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Investigation in Techniques for Using Sewage Sludge as an Energy Feedstock: Poland's Experience

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Abstract. The sludge generated from wastewater treatment facilities contains high nutrients and is characterized by high heating values. Thus, the sludge enriched with organic matter and nutrients is a potential candidate for its application as fertilizers and an alternate energy feedstock. Nowadays, energy independence contributes to the economic stability of the country, and therefore the search for alternate energy sources is an acute issue. This paper presents a case study on using sewage sludge as an energy feedstock in Poland. The physicochemical characteristics of the sewage sludge are presented. The fuel properties of sewage sludge generated from different waste water treatment plant (WWTP) are summarized. The calorific value of sewage sludge generated in Poland is insufficient for effective use as an energy raw material, therefore, energy potential of mixture of sludge with other waste have been studied. The general trend of sewage sludge formation and the quantitative forecast for the future showed that in 2020, compared to 2012, sludge accumulation increased by 6.9%, but compared to 2019 – decreased by 3%. From 2012 to 2020 the average, sewage sludge accumulation increased annually by 0.8%. This demonstrates the heterogeneity of waste streams for the production of alternative fuels and a modest increase in sewage sludge production in the coming years. This made it possible to prepare several options for the further development of research in the field of developing technologies for obtaining alternative energy. Also this study will help the prospective researchers understand sewage sludge generation and its use as energy feedstock.

Key words: waste, sludge, raw material component, use, alternative energy.

1. Introduction

An acute problem of the modern world is the energy independence of the state. Access to environmentally friendly modern energy services ensures the economic growth of the country and the social development of its citizens. The driving force behind sustainable energy supply is the search for cheap alternative energy sources.

In the same time, the problem that accompanies the treatment of industrial and domestic wastewater is the specific waste generated in the treatment process in the form of sewage sludge. The dynamic development of the construction and expansion of sewer networks and municipal WWTP, noted in recent years in Poland, leads to the formation of wastewater requiring treatment and subsequent generation of a significant amount of sewage sludge. From 2000 to 2020, the amount of industrial and municipal wastewater requiring treatment decreased by about 12% (GUS, 2021); however, from 2011 to 2018, this amount increased by 5.6% (PGW, 2019), and in 2019–2021 was about the same (GUS, 2021). Although the amount of sludge formed is approximately 1–3% of the volume of wastewater (Czekała et al., 2017), the use of modern and efficient WWT technologies leads to increase in the sludge amount.

In recent years in Poland, there has been a change in the WWT approach. Highly efficient WWT technologies have replaced the mechanical pollutants removal methods with the deep removal of nitrogen and phosphorus compounds (Fig. 1) (GUS, 2021). From 2000–2020, the share of mechanically treated wastewater decreased by 37%, and the amount of wastewater treated at WWTPs with increased nutrient removal more than doubled. In 2020, the amount of wastewater requiring mechanical treatment was 461.0×106 m^3, 22% of treated wastewater, and the amount of wastewater subjected to post-treatment was 1156.7×106 m^3 (56% of wastewater is treated) (GUS, 2021).

According to data published by the Central Statistical Office, in 2003, 447 thousand tons of dry matter of municipal sewage sludge was created in Poland, and in 2018 this amount was 583 thousand tons (Stanowisko Izby, 2019).

The resulting sludge can pose a potential threat to the environment if not handled properly, as it contains, among other things, heavy metals, pathogens, and even pharmaceutical compounds that cause hormonal imbalances, especially in reproductive processes, and also lead to increasing the drug resistance of microorganisms (Khan et al., 2021; Husain Khan et al., 2021). The urban sewage sludge is characterized by technological properties such as fermentation capacity, filtration, fuel, and fertilizer properties (Bień & Wystalska, 2011). Therefore, sewage sludge enriched with organic matter and nutrients can be used as a renewable energy source to strengthen the energy sector of the country (Staśkiewicz & Lelicińska-Serafin, 2020; Rećko, 2020). In turn, this will increase the economic opportunities of the country with the prospect of creating new jobs and improving the well-being of citizens. The amount of sewage sludge is expected to increase due to the growing demand for water in households and industry and due to the introduction of more efficient wastewater treatment technologies. The present study aims to determine the prospects for using sewage sludge for energy recovery in Poland and develop recommendations for further research.

2. Methodology

The review used open scientific publications. Relevant keywords in Polish were used for Google Scholar searches. The filter was configured as follows: publication date – from 2017, order – by relevance, type – any articles, including citations. Articles in Polish were selected, preference was given to publications with the highest citation. There were no restrictions on the ranking of scientific publications,

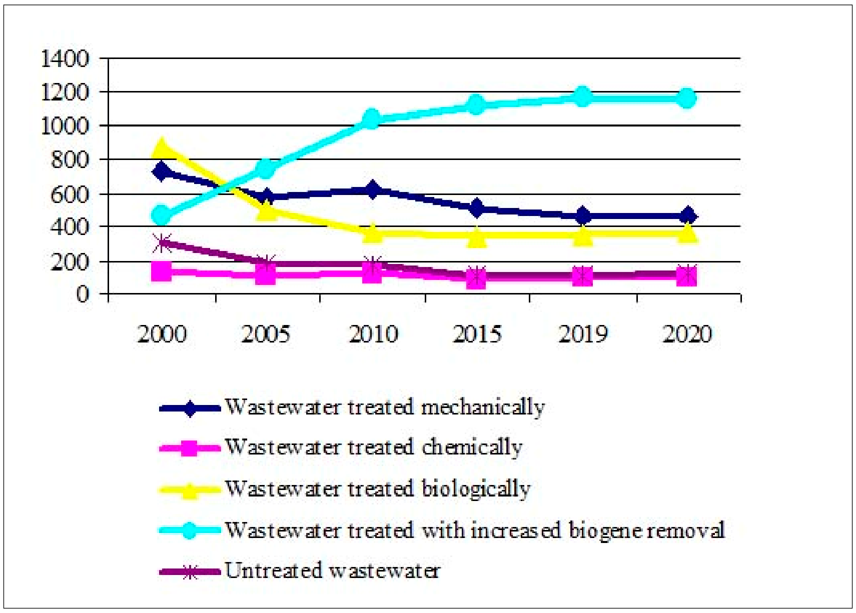

Figure 1. Industrial and municipal wastewater requiring treatment discharged (GUS, 2021)

indexing of publications in scientific databases, the number of pages of publication, etc. However, scientific publications, selected articles were checked against the criteria that all non-predator scientific publications must meet, such as the presence of ISSN , DOI, information about the publisher and edition, Certificate of state registration, a clear procedure for reviewing articles and accepting or rejecting them, etc. Where appropriate, studies were considered that were identified in the reference list by reviewing the selected sources and that did not meet the above criteria (e.g., year and language of publication) if it contained useful information for the current study. Analysis and synthesis methods were used to study the properties, potential of sewage sludge and factors that determine the suitability of sludge for use in various energy recovery processes, as well as to develop recommendations for further research. The statistics on the generation and use of sewage sludge are collected from the reports of the relevant government agencies, which are posted on their official websites. The study of the dynamics' development of the situation with the formation and use of sewage sludge, as well as forecasting their amount for the coming years, was carried out using methods of mathematical statistics. Indicators of dynamics series' analysis were determined, which characterize the intensity of changes in the amount of sludge formed. To compare the levels of the series, the following indicators were calculated: absolute increase; absolute growth rate (characterizes the absolute growth, measured in relative terms (%) and shows how much the compared level has changed in relation to the level taken as the basis for comparison); growth rate (growth factor), which characterizes the ratio of two levels of the series and can be expressed as a coefficient or as a percentage, determines what absolute value is hidden behind the relative indicator – one percent growth.

The logical chain of research is as follows:

- Studying the properties of Polish sewage sludge as waste,
- Possibilities for energy recovery from sewage sludge,
- Analysis of the general trend in the formation of sewage sludge in Poland and a quantitative forecast of the situation for the coming years,
- Based on the information received, draw conclusions, determine the prospects for the future and develop recommendations for further research.

3. Characteristics of Polish sewage sludge

The chemical composition and physical properties of sewage sludge are variable and depend on the type of wastewater being treated and the treatment processes used (Chalamoński & Szymczak, 2017). Sewage sludge is defined as the organo-mineral solid phase separated from wastewater or as a mixture of water and solid particles from various types of wastewater naturally or artificially in urban WWTPs (Ministerstwo Środowiska, 2018). Urban sewage sludge is characterized by its technological properties, such as fermentation capacity, filtration, fuel, and fertilizer properties (Bień & Wystalska, 2011; Staśkiewicz & Lelicińska-Serafin, 2020).

The sludge contains a significant amount of organic matter, nitrogen, phosphorus, and trace elements (https://sozosfera.pl/nauka-i-srodowisko/nowe-perspektywy-przyrodniczego-wykorzystania-komunalnych-osadow-sciekowych/). Therefore, one of the ways to dispose of sludges is to use their valuable agronomic properties and their fertilizing potential. However, the availability of the nutrients depends on the method of obtaining the sludge. The application of these components to the soil along with the sludge must be carried out in compliance with the generally applicable rules for applying fertilizers while respecting the management of environmental protection, including, in particular, soil and water protection. Although the presence of nitrogen, magnesium, and phosphorus in sewage sludge meets the needs of plants in fertilizers (Włodarczyk et al., 2014), nevertheless, the sludge may also contain dangerous toxic substances such as heavy metals in dissolved form, co-precipitated with metal oxides, as well as adsorbed or associated with biological residues (Ministerstwo Środowiska, 2018). Researchers have claimed that in recent years, the content of heavy metals in sludges has been decreasing (Chalamoński & Szymczak, 2017). At the same time, sludge containing more than 90% dry weight can be disposed of thermally (Milik et al., 2016). Since each process of thermal treatment of urban sewage sludge must ensure the optimal use of its energy, the essential characteristic is the calorific value (Bień & Wystalska, 2011). Obtaining the appropriate calorific value (taking into account their efficient combustion) depends on the degree of drying of sewage sludge during their treatment (Ministerstwo Środowiska, 2018). The content of dry organic matter also determines the calorific value of the sludge since it directly depends on the efficiency of their primary treatment during the fermentation process. The higher the fermentation efficiency, the lower the dry matter contents of the anaerobically stabilized sludge and, consequently, the lower the calorific value of the dry mass of sludge. Some physical and chemical properties of Polish sewage sludge in recent years are presented in Table 1.

Sludge is separated from wastewater in settling tanks until a dense pulp is formed (Cupial et al., 2011) and sludge contains about 12% (by weight) of biodegradable organic matter, 79% water, 9% ash, and a small amount of harmful substances. The calorific value of they usually does not exceed

Table 1. Characteristics of sewage sludge in Poland.

pH	Nitrogen total, %	Phosphorus total, %	Calcium, %	Dry weight of sludge, %	Reference
10.0–12.4	3.6–6.7	1.6–0.9	10.1–5.44	29.2–18.0	Włodarczyk et al., 2014
6.21–6.87	-	-	-	49.36–63.15	Milik et al., 2016
5–8	-	-	-	-	Bauman-Kaszubska & Sikorski, 2011
5.8–8.7	-	-	-	-	Maćkowiak & Igras, 2005

1 MJ/kg, which makes them incapable of spontaneously maintaining the combustion process. The drainage of sewage sludge is the primary condition for its possible use as a fuel. It depends on the possibility of its development in the region, the content of harmful elements, and the implementation conditions (Chalamoński & Szymczak, 2017).

4. Energy from sewage sludge

4.1. Fuel properties of Polish sewage sludge

The sewage sludge is a potential fuel that needs to be properly processed so that the gasification process can be considered a promising way to produce heat and energy (Chalamoński & Szymczak, 2017). Thermal waste disposal in order energy generation, recommended in a feasibility study for several Polish cities and used in more than 400 waste incineration plants in Europe, is widely known, economically, and environmentally proven (Dziołak, 2010).

The calorific value of sewage sludge depends mainly on its chemical composition (mass of organic compounds) (Jąderko-Skubis & Kurus, 2020). In addition, a high degree of hydration of sewage sludge (up to 99%) reduces its energy properties and their calorific value often becomes negative. Autothermal sewage sludge incineration is possible when its hydration is not more than 50%, the content of combustible sub-stances is more than 25%, and the content of non-combustible substances is less than 60% (Heidrich & Witkowski, 2015). Complete sewage sludge combustion without a catalyst is possible when its calorific value exceeds 8×10^3 kJ/kg of dry mass (Bień & Wystalska, 2011).

To reduce the mass and density of sludge from urban WWTPs, it is dried at a temperature of 220–240°C. The calorific value of the dried sludge is about 11 MJ/kg and is comparable to the calorific value of raw wood 8 MJ/kg and lignite 9–17 MJ/kg. Therefore, the dried sludge has the potential to be used as an energy resource. Sewage sludge with a moisture content of not more than 10% and a calorific value of at least 10 MJ/kg is not biodegradable and can only be neutralized by its thermal transformation (Staśkiewicz & Lelicińska-Serafin, 2020). The content of organic compounds in stabilized sewage sludge are 30–50% dry weight (Bartkowska et al., 2019) and even up to 79.14% (Bień et al., 2014) (Table 2).

The presence of harmful and hazardous components in the sewage sludge, such as chlorine, sulphur, heavy metals (zinc, copper, lead, mercury, cadmium, nickel, and chromium), as well as organic compounds (dioxins, furans, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, halogen-containing compounds are absorbed) makes them unsafe from an environmental point of view (Kurzydło, 2014). This is explained by the fact that during the thermal utilization of sludge for the purpose of energy recovery, these substances can enter the environment through emissions into the atmosphere.

Thus, in a study (Skawińska et al., 2017), it was shown that in samples of sewage sludge and secondary fuels, the chlorine content was above the maximum permissible value (0.2%), which significantly increases the risk of equipment corrosion and, taking into account legal regulations, deprives such material of suitability for use in energy. At the same time, an effective content of the above hazardous substances is also observed in modern household waste, which often exceeds the permissible limits. However, this fact does not prevent efficient and environmentally sound energy recovery from these wastes (Zhang et al., 2010; Vambol et al., 2017). When introducing new equipment in Swedish heat generation companies, it is assumed that the most important are emissions from thermal waste treatment and the cost of 1 kWh of generated energy (both electricity and heat). Moreover, the new equipment allows for working on sewage sludge or their mixture with other types of waste. Importantly, in this process, the flue gas treatment plants are designed per the most stringent requirements of the EU Waste Directive (Dziołak, 2010).

In mechano-biological technology, a severe problem is handling high-calorie waste fractions since their excess is observed (Żygadło, 2018). In this regard, in recent years, research has been developed aimed at using a mixture of sewage sludge with other types of waste in thermal processes for energy recovery.

4.2. The energy use of sewage sludge

The possibility of using a mixture of sewage sludge with beech sawdust and sewage sludge with lignite was studied (Constantinescu et al., 2018); with wood waste, rapeseed and rye straw, pine bark, and coal in various mass ratios (Chalamoński & Szymczak, 2017) (Table 3). Although the production of energy from secondary fuels is economically feasible due to their lower price than fossil fuels, the high variability and instability of the quality of waste-derived fuels should be considered (Skawińska et al., 2017).

5. Analysis of the general trend in the formation of sewage sludge in Poland

5.1. Definition of dynamics' statistical indicators

To analyse the formation and use of urban waste-water sludge in Poland, statistical mutually consistent and complementary information was compiled for 2012–2020 (GUS, 2021; Ministerstwo Środowiska, 2018) (Table 4).

The trend in precipitation formation and forecasting can be traced by assessing the statistical indicators of dynamics (Table 5). The most crucial statistical indicator is the absolute

Table 2. Fuel properties of sewage sludge generated in Poland

No	Indicator	Reference		
		Wastewater sludge that generated		Wastewater sludge that drained
		Staśkiewicz & Lelicińska-Serafin, 2020	Rećko, 2020	Chalamoński & Szymczak, 2017
1	Moisture, %	82.2	80.22	10.90
2	Content of combustible components, %	13.1	-	-
3	Content of non-combustible Components, %	4.7	33.54	30.20
4	Volatile component content in combustible parts, % cz.p.	86.4	59.75	53.29
5	Combustion heat, kJ/kg s.m.	17,405	-	13,350
6	Calorific value, kJ/kg	178	890	12,401

Table 3. Mixtures of sewage sludge with other wastes for use as secondary fuels

No	Additive to sewage sludge that generated in Poland	Reference
1	beech sawdust	Constantinescu et al., 2018
2	90% sawdust or bark and 10% dried sewage sludge	Chalamoński & Szymczak, 2017
3	waste wood, pine bark	Wasielewski & Sobolewski, 2015
4	rapeseed and rye straw	Wasielewski & Sobolewski, 2015
5	Coal	Wasielewski & Sobolewski, 2015
6	rubber waste, hazelnut and walnut shells	Dąbrowski & Dąbrowski, 2016

Table 4. Statistical information

Indicator	Year								
	2012	2013	2014	2015	2016	2017	2018	2019	2020
Formation of urban sewage sludge, thus. Mg dry matter	533.3	540.3	556.0	568.0	568.3	577.05	585.8	587.5	570.1

Table 5. Indicators of the series of dynamics

Year	Sludge accumulation, thous. Mg dry matter	Absolute increase		Growth rate (reductions), %		Growth of increase, %		Gain rate, %
		Chain	Basic	Chain	Basic	Chain	Basic	Chain
2012	533.3	-	-	-	-	100	100	0
2013	540.3	7	7	1.31	1.31	101.31	101.31	1.31
2014	556	15.7	22.7	2.91	4.26	102.91	104.26	2.94
2015	568	12	34.7	2.16	6.51	102.16	106.51	2.25
2016	568.3	0.3	35	0.053	6.56	100.05	106.56	0.056
2017	577.05	8.75	43.75	1.54	8.2	101.54	108.2	1.64
2018	585.8	8.75	52.5	1.52	9.84	101.52	109.84	1.64
2019	587.5	1.7	54.2	0.29	10.16	100.29	110.16	0.32
2020	570.1	-17.4	36.8	-2.96	6.9	97.04	106.9	-3.26

increase, which shows how much, in complete terms; the level of the current period is more (less) than the base one and is determined by comparing the difference between two levels of a series of dynamics in units of initial information. Basic absolute increase – the difference between the current value and the value taken as a constant comparison base $y_{bi} = \Delta y_i - y_0$. Chain absolute increase – the difference between current and previous values $y_{ci} = \Delta y_i - y_{i-1}$. Growth rate (reductions) – the ratio of two series levels (can be expressed as a percentage). Basic growth rate – the ratio of the current value and the value taken as a constant comparison base $T_b = y_i / y_1$. Chain growth rate – the ratio of the current and previous values $T_c = y_i / y_{i-1}$. Basic rate of increase – the ratio of the absolute base increase and the value of the comparison taken as a constant base $TIncr_{bi} = \Delta y_{bi}/y_1$. Chain rate of increase – the ratio of absolute chain growth and the previous value of the indicator $TIncr_{ci} = \Delta y_{ci}/y_{i-1}$. Gain rate – the ratio of chain absolute increments to the level taken as a constant comparison base $TIncr_{ci} = \Delta y_{ci}/y_i$.

In 2020, compared to 2019, sludge accumulation decreased by 3% (17.4 thous. Mg dry matter). The maximum increase is observed in 2014 (15.7 thous. Mg dry matter). The minimum increase was recorded in 2020 (-17.4 thous. Mg dry matter). The increase rate shows that the series trend is decreasing, which indicates a slowdown in the accumulation of sludge. In 2020, compared to 2012, sludge accumulation increased by 36.8 thous. Mg dry matter or by 6.9%.

5.2. The rows average characteristics

The average level of the series y of the dynamics characterizes the typical value of the absolute levels. The average level of the interval series is

$$\bar{y} = \frac{\sum y_i}{n} = 565.15,$$

that is the average value of sewage sludge accumulation from 2012 to 2020 was 565.15 Mg.

The average growth rate (or dynamics of phenomenon' development for any period on average) is

$$\overline{T}_p = \sqrt[n-1]{\frac{y_n}{y_1}} = 1.0084,$$

that is on average, for the entire period, the increase in sewage sludge amounted to 1.0084. Hence the average growth rate is

$$\overline{T}_{np} = \overline{T}_p - 1 = 0.0084$$

or on average, sewage sludge accumulation increased annually by 0.8%.

The average absolute increase is a generalized characteristic of absolute individual gains in a dynamics series:

$$\bar{d}_y = \frac{y_n - y_1}{n-1} = 4.6,$$

that is Every year, sewage sludge accumulation increased by an average of 4.6 thous. Mg dry matter. Forecast of sewage sludge accumulation up to 2025 is presented in Table 6.

Table 6. Forecast values

Year	2021	2022	2023	2024	2025
Sludge accumulation, thous. Mg dry matter	574.7	579.3	583.9	588.5	593.1

It's clear that the sewage sludge production will increase quite moderately (Fig. 2).

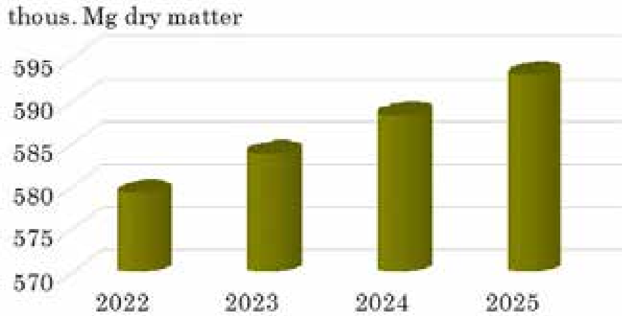

Figure 2. Quantitative forecast of municipal sewage sludge production in Poland

6. Conclusions

Due to the ever-increasing demand for energy resources, the country's economic growth cannot be sustainable in terms of consuming exclusively fossil fuels. To meet the demand for energy resources and ensure the economic growth of the country, it is necessary to introduce new technologies for energy recovery from raw materials that are consistently available.

Water treatment and wastes from the treatment plant, in particular, sewage sludge, contain a biodegradable fraction, which makes it possible to consider them as a renewable source of energy. The present study demonstrates the heterogeneity of waste streams for the production of alternative fuels and a modest increase in sewage sludge production in the coming years. Therefore, the key research for the coming years in order to achieve broad and sustainable economic growth by ensuring the energy security of the country should be the development of technology development research:

1. for WWT, allowing the production of sludge, the properties of which are as close as possible to the properties of waste used for energy recovery. This will reduce the time for additional processing of this waste type;

2. to extract the energy potential of sewage sludge by co-incineration with other types of waste, to obtain high-quality alternative fuels, and reduce harmful emissions into the environment during thermal processes. The present studies in this direction well demonstrate the economic benefits of the techniques, environmental safety, and the possibility of obtaining fuels with suitable properties for their practical application.

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