Title: The use of sewage sludge in anaerobic digestion process: formation, properties, and implementation

Authors: Agnieszka A. Pilarska, Tomasz Kałuża, Maciej Pawlak, Tomasz Kulupa

To appear in: Technical Sciences

Received 24 October 2024;

Accepted 22 November 2024;

Available online 25 November 2024.

The use of sewage sludge in anaerobic digestion process: formation, properties, and implementation

Agnieszka A. Pilarska *, Tomasz Kałuża, Maciej Pawlak, Tomasz Kulupa

Department of Hydraulic and Sanitary Engineering, Poznań University of Life Sciences, Piątkowska 94A,
60-649 Poznań, Poland
Corresponding author: agnieszka.pilarska@up.poznan.pl

Abstract

The effect of municipal wastewater treatment, in addition to improving its quality, is sludge formation. Disposal of sewage sludge (SS) is a critical environmental problem that requires careful management. Under current legislation, SS represents waste requiring stabilisation to eliminate pathogenic microorganisms and substances potentially harmful to the environment. Anaerobic digestion (AD) is an efficient method of treating SS, and it produces biogas as a renewable energy source (RES). The efficiency of the process can be increased by combining SS with other organic wastes as cosubstrates. Therefore, AD allows for a twofold benefit crucial for sustainable waste and energy management, i.e. sludge stabilisation and biogas production. Another equally important consideration in the construction of biogas plants at wastewater treatment plants is reducing the plant's operating costs by using the electricity and heat generated in the cogeneration units for the plant's needs. This paper discusses the formation technology and properties of sewage sludge, the legal aspects of using and disposing of SS, the conditions for employing their anaerobic biodegradation, and the co-digestion systems used.

Keywords: sewage sludge processing; sewage sludge properties; legal aspects; anaerobic digestion; cosubstrates; biogas production

Introduction

The dynamic development of sewerage networks and wastewater treatment plants generates large quantities of municipal sewage sludge. The development of water supply and sewerage networks is accompanied by an increase in the capacity of municipal wastewater treatment plants and the application of enhanced nutrient removal at these plants. Due to the construction of new wastewater treatment plants and the modernisation and expansion of existing ones, the amount of municipal sewage sludge requiring management is forecast to increase (Domańska 2022). Municipal wastewater, which contains suspended solids forming municipal sewage sludge, is primarily a mixture of domestic and industrial wastewater, fed also by infiltration and rainwater. The quantitative and qualitative characteristics of municipal wastewater depend on the type and technical condition of the sewerage system, urban industrialisation, the amount of water used, and the inhabitants' standard of living (Podedworna and Umiejewska 2008).

The generation of SS is associated with the treatment of municipal or industrial wastewater. It is formed as a by-product of wastewater treatment in wastewater treatment plants and consists mainly of organic and inorganic substances and microorganisms (Gromiec 2020). Processes that lead to the formation of sludge include sedimentation, a common method of separating solids from liquids; biological processes—the degradation of organic matter by microorganisms; chemical treatment through the addition of chemicals to coagulate and flocculate contaminants; and dewatering processes followed by mechanical or thermal removal of water from sludge (Chmielowski et al. 2015). Sewage sludge can be hazardous due to its content of heavy metals, pathogens or toxic substances. Their further treatment includes stabilisation (e.g. anaerobic digestion), composting, and thermal treatment (incineration, pyrolysis). Sludge management is a considerable environmental challenge, which is why sludge treatment and reuse technologies (e.g. fertilisers or energy production) are constantly being developed (Pilarska et al. 2019).

Anaerobic digestion (AD) of SS is a popular treatment method. It reduces the volume and nuisance odours generated by SS, stabilises organic material, and produces biogas as an alternative energy source (Dąbrowska and Masłoń 2020). A benefit of AD using sewage sludge is also the possibility of producing organic fertiliser in the form of digestion residues, referred to as digestate, which is rich in plant nutrients (Czekała et al. 2017). Sewage sludge, which contains a significant amount of organic matter, is a suitable substrate for AD. However, the low proportion of solids in the material is a problem. For this reason, it is combined with other cosubstrates to increase process efficiency (Montusiewicz 2012). Co-substrates used in anaerobic digestion of sewage sludge include food waste, agricultural residues, animal manure, industrial by-products, grease trap waste, glycerol, fruit and vegetable waste, municipal organic waste, algae biomass, and food or beverage industry wastewater. Research into this is carried out in numerous research centres worldwide (Fonoll et al. 2015, Marañón et al. 2012). Globally, the number of biogas plants at wastewater treatment plants is increasing. However, in Poland, only a small number are in operation (88 facilities of 50 kW–1 MW (32 MW in total) and eight of more than 1 MW (12.5 MW in total) (Woźniak 2016). The main technological challenges are the contaminants present in the sludge, mainly heavy metals, toxic substances or pathogens, which hinder digestion and further use of the digestate, as well as the management of excess sludge, some of which, despite the volume reduction, remains and must be managed accordingly. Investment costs are also an issue – constructing an anaerobic digestion plant requires significant financial outlay, although biogas production can reduce operating costs. Investing in biogas plants offers the potential, proven in practice, to reduce the costs of the company's gas and electricity consumption, as well as the sewage sludge generated will no longer make life difficult for local residents (Masłoń et al. 2020).

This work aims to present a schematic of the formation technology and characteristics of sewage sludge and discuss the legal aspects of the use and disposal of SS and the conditions and equipment used in its biological anaerobic stabilisation. The analysis of sewage sludge co-digestion systems with other organic wastes also features prominently in the work.

Sewage sludge formation

Municipal wastewater, containing suspended solids that form sewage sludge, is mainly a mixture of domestic and industrial wastewater, supplemented by rainwater and infiltration water. Importantly, there is no typical composition and quality of municipal wastewater. Each municipality and city generates a different composition and unit volume of wastewater, so it is impossible to adopt a uniform rule for the quantitative and qualitative characteristics of the generated municipal sewage sludge. In contrast, it must be assumed that almost the entire pollutant load flowing into the treatment plant is converted into biomass, so wastewater treatment is sludge production. In each wastewater treatment plant and project implemented, the mass balance of the pollutant load must be completed, considering all inputs and outputs, thus balancing proper sludge management (Podedworna and Umiejewska 2008).

Sewage sludge is the main waste generated in wastewater treatment plants from three treatment processes: mechanical, biological, and chemical. According to the Waste Act of 14 December 2012, SS is "municipal sewage sludge means sludge from digesters and other facilities used for the treatment of municipal sewage and other sewage similar in composition to municipal sewage" (*Waste Act* 2012). Raw sludge is a waste material from wastewater treatment processes (it putrefies quickly and gives off unpleasant odours). These sludges consist of primary sludge and excess sludge, as shown in Figure 1.

Primary sludge is formed by the sedimentation of easily settled suspended solids (organic and mineral solids not retained in grit chambers) in a primary settlement tank (see Figure 1). These sludges are unmixed with other recirculated sludges (Gazda et al. 2012, Grobelak et al. 2016). This sludge is an excellent substrate for AD, as it decomposes quickly. The situation is different with excess sludge, which decomposes slowly and to a limited extent, mainly due to the resistance of the walls and cell membranes of microorganisms in conventional mesophilic reactors.

The proportion of excess sludge in the mixture significantly impacts digestion and the intensity of biogas production. Minimising the proportion of excess sludge in the mixture is recommended, which promotes more efficient digestion.

Secondary settlement tanks, on the other hand, produce secondary sludge. Typically, this waste is generated from biological treatment. It is reverted for treatment as recirculated sludge or used in a further process for treatment with excess sludge (Klimek et al. 2013).

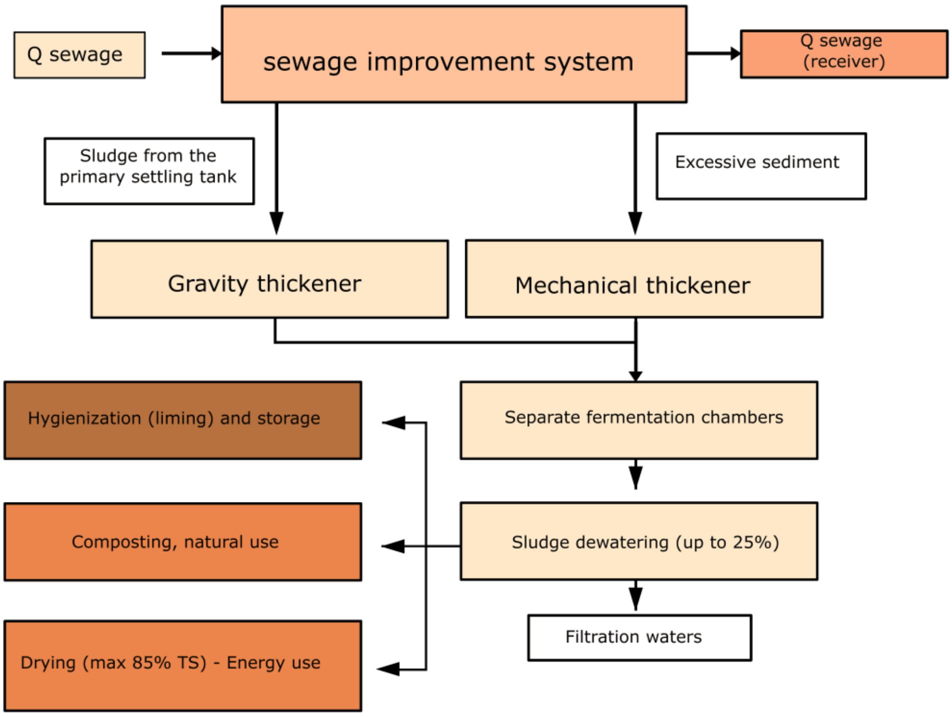

Figure 1. Standard blow diagram of a technological line for sewage sludge treatment, based on Gazda et al. 2012

The composition of the sludge stream varies and depends on the pollutant load of the incoming wastewater, the technology used at the wastewater treatment plant, the methods of the sludge treatment at the stabilisation stage, the mass reduction, the volume of sludge arriving, and the agents (such as reactants) used throughout treatment (Szwaja et al. 2019). The main parameters that differentiate sewage sludge based on the technology used are:

- the level of hydration, which is greater than 99% for raw sludge, in the range of 55 to 80% for dewatered sludge, but less than 10% immediately after thermal drying;
- the amount of organic compounds, which ranges from 75 to 85% for non-stabilised sludge and from 45 to 55% for stabilised sludge;
- the amount of nitrogen compounds, which ranges from 2 to 7% and significantly lower phosphorus and potassium contents;
- the varying abundance of heavy metals, which depends on the type of agglomeration and the population equivalent (p.e);
- the presence of various bacteria and pathogens, which are least abundant in stabilised and hygienised sludge and most abundant in primary raw sludge (Maćkowiak and Igras 2005).

Standard properties of raw sludge include its putrescibility (leading to odour nuisance), the presence of disease-causing microorganisms and parasites, and its filtration properties, i.e. the ability of the sludge to dewater, which is determined by the physico-chemical properties of the SS and the type of water it contains (Wim 2008), see Figure 2. The most difficult to remove are molecular and hygroscopic water bound biologically or chemically (which requires significant energy input in drying or combustion) and colloid-bound water, which is much more difficult to separate due to its binding by surface tension forces.

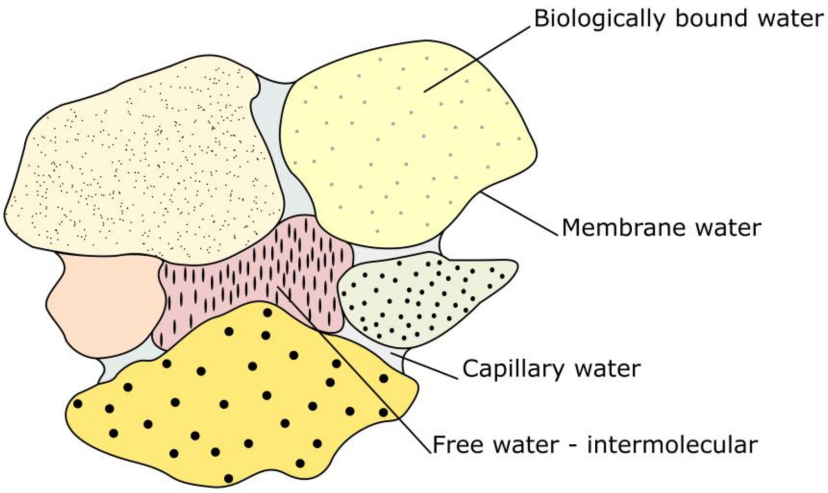

Figure 2. Scheme of water content in sewage sludge (scheme developed by the authors based on document.: *Exercise 5, Filtration properties of sewage sludge, Wrocław University of Science and Technology*)

The hydration of the sludge determines its mass and volume, which is important for designing the required sizes of sludge management facilities. Sewage sludge usually shows a high degree of hydration. From the point of view of cost-efficiency, logistics and efficiency of AD implementation, compaction is essential, as it yields twice the amount of dry matter in the sludge and a significant reduction in sludge volume (Czekała et al. 2017).

Municipal sewage sludge law – selected aspects

European Union legislation on sewage sludge management is primarily Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture, known as the Sewage Sludge Directive, which results in significant restrictions on the agricultural and natural use of sludge. The directive aims to promote the use of sewage sludge in agriculture while preventing its harmful effects on human health and the environment, including soil and living organisms. The directive contains requirements concerning the quality of sludge used in agriculture, the quality of the soil on which it is to be applied, and restrictions on its use for certain purposes and during certain periods. The main objective of these requirements is to reduce heavy metal contamination of the soil (Strategy, Ministry of the Environment, 2018).

The consolidated version of the European Union's Sewage Sludge Directive (Council Directive 86/278/EEC), effective as of January 1, 2022, aims to balance the environmental and agricultural benefits of sewage sludge use while mitigating potential risks. It continues to set strict limits for heavy metals in sludge and soils used in agriculture, ensuring safe application. The Directive also bans sludge use in specific contexts, such as on land where fruits and vegetables are growing, except for fruit trees. The updated Directive aligns with modern policies, including the European Green Deal and the Circular Economy Action Plan. It emphasizes nutrient recycling, particularly nitrogen and phosphorus, while addressing health and environmental risks. Recent evaluations (e.g., from 2020) found the Directive effective but highlighted areas for improvement, such as harmonizing it with newer EU biowaste and fertilizer regulations. The updates also stress more frequent soil analyses, improved sludge treatment techniques, and detailed record-keeping by member states to ensure compliance and traceability. Future revisions are under consideration to better integrate the Directive into broader sustainability goals, such as the Integrated Nutrient Management Plan under the Circular Economy framework (Implementation Report of Sewage Sludge Directive 86/278/EEC, 2022).

In turn, the key piece of legislation governing the thermal treatment of waste, including the incineration of municipal sewage sludge with energy recovery, is Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions. These directives aim to prevent or reduce, as far as possible, the adverse effects on the environment, in particular pollution through emissions to air, soil, surface water and groundwater, and the resulting risks to human health. As for Polish legislation, this issue has been regulated, among other things alia, in the Act of 27 April 2001—Environmental Protection Law (Journal of Laws of 2018, item 799, as amended) and the Waste Act, including the implementing regulations to these acts. Under Article 155 of the Waste Act, thermal treatment of waste is to be carried out only in waste incineration or waste co-incineration plants. Waste incineration and waste co-incineration plants are to be designed, constructed, equipped, and operated in a manner that ensures the least possible harm to human life, health, or the environment (Myszograj et al. 2013, Wieremiej et al. 2015).

The most important national legislation on the treatment and final management of municipal sewage sludge as waste is the *Waste Act* of 14 December 2012, which sets out the rules for handling waste, including municipal sewage sludge, insofar as it meets the definition of waste (*Waste Act* 2012). Therefore, it must first be assessed whether the sewage sludge generated at the wastewater treatment plant meets the criteria of the Waste Act's definition of waste. Municipal sewage sludge is not included in any of the exemptions from the application of the waste regulations contained in Article 2 of the *Waste Act* and, in particular, does not constitute wastewater or biomass. Sewage sludge generated from wastewater treatment becomes municipal sewage sludge after dewatering; it is a special category of waste (Wieremiej et al. 2015, Mełgieś and Malińska 2016). Municipal sewage sludge waste should be classified into the appropriate group, subgroup, and type of waste, according to the Regulation of the Minister of the Environment of 9 December 2014 on the Waste Catalogue (Journal of Laws of 2014, item 1923). The waste producer (first waste holder) makes this classification, taking into account, for instance, the source of waste, the specific production process in which it is generated, and its chemical composition.

Under the current legislation, waste may be deposited at a landfill site of a given type, provided that the criteria set out in the provisions of the Waste Act and the executive acts issued on its basis are met. The Regulation of the Minister of Economy of 16 July 2015 on admitting waste to landfill (Journal of Laws of 2015, item 1277) defines, among other things, in Annex 4, the criteria for admitting waste (code 19 08 05): stabilised municipal sewage sludge for disposal in a landfill for non-hazardous and inert waste, taking into account certain parameters that, in practice, make it impossible to landfill this waste without prior treatment. These provisions entered into force on 1 January 2016. As a result of the above regulation, there is an increased search for technologies that enable the safe disposal of SS. Stabilisation of sewage sludge using AD is an effective and environmentally friendly solution.

Use of compounds recovered from sewage sludge

Sewage sludge is increasingly regarded as a valuable resource rather than waste. Its complex composition includes nutrients beneficial for agriculture, such as nitrogen and phosphorus, but also contains heavy metals and other toxic substances. Managing and reusing it presents challenges but also offers opportunities for resource recovery, environmental sustainability, and energy production.

Sewage sludge is a rich source of nutrients essential for plant growth. Phosphorus, a limited resource for agriculture, can be effectively recovered from sludge. Common techniques include chemical precipitation and thermal treatment (e.g., incineration followed by ash processing). Technologies such as struvite precipitation enable phosphorus recovery by producing fertilisers that can replace non-renewable phosphate rock. Additionally, treated sludge (biosolids) can be applied directly to fields, enhancing soil fertility while reducing the use of synthetic fertilisers. Mihelcic et al. (2011) emphasise the growing importance of phosphorus recovery in addressing its global scarcity. Nitrogen, another key nutrient in sludge, can be directly utilised when the sludge is processed and applied as a fertiliser. Stabilised sludge, free from pathogens and with reduced heavy metal content, is widely used to improve soil fertility.

However, sewage sludge often contains heavy metals such as lead, cadmium, nickel, and chromium, posing environmental risks. As discussed by Wilk and Gworek (2009), these metals limit the direct use of sludge in agriculture due to their potential bioaccumulation in plants and animals. Advanced technologies, including pyrolysis, phytoremediation, and electrochemical methods, are being explored for metal recovery and detoxification. Pyrolysis is a thermal process that not only stabilises organic material but also enables metal recovery from the resulting biochar or ash. This approach aligns with circular economy principles, reducing waste while extracting valuable materials. Phytoremediation is a biological process where plants, algae, fungi, or microorganisms are used to remove, transform, or stabilise contaminants in the environment, including heavy metals from wastewater (Ali et al. 2013). In the context of metal recovery from sludge, this method offers a promising, eco-friendly, and cost-effective technology. Hyperaccumulating plants, such as *Brassica juncea* (Indian mustard), *Pteris vittata* (fern), and *Typha latifolia* (cattail), can accumulate heavy metals like lead, cadmium, nickel, and zinc. Once the phytoremediation process is complete, the plants are harvested and dried, with the biomass then incinerated or subjected to chemical processes (e.g., leaching) to recover metals. These recovered metals can be utilised in industries such as electronics, batteries, and catalysts (Ghosh et al. 2005) Electrochemical methods are also widely used for recovering heavy metals such as cadmium, nickel, and zinc. Techniques like electrochemical extraction and galvanisation allow for efficient recovery of metals, which are then reused in industries such as battery manufacturing and coatings. For example, cadmium recovered from wastewater is reused in battery production.

It should also be mentioned that recovered organic matter from sludge can serve as a raw material for producing biopolymers, adhesives, and building materials. An innovative solution involves developing biodegradable plastics from precursors derived from sludge. Kim et al. 2022 explored the potential of using alternative raw materials, including sewage sludge, for producing biodegradable polymers like PLA (polylactic acid). They assessed environmental impact through life cycle analysis, highlighting the benefits of waste-derived bioplastics in reducing dependence on fossil fuels.

On the international stage, count ries adopt different strategies for sludge management based on regulatory frameworks and technological capabilities. In Europe, Belgium commonly practises thermal conversion of sludge into energy and recoverable materials. Scandinavian countries prioritise composting and biogas production, integrating nutrient recovery with renewable energy generation. In Germany and the Netherlands, thermal processes are prevalent, whereas Scandinavian nations focus on biogas production. In the United States, the reuse of sewage sludge in agriculture, subject to strict safety standards, aligns with the Environmental Protection Agency (EPA) guidelines (Jaramillo and Restrepo, 2017). In Japan, innovative drying and incineration technologies are used to recover phosphorus from ash, turning waste into resources (Wiśniewski et al., 2023).

Challenges and opportunities associated with the use of substances in sewage sludge revolve around the following factors: (1) technological barriers – high costs and technical complexity of advanced recovery systems hinder their large-scale implementation; scaling laboratory innovations to industrial applications requires significant investment and regulatory suport, (2) environmental risks – improper handling of recovered materials can lead to secondary contamination; ensuring recovered products meet safety standards for reuse is a critical challenge, (3) eesearch opportunities – these include developing cost-effective bioremediation techniques using genetically modified microorganisms and enhancing the efficiency of membrane and adsorption technologies for broader industrial applications.

To sum up, recovering and utilising nutrients, heavy metals, and other components from sewage sludge aligns with global sustainable development goals and supports a circular economy. However, risk management, particularly concerning heavy metals and organic toxins, remains crucial to achieving safe and effective reuse. Collaboration among researchers, policymakers, and industry stakeholders is essential to optimise these processes and minimise environmental impact. Advancements in this field will not only reduce pollution but also create new economic opportunities.

Sewage sludge in biogas production

Biogas plants are an important part of the circular economy, where waste is utilised in addition to biogas production (Wilińska-Lisowska and Czerwionka 2021). Technology based on anaerobic digestion, in which sewage sludge acts as a substrate, is increasingly used. The anaerobic decomposition of the disposed substrate enriches the digestion mixture with organic matter and the bacterial microflora necessary for this process to take place properly (Korbag et al. 2021). Despite being a waste product, SS is, first and foremost, a renewable energy source. However, due to legal and environmental considerations, the primary objective of AD of sewage sludge is to eliminate its putrescibility and generate sludge that is easy to dewater and sanitary. This process also yields a stable and nutrient-rich digestate, which is a safer waste compared to raw sewage sludge, as well as electricity and/or heat, which contribute to the plant's profitability.

Sewage sludge is characterised by a low content of total solids (TS), in the range of 2–8%, most of which are organic compounds. Polysaccharides (39–48% TS) and proteins (30–46% TS) account for the largest share. Fats make up 6–31% TS, and fibrous substances

10–16% TS. Sewage sludge is valuable due to its high mineral content (macronutrients and micronutrients), which can potentially benefit the growth and metabolism of anaerobic bacteria and thus methane production efficiency (Pilarska et al. 2019). However, it contains a low amount of carbon and, as highlighted above, dry matter and hence requires combining with cosubstrates. Co-digestants should balance the sewage sludge, i.e. contain low nitrogen and have a high C/N ratio of biochemical methane potential (BMP). The pH of sewage sludge varies between 5.0 and 8.0, depending on the composition of the SS and the dominant compounds. Unfortunately, sewage sludge contains heavy metals and pathogens, which may preclude its agricultural or natural uses. Heavy metals in sludge depend on industrial contribution to the sludge (Olejnik 2024). These include zinc, copper, chromium or lead; nickel, cadmium, mercury, molybdenum, and other metals are found in lower concentrations (Montusiewicz 2012, Pilarska et al. 2016). It is also worth reflecting that digested (stabilised) SS has inoculative properties and shows a high buffer capacity. The increase in alkalinity, determined by the amount of carbonates and acid carbonates, is mainly due to the formation of HCO_3^- ions in the nitrate reduction process, during which denitrifying bacteria use protons and electrons from organic carbon compounds. These compounds include carbohydrates, organic alcohols, amino acids, and fatty acids. The following reaction equation shows the formation of HCO_3^- ions in the nitrate reduction reaction, using acetate (Pilarska et al. 2019):

$$5CH_3OO^- + 8NO_3^- + 3H^+ \rightarrow 10HCO_3^- + 4N_2 + 4H_2O \qquad (1)$$

Notably, denitrification, which takes place during the formation of the digestate as a potential fertiliser, is very important, for instance, for protecting water quality. Although nitrates are not as highly toxic as ammonia, high levels of nitrates adversely affect organism growth. According to Pilarska et al., 2016 and 2019, digested SS has a higher conductivity compared to raw sludge and, therefore, an increased content of minerals, including potassium, magnesium, and calcium. After digestion, the organic content drops by about 30%, and the sludge hydration decreases, causing the weight of solids to increase to 6÷7%. The content of sulphides and humic substances gives the sludge a black colour.

Under current legislation (Journal of Laws 2014, item 1923), sewage sludge is waste, and it must undergo appropriate treatment to remove pathogens that are toxic to humans and the environment and reduce unpleasant odours. The above requirements are met by using multi-stage treatment based on thickening; biological stabilisation (aerobic or anaerobic); thermal stabilisation (use of high temperature: pyrolysis, combustion, or gas: gasification, plasma gasification); drying, dewatering, or conditioning; hygienisation (radiation, pasteurisation, or liming (Borsukiewicz and Mocarski 2018). It should be noted that the above is a general list used to configure sludge treatment at a particular wastewater treatment plant for individual applications. In addition to meeting environmental requirements, these treatment methods also allow sewage sludge to be used, among other things, for energy or agricultural purposes. The composition of SS transforms it from a waste product into a high-potential feedstock. From an energy standpoint, sewage sludge's relatively high content of biodegradable organic matter is particularly interesting. As mentioned in the introduction, the variable organic matter content due to the nature and chemical composition of the influent and its treatment technology must be taken into account when analysing the energy suitability of SS.

Biogas plant processes at the wastewater treatment plant can be divided into four main stages, starting with the pre-treatment of SS, followed by anaerobic digestion, and finally, the production of biogas and the subsequent use of the digestate (see Figure 3). Before the sludge enters the separate digesters, it is screened and thickened. The sludge can also be pre-treated using disintegration technology.

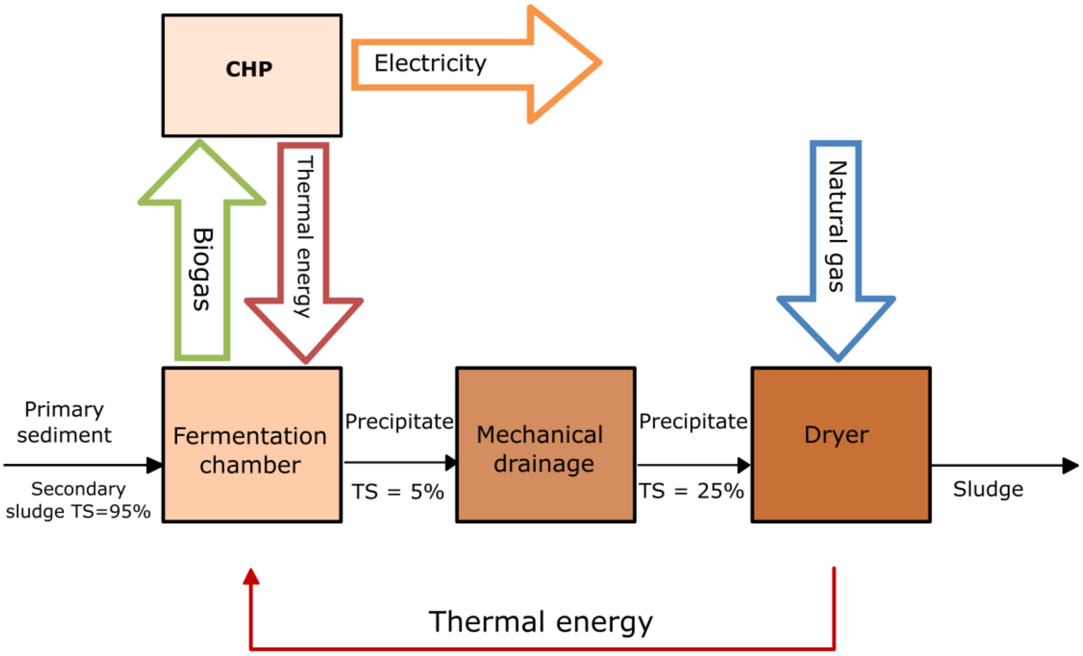

Figure 3. Schematic diagram of the technological cycle of sewage sludge use in biogas production based on https://www.odnawialne-firmy.pl/wiadomosci/pokaz/110,substraty-do-produkcji-biogazu-osady-sciekowe-czesc-25

Disintegration technologies like ultrasonics and hydrodynamic cavitation are commonly employed in wastewater treatment to enhance the anaerobic digestion of sewage sludge. These methods break down sludge flocs, improve solubilization of organic matter, and increase biogas yield. The ultrasonics use high-frequency sound waves (20-40 kHz) to create cavitation bubbles in the sludge (Movahed et al. 2023). When these bubbles collapse, they generate intense localized pressure and heat, breaking the cell walls of microorganisms and releasing intracellular material. The action of ultrasound contributes to: (1) increasing soluble chemical oxygen demand (SCOD), making organic matter more bioavailable for microbes, (2) enhancing methane production in anaerobic digestion by improving substrate availability and (3) reducing sludge viscosity, improving pumpability and overall handling. Hydrodynamic cavitation occurs when liquid passes through a constriction (e.g., an orifice or venturi tube), causing a rapid pressure drop that forms vapor bubbles (Song et al. 2022). These bubbles collapse, generating localized energy that disrupts sludge particles and cell walls. The hydrodynamic cavitation occurs when liquid passes through a constriction (e.g., an orifice or venturi tube), causing a rapid pressure drop that forms vapor bubbles. These bubbles collapse, generating localized energy that disrupts sludge particles and cell walls. The advantages of this method are: (1) lowing energy consumption compared to ultrasonics., (2) increasing disintegration efficiency for large-scale operations and (3) reducing pathogens and enhances sludge dewaterability (Dalfré Filho et al. 2015). Hydrodynamic cavitation is often integrated into continuous-flow systems for cost-effective sludge pre-treatment.

Both technologies discussed Both technologies are evolving to reduce energy demand and improve performance. Hybrid systems, such as combining ultrasonics with thermal or chemical treatments, are being explored for even better sludge disintegration and resource recovery. For example, studies show enhanced performance when cavitation methods are combined with oxidative processes (e.g., ozonation).

Returning to the discussion of the technological cycle (see Figure 3), in the next stage the sludge is pumped into a separate digester, where methane is digested under anaerobic and mesophilic conditions with continuous mixing. During the process, microorganisms break down some organic matter in the sludge and produce biogas. Digestion is carried out in enclosed separate digesters, usually made of concrete. There are generally three digester types: liquid, plug-flow, and solid-state type digesters. Regardless of type, thermal insulation and sealing are required. The material to be digested is introduced via a pipeline from the top, while the digested sludge, which falls to the bottom of the digester, is discharged via a screw conveyor. The biogas produced accumulates under the lid and, depending on its type (mobile or fixed), is discharged periodically or continuously (Kwaśny 2012). The process is either wet or dry. The difference lies in the percentage of dry matter in the digested sludge. In wet digestion, which is most often used, the dry matter stays at 12 to 15%; this content allows the raw materials in the separate digester to be pumped easily and helps the mixers to work more efficiently. Dry digestion, on the other hand, involves a dry matter content of 15 to 16% (or more) and is used much less frequently in this type of facility, mainly because a suitable technology is challenging to find. If the process is to proceed naturally, a suitable environment for bacterial growth must be provided (Owczuk et al. 2016).

The key to the entire process is the transformation of complex organic compounds into chemically stable simple compounds and biogas with the following composition: methane (approx. 50–75 vol. %) and carbon dioxide approx. 19–44 vol. %), a mixture of sulphide, hydrogen, nitrogen, and oxygen, and the digestate as a by-product (Wilk 2011). The biogas produced has a high calorific value, in the range of 19 to 25 MJ/m^3 (by comparison, natural gas with a high methane content has a calorific value of approximately 36 MJ/m^3). For confirmation, the biogas generated at the biogas plant at the Wola Dalsza wastewater treatment plant, as reported by Koc-Jurczyk et al. 2020, 2020, contains 61% CH_4, 34% CO_2, 384 ppm H_2S, 0.50% O_2, 1.10% CO, and 0.40% N_2. The raw biogas has to be dried, and hydrogen sulphide and other trace substances should be removed. After purification, the biogas can be upgraded to biomethane or cogenerated into electricity and heat simultaneously (see Figure 3). On the other hand, the digestate can be pressed, centrifuged, and heat-dried, depending on its further use. It can be used, as mentioned earlier, in agriculture as a fertiliser or transported to an incinerator. The final disposal and recycling depend on the costs generated and the regulations in the country concerned (Bachmann 2015).

Substrates used in anaerobic co-digestion with sewage sludge

Anaerobic co-digestion (AcoD) involves combining at least two components from different sources (Pilarska et al. 2023). The chemical composition and availability in the local market are important in selecting cosubstrates. Materials subjected to AD in sludge systems must have high organic compound concentrations, good biodegradability, including hydration, an appropriate carbon/nitrogen ratio, and high dry matter content. Such cosubstrate properties eliminate the risk of process stalling caused by a too dry/pulpy mix, compensate for nutrient deficiencies, and reduce pathogens and substances that can inhibit AD (Zajda et al. 2011).

In practical terms, supplying the biogas plant operating at the wastewater treatment plant with raw materials from nearby plants reduces logistical costs and is beneficial from both a financial and ecological point of view (Pilarska et al. 2018). Combining sewage sludge with food waste is a noteworthy approach, which enables 2–3 times more biogas and improves the balance of essential components in the feedstock. Brewery waste, whey, and distiller's grain are cosubstrates that digest on their own and can be used without additional facilities (Koc-Jurczyk et al. 2020). Co-digestion also provides an opportunity to dispose of and treat waste that is difficult to biodegrade, including horticultural waste and landfill or fat leachate.

Therefore, AcoD has many advantages. Its main objective is to increase the efficiency of biogas production (compared to mono-digestion of a given substrate) by ensuring optimal process parameters and maintaining the adopted environmental regime (Wilińska-Lisowska and Czerwionka 2021). Groups of wastes that can act as cosubstrates in sludge systems are described below.

Organic municipal waste is supplemented with SS through co-digestion. It is distinguished by a high concentration of readily biodegradable organic compounds and a high C/N ratio. Therefore, the organic fraction of municipal waste enriches the composition of sewage sludge and increases biogas production. Due to its high dry matter content, this waste requires dilution and pulverisation for co-digestion with sewage sludge. Young and mature landfill leachate can mainly be used for this. As reported in the literature, the wide variety of organic municipal waste makes it difficult to assess this cosubstrate's suitability for biogas production (Montusiewicz 2012).

Another noteworthy example of a cosubstrate is fatty waste, which is considered one of the best for co-digestion with sewage sludge due to its good biodegradability, low nitrogen content, and, most importantly, high methane potential (Pilarska et al. 2019). Fatty waste as a monosubstrate can cause technical problems, i.e. clogging of digesters, reduction of cell protection functions and mass transport, and inhibition of methanogenic bacteria due to the intensified release of volatile fatty acids (VFA) in the first stages of AD. Its use as a cosubstrate improves process parameters and increases methane concentration in biogas. Fat waste is produced by food production facilities, such as abattoirs, oil and fat plants, oil presses, dairies, restaurants, and flotates from municipal and industrial wastewater treatment plants. It has a very diverse chemical composition, a high dry matter concentration of 7.5–42%, of which 80–99% is organic, a favourable C/N ratio and an acidic pH. Due to these parameters, it has a high biogas potential. Pre-treatment is recommended to disintegrate fatty waste and degrade long-chain fatty acids more quickly (Pilarska et al. 2019).

The most extensive and diverse group of cosubstrates is agri-food industry waste (Pilarska et al. 2023). The most desirable cosubstrates are those from the brewing and malting industries, spirits, dairy and fruit, and vegetable pulps or whey (Pilarska et al. 2014, Di Maria et al. 2014). They have a high nutrient content and many easily biodegradable organic compounds, which makes them an attractive material for biogas production. Due to their high availability, they have become popular in AcoD systems with sewage sludge. Their chemical composition varies depending on the source and production process. Abattoir waste has low C/N ratios and high compositional variability, so process efficiency in biogas production is variable (Davidsson et al. 2008). Distiller's grain has a high organic compound load well taken up by bacteria, a favourable C/N ratio, low pathogen content, and high temperature (Pilarski et al. 2021). Its weaknesses are high hydration, which contributes to decreased dry matter concentration in the digester feed mixture, seasonal production, and low pH. As a monosubstrate, the distiller's grain has a high biogas potential in two-stage digestion with acid phase separation; with single-stage technology, the process is unstable due to reactor acidification. Introducing a suitably adjusted distiller's grain dose into AcoD with SS can benefit the process by improving the chemical composition of the reactor feed mixture. Brewery waste, on the other hand, is particularly desirable as a cosubstrate for AcoD with SS due to its high content of readily biodegradable organic nutrient compounds, favourable C/N ratio value, high alkalinity, high biogas potential, and low pathogen content. The drawback is the cadmium content. Another cosubstrate is whey. Like the materials described above, it contains a high concentration of readily biodegradable organic compounds, essential nutrients, and a significant amount of proteins, lactose, vitamins, and mineral elements. It can positively alter the chemical composition of the feedstock. Its composition depends on the quality and composition of the milk or cheese-making technology. A low pH in acid whey and a low C/N ratio in sweet whey can adversely affect the stability of the process. Whey is not recommended as a monosubstrate in biogas production, but studies show high biogas potential in a co-digestion system with sewage sludge (Pilarska et al. 2016). The biogas yields of sewage sludge in systems with agricultural and food waste were presented by Pilarska et al. 2023.

The last discussed group of cosubstrates for AcoD with SS is livestock waste, which is rarely used due to the possibility of exacerbating the unfavourable C/N ratio and the need for pre-treatment (Koc-Jurczyk et al. 2020). Other disadvantages are the low biogas potential and the too short digestion time (unsuitable for other potential cosubstrates). In addition, ruminant waste contains lignocellulosic compounds, which are hard and slow to hydrolyse. In co-digestion systems with sewage sludge, it is used as a multisubstrate. Due to possible inhibition by ammonia, it has a low efficiency in biogas production.

Agri-food processing waste, organic fractions of municipal waste, grease waste and landfill leachate are considered most desirable as digestion systems with sewage sludge. The choice of cosubstrate should consider the opportunity to manage the waste without additional financial outlay, the possibility of utilising it in a biogas process, and the benefits of its physical and chemical properties.

In summary, biogas plants located at wastewater treatment plants fit into the idea of a circular economy, using anaerobic digesters and enabling additional use of the digestate as fertiliser. Wastewater treatment plants enjoy a continuous supply of substrate, while biogas plants reduce the costs of managing sewage sludge, which is expensive to dispose of. By introducing such a solution, not only is the amount of waste reduced and the burden on the environment reduced, but it also contributes to energy efficiency by recovering energy from secondary feedstock. By doing so, the economy becomes more sustainable and environmentally friendly. For many medium-sized and large wastewater treatment plants, co-digestion makes energy self-sufficiency possible, resulting in an ever-increasing number of biogas plants being set up at treatment plants. Organic waste, characterised by a rapid increase in biogas production during digestion, can be an energy store. The resulting reserve is used when there is increased demand for electricity or when the digesters' productivity drops. The key point is the appropriately selected composition of the cosubstrates to cover the plant's energy needs and, in addition, enable their sale. Another equally important factor in determining the potential and use of biogas in wastewater treatment plants is the population a plant serves. This affects the amount and composition of biogas and the thermal and electrical energy requirements of the individual plant components. Emerging technologies demonstrate the great potential for sewage sludge treatment and management (Gromiec 2020).

Conclusions

The idea of a circular economy can be successfully implemented in biogas plants operating at wastewater treatment plants. Sewage sludge, in the form of primary or surplus activated sludge, is the main feedstock for digesters. Therefore, such a location is a significant advantage for biogas plants, as they have a stable feedstock supply throughout the year. The safe and efficient disposal of SS in anaerobic biodegradation is a complex problem that requires a comprehensive approach to protect the environment and public health.

Operating a biogas plant at wastewater treatment plants that fit into an environmental and energy management system has many advantages. Digestion reduces the volume of SS, lowering the costs of storing or treating it as waste. Digested sewage sludge is more stable and has better fertilising properties, paving the way for its further use in agriculture. The production of renewable energy is very relevant to this topic. The biogas produced at wastewater treatment plants is used to produce electricity, heat or as fuel, reducing the need for fossil fuels and thus greenhouse gas emissions.

Investment costs undoubtedly come first among the challenges and difficulties: building and maintaining a biogas plant requires a lot of money, which can be a barrier, especially for smaller treatment plants. Furthermore, the technological complexity, the management of digestate, the variability in the quantity and quality of sewage sludge, and the availability of cosubstrates may, despite the streamlining and organisational measures in place, remain problematic in terms of process monitoring, transport, storage, or use of digestate or the specific variability in the quantity and quality of SS, respectively, which affects the efficiency of biogas production.

Developing biogas plants at sewage treatment plants is necessary but still challenging in Poland. Such plants have considerable potential to reduce the environmental impact of wastewater treatment while generating valuable energy. However, their efficiency and profitability depend on proper technology management and financial and regulatory support.

References

Ali, H., Khan, E., Sajad, M. A. 2013. *Phytoremediation of heavy metals—Concepts and applications. Chemosphere*, 91(7), 869-881.

Bachmann, N. 2015. *Sustainable biogas production in municipal wastewater treatment plants. International Energy Agency (IKA) Bioenergy*, France, Paris, ISBN 978-1-910154-22-9.

Borsukiewicz, A., Mocarski, S. 2018. *Zastosowanie siłowni ORC do zwiększenia mocy elektrycznej gazowego silnika wysokoprężnego zasilanego biogazem z oczyszczalni ścieków. Instal,* 3, 49–51.

Chmielowski, K., Młyńska, A., Młyński, D. 2015. *Efektywność pracy oczyszczalni ścieków w Kołaczycach. Inżynieria Ekologiczna*, 45, 44–50.

Czekała, W., Smurzyńska, A., Kozłowski, K., Brzoski, M., Chełkowski, D., Gajewska, K. 2017. *Kofermentacja osadów ściekowych jako sposób na ich zagospodarowanie oraz produkcję energii. Problemy Inżynierii Rolniczej*, 1(95), 5–14.

Davidsson, A., Lövstedt, C., la Cour Jansen, J., Gruvberger, C., Aspegren, H. 2008. *Co-digestion of grease trap sludge and sewage sludge. Waste Management*, 28, 986–992.

Dąbrowska, S., Masłoń, A. 2020. *The use of biogas from anaerobic digestion of sewage sludge to improve the energy balance of wastewater treatment plants. Czasopismo Inżynierii Lądowej, Środowiska i Architektury*, 37, 5–18.

Di Maria, F., Sordi, A., Cirulli, G., Gigliotti, G., Massaccesi, L., Cucina M., 2014. *Co-treatment of fruit and vegetable waste in sludge digesters. An analysis of the relationship among bio-methane generation, process stability and digestate phytotoxicity. Waste Management* 34, 1603–1608.

Directorate-General for Environment (European Commission) 2022. Unit B3, Circular Economy – From waste to Resources. Publications Office of the European Union, Luxembourg.

Domańska, W. 2022. *Statistical analyses. Environment*. Statistics Poland, Spatial and Environmental Surveys Department, Poland, Warsaw.

Dong, B., Liu, X., Dai, L. 2013. *Changes of heavy metal speciation during high-solid anaerobic digestion of sewage sludge. Bioresource Technology*, 131, 152−158.

Fonoll, X., Astals, S., Dosta, J., Mata-Alvarez, J. 2015. *Anaerobic co-digestion of sewage sludge and fruits wastes: Evaluation of the transitory states when the co-substrate is changed. Chemical Engineering Journal*, 262, 1268–1274.

Gazda, M., Rak, A., Sudak, M. 2012. *Badania kofermentacji osadów ściekowych z tłuszczami odpadowymi w oczyszczalni ścieków w Brzegu. Infrastruktura i Ekologia Terenów Wiejskich*, 3, 79–90.

Ghosh, M., Singh, S.P. 2005. *A review on phytoremediation of heavy metals and utilization of its byproducts. Applied Ecology and Environmental Research*, 3(1), 1–18.

Grobelak, A., Stępień, W., Kacprzak, M. 2016. *Osady ściekowe jako składnik nawozów i substytutów gleb. Inżynieria Ekologiczna*, 48, 52–60.

Gromiec, M., 2020. *Nowe koncepcje gospodarki wodno-ściekowej-osadowej,* in *Ocena gospodarki ściekowo-osadowej w Polsce*, eds. Bień, J., Gromiec, M., Pawłowski, L., *Wydawnictwo Polskiej Akademii Nauk, Komitet Inżynierii Środowiska*, Monografie, 166, 7–32.

Jaramillo, M.F., Restrepo, I., 2017. *Wastewater reuse in agriculture: A review about its limitations and benefits. Sustainability*, 9(10), 1734.

Kim, T., Bhatt, A., Tao, L., Benavides, P.T. 2022. *Life cycle analysis of polylactic acids from different wet waste feedstocks. Journal of Cleaner Production*, 380, 135110.

Klimek, A., Rolbiecki, S., Rolbiecki, R., Długosz, J., Musiał, M. 2013. *Wykorzystanie kompostowanego osadu ściekowego i ektopróchnicy leśnej do wzbogacania gleb w uprawie szkółkarskiej lipy drobnolistnej (Tilia cordata Mill.). Rocznik Ochrona Środowiska*, 15, 2811–2828.

Koc-Jurczyk, J., Jurczyk, Ł., Wanowicz, D. 2020. *Wykorzystywanie komunalnych osadów ściekowych jako źródła energii elektrycznej. Polish Journal for Sustainable Development*, 24(2), 54–62.

Korbag, I., Omer, S.M.S., Boghazala, H., Abusasiyah, M.A.A. 2020. *Recent advantaces of biogas production and future perspective. Biogas – recent advances and integrated approaches*, 1,3–42, DOI: 10.5772/intechopen.93231.

Kwaśny, J., Banach, M., Kowalski, Z. 2012. *Przegląd technologii produkcji biogazu różnego pochodzenia. Czasopismo techniczne. Chemia*, 109(2), 83–102.

Maćkowiak, C., Igras, J. 2005. *Skład chemiczny osadów ściekowych i odpadów przemysłu spożywczego o znaczeniu nawozowym. Inżynieria Ekologiczna*, 10, 70–77.

Marañón, E., Castrillon, L., Quiroga, G., Fernández-Nara, Y., Gomez, L., Garcia, M.M. 2012. *Co-digestion of cattle manure with food waste and sludge to increase biogas production. Waste Management*, 32, 1821–1825.

Masłoń, A., Czarnota, J., Szaja, A., Szulżyk-Cieplak, J., Łagód, G. 2020. *The enhancement of energy efficiency in a wastewater treatment plant through sustainable biogas use: case study from Poland. Energies*, 13, 6056.

Mełgieś, K., Malińska, K. 2016. *Aspekty prawne przetwarzania komunalnych osadów ściekowych do biowegla. Prace Instytutu Ceramiki i Materiałów Budowlanych*, 26, 96–107.

Mihelcic, J.R., Fry, L.M., Shaw, R. 2011. *Global potential of phosphorus recovery from human urine and feces. Chemosphere*, 84, 832–839.

Ministerstwo Środowiska. 2018. *Strategia postępowania z komunalnymi osadami ściekowymi na lata 2019–2022*, Warszawa.

Montusiewicz, A. 2012. *Współfermentacja osadów ściekowych i wybranych kosubstratów jako metoda efektywnej biometanizacji. Polska Akademia Nauk, Komitet Inżynierii Środowiska*, Monografie, vol. 98, Lublin, Poland.

Movahed, S.M.A., Calgaro, L., Marcomini, A. 2023. *Trends and characteristics of employing cavitation technology for water and wastewater treatment with a focus on hydrodynamic and ultrasonic cavitation over the past two decades: A Scientometric analysis. Science of The Total Environment*, 858, 159802.

Myszograj, S., Sadecka, Z., Suchowska-Kisielewicz, M. 2013. *Aspekty prawne i technologiczne współspalania osadów ściekowych. Inżynieria Środowiska*, 30, 65–78.

Olejnik, D. 2024. *Evaluation of the heavy metals content in sewage sludge from selected rural and urban wastewater treatment plants in Poland in terms of its suitability for agricultural use. Sustainability*, 16, 5198.

Owczuk, M., Matuszewska, A., Wojs, M.K., Orliński, P., Kruczyński, S.W. 2016. *Effect of biogas composition on performance of the engine. Przemysł Chemiczny*, 95(11), 10.15199/62.2016.11.21.

Pilarska, A.A. 2018. *Anaerobic co-digestion of waste wafers from confectionery production with sewage sludge. Polish Journal of Environmental Studies*, 27(1), 237–245.

Pilarska A.A., Kulupa T., Kubiak A., Wolna-Maruwka A., Pilarski K., Niewiadomska A. 2023. *Anaerobic digestion of food waste – A short review. Energies*, 16(15), 5742.

Pilarska, A., Pilarski, K, Ryniecki, A. 2014. *Wykorzystanie fermentacji metanowej do zagospodarowania wybranych produktów odpadowych przemysłu spożywczego. Nauki Inżynierskie i Technologie*, 4(15),100-111

Pilarska, A.A., Pilarski, K., Waliszewska, B., Zborowska, M., Witaszek, K., Waliszewska, H., Kolasiński, M., Szwarc-Rzepka, K. 2019. *Evaluation of bio-methane yields for high-energy organic waste and sewage sludge: A pilot-scale study for a wastewater treatment plant. Environmental Engineering Management Journal*, 18, 2019–2030.

Pilarska, A.A., Pilarski, K., Witaszek, K., Waliszewska, H., Zborowska, M., Waliszewska, B., Kolasiński, M., Szwarc-Rzepka, K. 2016. *Treatment of dairy waste by anaerobic digestion with sewage sludge. Ecological Chemistry and Engineering S*, 23, 99–115.

Pilarski, K., Pilarska, A.A., Niedbała, G., Boniecki, P., Piekutowska, M., Witaszek, K., Idzior-Haufa, M., Wawrzyniak, A. *Biomass Conversion Degree in Integrated Bioethanol and Biogas Production. Energies*, 14(22), 7763–7779.

Podedworna, J., Umiejewska, K. 2008. *Sewage Sludge Technology*. *Publishing House of the Warsaw University of Technology*, Poland, Warsaw.

Song, Y., Hou, R., Zhang, W., Liu, J. 2022. *Hydrodynamic cavitation as an efficient water treatment method for various sewage – A review. Water Science & Technology* 86(2), doi: 10.2166/wst.2022.201.

Rozporządzenie Ministra Gospodarki z dnia 16 lipca 2015 r. *w sprawie dopuszczania odpadów do składowania na składowiskach*, Dz. U. z 2015 r., poz. 1277.

Rozporządzenie Ministra Środowiska z dnia 9 grudnia 2014 r. *w sprawie katalogu odpadów*, Dz. U. z 2014 r., poz. 1923.

Szwaja, S., Poskart, A., Zajemska, M., Szwaja, M., Chwist, M. 2019. *Zgazowanie osadu ściekowego ze ślazowcem pensylwańskim. Przemysł Chemiczny*, 98(2) 278–282.

Ustawa z dnia 14 grudnia 2012 r. *o odpadach*, Dz.U. z 2013 r. poz. 21.

Ustawa z dnia 27 kwietnia 2001 r. – *Prawo ochrony środowiska*, Dz. U. z 2018, poz. 799.

Wieremiej, W., Kuziemska, B., Pieniak-Lendzion, K., Trębicka, J., Wyrębek, H. 2015. *Prawne aspekty przyrodniczego wykorzystania osadów ściekowych. Zeszyty Naukowe Uniwersytetu Przyrodniczo–Humanistycznego w Siedlcach*, 104, 207–218.

Wilińska-Lisowska, A., Czerwionka, K. 2021. *Wpływ kofermentacji odpadów rolno-spożywczych z osadami ściekowymi na produkcję biogazu oraz na skład frakcji ciekłej osadu przefermentowanego*. *Technologia Wody*, 2, 52–55.

Wilk, M., Gworek, B. 2009. *Metale ciężkie w osadach ściekowych. Ochrona Środowiska i Zasobów Naturalnych*, 39, 40–59.

Wim, R., 2008. *Sewage sludge as biomass resource for the production of energy: overview and assessment of various options*. *Energy Fuels* 22, 9−15.

Wiśniewski, D., Gawdzik, J., Traczewska, T.M. 2023. *Phosphorus recovery from sewage sludge ash: Current state and future trends. Environmental Science and Pollution Research*, 30(4), 4157–4169.

Woźniak, E. 2016. *Występowanie elektrowni biogazowych w Polsce i czynniki ich lokalizacji. in book: Interdyscyplinarne Zagadnienia w Inżynierii i Ochronie Środowiska*, Wydawnictwo Politechniki *Wrocławskiej*, Wrocław, pp 334–344.

Zajda, A., Kuglarz, M., Mrowiec, B. 2011. *Efektywność metanogenezy w warunkach współfermentacji osadów ściekowych i bioodpadów kuchennych. Nauka Przyroda Technologie*, 5(4), 62