

Management of sewage sludge energy use with the application of bi-functional bioreactor as an element of pure production in industry

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Abstract. The increase in sewage sludge makes it necessary to improve the direction of sewage sludge management policy and disposal, which requires a larger amount of incineration or land reclamation. It was shown that the result of methane fermentation, which is a more complex process of extracting energy contained in waste. High costs of implementation of sludge processing technology and low efficiency of sewage treatment plants in which sewage sludge is insufficient to recover energy from them, have a negative impact on the development of energy generation from sediments. The model waste system for energy is characterized, which includes two stages. The proposed solution can be applied to small wastewater treatment plants and it is justifiable to use the concept of bi-functional bioreactors in which anaerobic and aerobic processes can be carried out with much lower construction and maintenance costs. The use of bioreactors allows to exclude the energy demand needed to stabilize sewage sludge at a low cost compared to the expenditure that is currently incurred by disposal. The proposed solution works perfectly with industrial plants, due to the possibility of their creation in the time of the creation and application of a circular economy.

1 Introduction

The management of sewage is associated with large expenditures on electricity, indispensable both to maintain the network (pumping stations) and to carry out the treatment process and subsequent management of generated wastes such as sewage sludge and fats [1].

Sewage management also involves the costs incurred for the development of infrastructure, improvement of treatment technologies or the application of generation technologies of energy contained in municipal sewage sludge [2].

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Sewage treatment plants in Poland can be divided into three types – mechanical, biological and those with higher removal of nutrients. In the years 2010 – 2016 there was an increase in the total number of municipal sewage treatment plants from 3136 to 3253, including the number of biological treatment plants (from 2263 to 2408) and treatment plants with higher removal of nutrients (from 814 to 826). In the analyzed period, we could witness a systematic decrease in the number of treatment plants of the lowest grade (mechanical) from 59 to 19 [1, 3]. The number of municipal sewage treatment plants set up in the years 2010 – 2016, broken up into particular types is presented in Table 1.

With the growing number of sewage treatment plants, the amount of produced sewage sludge increased from 526700 Mg of dry matter in 2010 to 568 300 Mg of dry matter in 2016. The main management directions of sewage sludge policy involve principally agriculture, land reclamation purposes, cultivation of plants for compost, thermal processing and landfilling.

Table 1. Sewage treatment plants in Poland in 2010 – 2016 acc. individual types.

Year	Sewage treatment			
	Total	Mechanical	Biological	With higher removal of nutrients
2010	3136	59	2263	814
2011	3143	55	2261	827
2012	3191	55	2316	820
2013	3264	39	2405	820
2014	3288	22	2446	820
2015	3273	20	2427	826
2016	3253	19	2408	826

Source: own elaboration based on [3].

Sludge for agricultural purposes is most commonly used in Poland. In 2016, it accounted for 20% of their volume. Thermal transformation is also an important technology for their recovery, which is now becoming a significant trend for neutralization with energy recovery. 18% of sludge volume is currently subjected to thermal processing. The problem of thermal processing of waste, requires a larger number of incinerators in Poland. In the years 2015 – 2017 only seven incinerators were built. Thermal technology requires the implementation of logistic solutions and the transport of sediments over long distances. According to the newest The EU Environmental Implementation Review, Country Report – POLAND (2017) Poland should prepare national and regional waste management plans that would move Poland towards prevention and recycling rather than creating incineration overcapacities. Other sludge management directions, such as landfilling, land reclamation or cultivation of compost plants, have marginal significance, accounting for 4% to 6% of all municipal sludge generated in 2016 [4].

The processing of sewage sludge with the application of any of the above methods is possible only after its former stabilization by composting or anaerobic processing and dehydration [5, 6].

When using sludge in the composting process, it should be mixed with a structure-forming material containing carbon. Methane fermentation is a more complex process, but it enables the extraction of the energy contained in the wastes [8]. The anaerobic sewage sludge treatment yields biogas as the main product. It contains about 67% of methane, 30% of carbon dioxide, up to 2% of hydrogen sulphide and water vapor. It is estimated that from 1 Mg of dry matter of sludge, 400 – 600 m³ of sewage gas of the calorific value of approx. 18 – 23 MJ/m³ can be produced [4]. As it has been demonstrated, sewage sludge is a much

better energy carrier than municipal waste, and its decomposition process can yield 90 – 200 m³ of biogas with the calorific value of 17 MJ/m³ [8]. Technological sewage discharged by particular types of mining into waters, into the ground or into the sewage system constitutes a significant percentage, and in the case of brown coal mining only into waters (surface watercourses). Brown coal mines discharge mine waters in the form of sewage, in the amount of about 49.8% of all discharged mine waters being discharged. Therefore, the problem of the possibility of using them is one of the elements of environment management in the mining enterprise.

2 Problem statement

The operation of sewage treatment plants, including technological processes and the transport of sewage by sewerage networks consumes a significant amount of electricity. It is estimated that nearly 35% of electric power of all municipal facilities is consumed by sewage treatment plants [9]. Biological treatment of sewage in the activated sludge systems requires the largest demand of electricity, which is at the level of 50 – 60%, and in some cases even up to 80% of gross electricity [10].

The costs incurred by the operation of a sewage treatment plant are not only confined to electricity, but they also comprise the disposal of wastes such as the content of sand filters, screenings, fatty wastes or sewage sludge, which should be properly disposed of [11]. When we consider all wastes, it is sewage sludge that constitutes the largest budget burden in waste management costs at sewage treatment plants. A number of the sewage treatment plants in Poland have already been equipped with digestion chambers used for the production of biogas, which is then applied to produce electricity and heat in the incineration process in cogeneration units [12]. However, the process of methane fermentation creates another problem – the disposal of digestate, which should be dehydrated before its further use, and its collection, e.g. by biodegradable waste processing plant, should be paid for.

Most frequently, decanter centrifuges are used for the dehydration of sewage sludge, and for the drying process, solar and hybrid dryers or more complicated disk dryers with a heated rotor can be applied. In smaller sewage treatment plants located mainly in rural areas, due to the lack of financial resources, all electricity consumed by sewage treatment plants is purchased from external suppliers, and sewage sludge is only subjected to the dehydration process in centrifuges. Obviously, apart from expensive investments, what depends on the life cycle of the treatment plant involving the construction of technical infrastructure, also complex solutions involving modern control systems such as multi-threaded, hierarchical predictive control streamlining transformation processes must be taken into account [13].

Purpose of the research is to substantiate the energy use of sewage sludge with the application of bi-functional bioreactors.

3 Material and Methods

All wastes contain energy and have material values that can be properly taken advantage of by implementing appropriate methods for their processing. One of such methods is sewage sludge treatment system, reported to the Patent Office of the Republic of Poland, operating in a dual-purpose technological system in which electricity and heat are generated, yielding organic fertilizer as the final product. The technology of fermentation of sewage sludge and its dehydration or drying techniques are used. Additionally, management method of biogas produced from sewage sludge involves the production of energy in a cogeneration system

are used. The concept of bi-functional bioreactors is used, in which anaerobic and aerobic processes can be carried out with much lower costs of construction and maintenance of the infrastructure.

4 Results and Discussion

According to the statistics of the Energy Regulatory Office (URE), there were only 106 biogas plants producing energy from biogas generated in sewage treatment plants in 2016, which accounts for about 4% of all biological sewage treatment plants located in Poland [13]. The main causes accountable for this state of affairs can be attributed to problems with financing the construction of expensive sludge processing technologies and low capacity of sewage treatment plants, in which sewage sludge is generated in insufficient (unprofitable) amounts to retrieve energy from them. It is assumed that only at treatment plants having the habitat equivalent (EH) similar or higher than 100 000 units, the recovery and use of biogas can be profitable [14]. The management of municipal waste or other waste should be approached allowing for the economic and ecological aspects, considering also at the supranational and national levels of management of the global value chain [2, 15, 16].

The sludge processing system is contained in closed bioreactors, in which the process of biochemical gasification of high molecular organic substances such as proteins and fats is carried out in anaerobic conditions, followed by an intensified decomposition of organic matter by microorganisms under aerobic conditions.

Waste processing systems in bioreactors are acknowledged for the installations of Mechanical and Biological Processing of wastes (MBP) in which intensive biological decomposition of organic matter is carried out in aerobic conditions, but so far they have not been implemented for sludge management purposes at sewage treatment plants in Poland in the way presented by the team of researchers. The size of the installation (bioreactors) is selected depending on the volume of sludge produced daily, and practically there are no application limitations of the technology in terms of habitat equivalent (EH), in contrast to sludge processing in separate digesters (WKF).

Theoretically, for a sewage treatment plant generating annually only 1000 Mg (909 m³) of sewage sludge of an estimated density of 1.1 Mg/m³, 1 bioreactor 5m high, 5 m wide and 12 m long would be sufficient, loaded up to the maximum height of 2.5 m, which gives 150 m³ of sludge for 1 batch. The duration of sludge processing for both stages would be 42 days in total, so over the time period of one year, the maximum capacity of 1 bioreactor would be sufficient for 8 full cycles per year. To process 909 m³ of sludge, it would suffice to have 6 cycles a year. However, long retention time of sludge and the inability to process new material would be a problem as well as small daily volume of collected sewage sludge, which amounts to approx. 2.7 Mg (0.135 Mg of organic dry matter), which yields approx. 2.4 m³. This would mean that sludge feeding would last over 2 months. Therefore, for this type of treatment plant, it is advisable to use 7 bioreactors of the dimensions 3 × 3 × 3 m fed consecutively one after another to keep the continuity of sludge management.

4.1 Stage I – anaerobic fermentation

The processing of sludge was divided into two stages. In the first stage (the conceptual diagram of stage I is presented in Fig. 1), the sludge is loaded into the 3 × 3 × 3 m bioreactor by means of pumps to the optimum height of 1.9 m. The sludge retention time for the stage I is 21 days, during which the biogas is retrieved and supplied through the conditioning station, where the desulphurization and dehydration processes take place, to the spherical biogas tank and then to the cogeneration unit in which it is burnt.

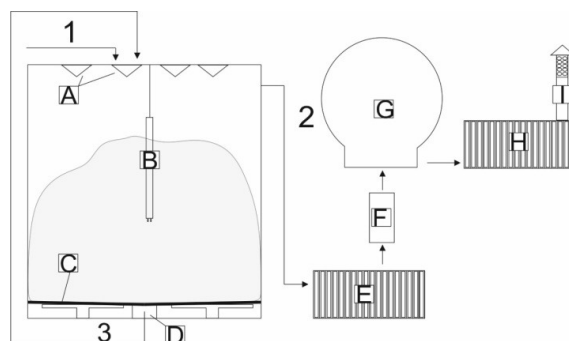


Fig. 1. Diagram of biological processing – stage I: 1 – Loading of sludge; 2 – Collection and transport of biogas; 3 – Recirculation of leachates; A – Pressure nozzles; B – Measurement probe; C – Flooring inclined towards the drain; D – Drainage duct of leachates; E – Container station of biogas conditioning; F – Dehydrator; G – Biogas tank; H – Container station with a cogeneration motor; I – Torch.

At the same time, the recirculation of leachate from the fermented sludge is carried on. It is delivered to the material being processed, using blast nozzles placed under the ceiling of the bioreactor. Process water under pressure penetrates the sludge and then gravitationally flows into the drainage duct. Such a method of water flow through the sludge brakes up the material and brings about an effect similar to that of mixing by means of mechanical stirrers known from standard sludge treatment processes in separate digester tanks WKF. This ensures a more efficient run of biochemical processes as compared to static treatment techniques, and it balances the temperature of sludge. The maintenance of constant temperature is extremely important in anaerobic processes, since each fluctuation of temperature slows down the process. And therefore, pipes have been installed in the floor, on the walls and on the ceiling, through which a liquid maintaining a constant temperature inside the bioreactor flows. Process water (leachate) is supplied to the nozzles from a heated tank while maintaining a constant optimal temperature. Temporary surpluses of biogas resulting from breaks in the operation will be burnt in a roof torch placed on the roof of the container station of the cogeneration module.

4.2 Stage II – intensive composting

The second stage (Fig. 2) starts with the supply of air along the channels installed in the bioreactor's floor. At the same time, the post-process air is extracted through the outlet in the bioreactor's ceiling and subjected to deodorization and treatment in a biofilter on a biological deposit consisting of 6 layers alternately lined with deciduous root wood, coniferous root wood and pine bark. The effluents from the digestate are passed to the leachate tank from where they enter into a new cycle in order to inoculate the batch and accelerate the decomposition process.

After an initial desiccation, other biodegradable wastes (grass, leaves, food residues) should be added to the sludge, which helps to obtain the final product in the form of compost [17]. The wastes subjected to processing are sprinkled with seep liquid from previous processes in order to maintain optimal humidity. Maintaining the humidity within 40 – 50% is essential, because if the waste is dried too much, the processing of organic matter is much slower, similarly as in the case when the temperature is too low or too high.

The second stage lasts 21 days (7 days of initial drying, after which other wastes can be added to the sludge and mixed using a wheel loader, followed by 14 days of joint composting), and the dry matter content in the waste after this stage is within 50 – 55%.

The processed waste are unloaded with an electric wheel loader, passed through the entrance gate and deposited in piles. Obviously, depending on the type of waste added to the sludge, the duration of the composting process may be longer. Such wastes as shredded branches or leaves need much more time to undergo full decomposition.

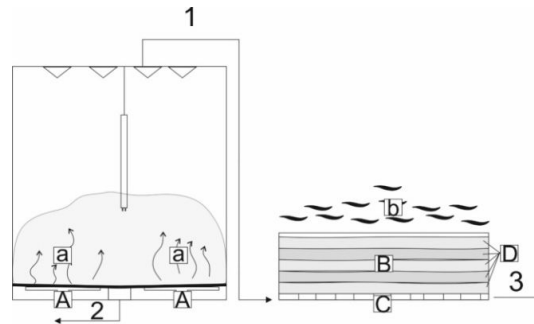


Fig. 2. Diagram of biological processing – stage II: 1 – Intake and transport of post-process air; 2 – Intake and transport of sludge leachate; 3 – Intake and drainage of condensed water vapor; a – Air flow trough the processed sludge; b – Evaporation; A – Aeration channels; B – Biofilter; C – Drain channel; D – Layered biological deposit.

4.3 Biogas parameters and the amount of produced energy

In order to determine the composition of biogas produced by methane fermentation of municipal sludge and its calorific value, the biogas produced in laboratory conditions was tested. The representative sample was collected from the municipal sludge at the sewage treatment plant located in the country of Nowy Sącz, having the actual capacity of 500 m³/day. The results of the tests are presented in the Table 3. The obtained test results are similar to those presented in the literature [11].

Table 2. Composition of biogas from sewage treatment plants and its calorific value.

Measured quantity	Unit	Value
Content of CH ₄	%	63.1
Content of CO ₂	%	36.4
Content of N ₂	%	0.3
Content of O ₂	%	0.2
Concentration of H ₂ S	mg/m ³	796
Calorific value	MJ/m ³	21

Source: own elaboration on the basis of research results.

The value of the dry matter of sludge in 1 000 Mg of “fresh” sludge is 50 Mg. From 1 Mg of organic dry matter 450 m³ of biogas of the calorific value of 21 MJ/m³ can be produced in the bioreactor processing technology, which yields 22 500 m³ of biogas per year (1). Biogas production per year:

$$\frac{50 \text{ Mg} \cdot 450 \text{ m}^3}{1 \text{ Mg}} = 22\,500 \text{ m}^3 \quad (1)$$

Electric power production per year:

$$22\,500 \text{ m}^3 \cdot 21 \frac{\text{MJ}}{\text{m}^3} \cdot 0.000278 \frac{\text{MWh}}{\text{MJ}} = 131 \text{ MWh} \quad (2)$$

The production of 131 MWh of electricity per year (2) is sufficient to close the annual energy balance sheet with a positive result, because the demand of the installations about 110 MWh/year. It means that the produced amount of sludge is able to finance its processing, leaving a surplus of electricity to be used to charge the batteries of the electric wheel loader.

4.4 Heat circulation in the process

In the processing of municipal sludge in the system of bifunctional bioreactors, along with the combustion of biogas in a cogeneration engine, several heat sources can be distinguished: heat generated in the bioreactor during anaerobic degradation of the biodegradable fraction; heat from post-process air; heat resulting from the combustion of biogas in the cogenerator. Depending on the waste processing stage, a different temperature is required to ensure that the process is carried out correctly. In the first stage, carried out at the thermophilic temperature, it is essential to reach 50 °C as soon as possible and maintain it until the end of this stage. Therefore, the heat should be supplied through the piping system placed in the floor, ceiling and walls of the bioreactor and by spraying process water (leachate devoid of suspensions) at a suitable temperature. The temperature of processed waste as a result of biological changes automatically begins to increase, and after 3 – 5 days the heat must be discharged outside [18, 19].

In the second stage, hot air must be supplied for initial sludge drying, its hygienization (required temperature of at least 70 °C for 7 days) and faster composting (the temperature of 50 °C). The heat from the post-process air discharged to the biofilter is delivered to the low temperature heat accumulator (LT), which also accumulates heat from the first stage. The thermal energy generated in the combustion process in the cogenerator is supplied to the high temperature heat accumulator (HT) and for domestic purposes. The block diagram of heat circulation in the installation of bifunctional bioreactors is presented in Fig. 3.

The heat from the LT accumulator is used to heat the bioreactor and the tank of filtered leachate, while the heat energy from the HT accumulator is used to heat the air injected into the bioreactor in the second stage, and if necessary to support the heating of the LT accumulator [20, 21].

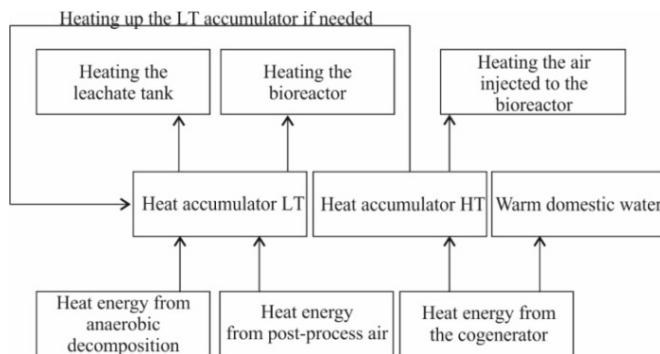


Fig. 3. Block diagram of heat circulation in the process.

4.5 Water circulation in the process

The applied waste processing technology in bioreactors is practically self-sufficient in terms of water use. The leachates from the fermented sludge as well as the leachates from the composted waste are passed through the treatment station to the heated tank from where

they are collected to the process [22]. The block diagram of water circulation in the process is presented in Fig. 4.

Clean (cool) water is collected if it is needed, only to ensure the right temperature of water supplied to the process. It mixes with warm water to the preset temperature.

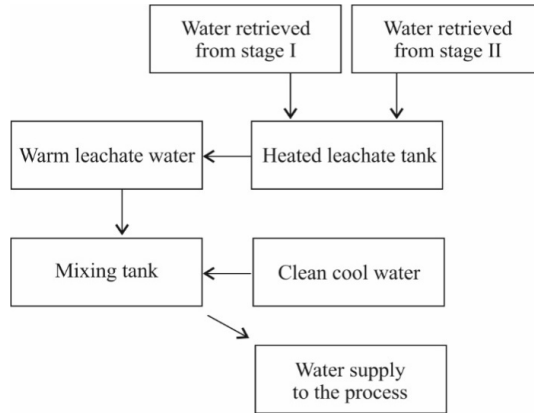


Fig. 4. Block diagram of water circulation in the process.

4.6 Final product

After the mixing process of sludge with other wastes and their joint composting, the sludge loses its waste status and becomes a fully-fledged compost that can be introduced into the overall circulation when it meets the requirements set out in the Act on fertilizers and fertilization [23], and the already mentioned Regulation on the implementation of certain provisions of the Act on fertilizers and fertilization. The final content of such components as phosphorus, nitrogen or potassium depends on the material that is added to the sewage sludge. In addition, when adding leaves, shredded branches or bark, it may be necessary to screen the treated waste to extract non-composted fractions.

Screening should be carried out on a rotating screen with the mesh width of 0 – 20 mm, which yields 2 waste fractions: 0 – 20 mm – ready compost; 20 mm – non-composted fractions returned again to composting in the bioreactor together with “fresh” waste.

The advantage of mixing the pre-composted waste with new material is that the decomposition of organic matter is accelerated.

The volume of 1000 Mg of sewage sludge (with the density of 1.1 Mg/ m³) is approx. 909 m³. To process such a quantity of sludge, theoretically 1 bioreactor of the dimensions 5 m in height, 5 m in width and 1m in length would be sufficient. It should be loaded up to the maximum height of 2.5 m, which gives 150 m³ of sludge per 1 batch. The duration of sludge processing for both stages was 42 days in total, so over one year, the maximum capacity of one bioreactor is 8 full cycles. To process 909 m³ of sludge, 6 cycles a year are sufficient.

However, the problem is that the retention time of sludge is long, it is not possible to process fresh material and the daily volume of collected sewage sludge is small, amounting to approx. 2.7 Mg (0.135 Mg of dry organic matter), which is approx. 2.4 m³. This would mean that sludge loading would last over 2 months. Therefore, for this type of treatment plant it is advisable to use 7 bioreactors of the dimensions 3 × 3 × 3 m, fed one after another to maintain the continuity of sludge management.

To determine the content of heavy metals in municipal sewage sludge, a representative sample of sludge from a sewage treatment plant located in the country of Nowy Sącz, with

the actual capacity of 500 m³/day, producing yearly 1000 Mg of sludge with the 5% content of dry matter. The results of the research on raw sewage sludge are presented in Table 3, in which the permissible values in organic fertilizers supporting plant cultivation were also compiled, in line with the Regulation of the Minister of Agriculture and Rural Development on the implementation of some provisions of the Act on fertilizers and fertilization [24].

The tested sample of raw sludge meets the requirements involving the content of heavy metals (for the final product, i.e. organic fertilizer), and therefore the sludge can be successfully subjected to composting. The contents of chromium, nickel and lead were well below the permissible level, while cadmium and mercury were not found at all [25].

The said regulation does not permit the presence of the living eggs of enteric parasites *Ascaris* sp., *Trichuris* sp., *Toxocara* sp. or bacteria of *Salmonella* type in fertilizers. The sludge was not subjected to biological testing because the presence of these bacteria is certain, but as it was proved, high-temperature oxygen treatment of sludge leads to its full hygienization.

Table 3. Content of heavy metals in tested raw sludge and permissible values.

Metal	Representative sample	Permissible values
	Result [mg/kg of dry matter]	
Chromium (Cr)	12.5	100
Cadmium (Cd)	0	5
Nickel (Ni)	47	60
Lead (Pb)	7.1	140
Mercury (Hg)	0	2

Source: [24].

5 Conclusions

Based on the analysis of the use of the concept of bifunctional bioreactors, the following inferences can be drawn.

Larger sewage treatment plants in Poland have already been modernized, facilitating in this way the extraction of the energy potential contained in sewage sludge, thus contributing to the reduction of financial expenditures for electricity and heat. However, despite the commonly recognizable technology of fermentation of sewage sludge and its dehydration or drying techniques, only a small part of the sewage treatment plant has been adequately equipped. According to the statistics provided by the Energy Regulatory Office in Poland, there are only 106 biogas plants that process biogas from sewage treatment plants (as of 31/12/2016), which accounts for about 4% of all biological treatment plants.

The main obstacle hampering the development of the energy potential of sewage sludge is the financial aspect related to the construction and operation of relevant infrastructure whereof costs can amount to tens of millions of PLN. The problem of high costs generated by such installations can be solved by the concept of bi-functional bioreactors presented by the authors, in which anaerobic and aerobic processes can be carried out with much lower costs of construction and maintenance of the infrastructure. The use of bioreactors allows to shut off the demand for energy needed to stabilize sewage sludge at low costs as compared to the expenses that are currently incurred by its disposal.

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