) in cement mortar. *ARPN Journal of Engineering and Applied Sciences*, 11 (4), 2242–2247.
- Gawdzik, J., & Latosińska, J. (2014). Ocena immobilizacji metali ciężkich z popiołów ze spalania osadów ściekowych. *Inżynieria i Ochrona Środowiska*, 17(3), 415–421.

- Grübel, K., Kuglarz, M., Mrowiec, B., & Suschka, J. (2014). Zastosowanie wstępnej hybrydowej hydrolizy osadu czynnego dla zwiększenia efektywności dwustopniowej fermentacji metanowej. *Inżynieria i Ochrona Środowiska*, 17(2), 255–268.
- Hartmann, T. E., Möller, K., Meyer, C., & Müller, T. (2020). Partial replacement of rock phosphate by sewage sludge ash for the production of superphosphate fertilizers. *Journal of Plant Nutrition and Soil Science*, 183, 233–237. <https://doi.org/10.1002/jpln.201900085>
- Herzel, H., Krüger, O., Hermann, L., & Adam, C. (2016). Sewage sludge ash – A promising secondary phosphorus source for fertilizer production. *Science of The Total Environment*, 542 (B), 1136–1143.
- Hudziak, G., Gorazda, K., & Wzorek, Z. (2012). Główne kierunki w zastosowaniu popiołów po termicznej obróbce osadów ściekowych. *Czasopismo Techniczne*, 16, 41–50.
- Hunter, P. R., Pond, K., Jagals, P., & Cameron, J. (2009). An assessment of the costs and benefits of interventions aimed at improving rural community water supplies in developed countries. *Science of Total Environment*, 407(12), 3681–3685.
- Jang, H. M., Cho, H. U., Park, S. K., & Ha, J. H. (2014). Influence of thermophilic aerobic digestion as a sludge pre-treatment and solids retention time of mesophilic anaerobic digestion on the methane production, sludge digestion and microbial communities in a sequential digestion process. *Water Research*, 48, 1–14.
- Jang, H. M., Park, S. K., Ha, J. H., & Park, J. M. (2013). Microbial community structure in a thermophilic aerobic digester used as a sludge pretreatment process for the mesophilic anaerobic digestion and the enhancement of methane production. *Bioresource Technology*, 145, 80–89.
- Karolinczak, B., & Miłaszewski, R. (2016). Zastosowanie metod oceny ekonomicznej efektywności obiektów wodociągowych i kanalizacyjnych. *Rocznik Ochrony Środowiska*, 18, 770–782.
- Karolinczak, B., Miłaszewski, R., & Sztuk, A. (2015). Analiza efektywności kosztowej różnych wariantów technologicznych przydomowych oczyszczalni ścieków. *Rocznik Ochrony Środowiska*, 17, 726–746.
- Kato, S., Fogarty, E., & Bowman, D. (2003). Effect of aerobic and anaerobic digestion on the viability of *Cryptosporidium parvum* oocyst and *Ascaris* eggs. *International Journal of Environmental Health Research*, 13(2), 169–179.
- Miłaszewski, R. (2003). *Ekonomika ochrony wód powierzchniowych*. Białystok: Wydawnictwo Ekonomia i Środowisko.
- Molinos-Senante, M., Hernández-Sancho, F., & Sala-Garrido, R. (2010). Economic feasibility study for wastewater treatment: A cost-benefit analysis. *Science of The Total Environment*, 408(20), 4396–4402.
- Novak, J. T., Banjade, S., & Murthy, S. N. (2011). Combined anaerobic and aerobic digestion for increased solids reduction and nitrogen removal. *Water Research*, 45, 618–624.
- Pagilla, K. R., Kim, H., & Cheunbarn, T. (2000). Aerobic thermophilic and anaerobic mesophilic treatment of swine waste. *Water Research*, 34(10), 2747–2753.
- Payá, J., Monzó, J., Borrachero, M. V., & Soriano, L. (2019). Sewage sludge ash. In J. de Brito & F. Agrela (Eds.), *New Trends in Eco-efficient and Recycled Concrete* (pp. 121–152). Duxford: Woodhead Publishing.
- Rashid, M. M., & Hayes, D. F. (2011). Needs-based sewerage prioritization: event conventional cost-benefit analysis. *Journal of Environmental Management*, 92(10), 2427–2440.

- Sall, M., Gueye, P. M., Traoré, A., Diouf, S., Sy, M., Bouchez, G., Wade, A. C., Sané, M. L., Dieye, G., & Diop, D. (2020). Assessment of Fine and Coarse Sewage Sludge Ashes for Their Potential Use in Civil Engineering. *Journal of Civil, Construction and Environmental Engineering*, 5(4), 99–106. <https://doi.org/10.11648/j.jceec.20200504.13>
- Shin, J., Jang, H. M., Shin, S. G., & Kim, Y. M. (2019). Thermophilic anaerobic digestion: Effect of start-up strategies on performance and microbial community. *The Science of the total environment*, 687, 87–95. <https://doi.org/10.1016/j.scitotenv.2019.05.428>
- Wang, F., Hidaka, T., Uchida, T., & Tsumori, J. (2014). Thermophilic anaerobic digestion of sewage sludge with high solids content. *Water Science and Technology*, 69(9), 1949–1955.
- Zawieja, I., Wolny L., & Próba M. (2016). Efektywność generowania lotnych kwasów tłuszczowych podczas mezofilowej i termofilowej fermentacji metanowej osadów nadmiernych. *Inżynieria Ekologiczna*, 48, 226–232. <https://doi.org/10.12912/23920629/63267>
- Zupančič, G. D., & Roš, M. (2008). Aerobic and two-stage anaerobic–aerobic sludge digestion with pure oxygen and air aeration. *Bioresource Technology*, 99, 100–109.