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To appear in: Technical Sciences

Received 9 August 2024;

Accepted 14 November 2024;

Available online 25 November 2024.

Operation and challenges of biogas technology: A fundamental overview

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Abstract

The modern world is facing a huge energy crisis related to the depletion of conventional energy sources. Therefore, obtaining energy from alternative sources is sparking increasing interest, expressed by both scientists and entrepreneurs. One such source is biogas, which has great potential to become, along with wind and solar energy, an important renewable energy source (RES). The development of biogas production should proceed in a sustainable manner, meaning it should be economically stable and minimize negative environmental impacts. Its goal is to create efficient and eco-friendly energy solutions – largely based on the use of organic waste – that support a circular economy and help reduce greenhouse gas emissions. Achieving these conditions, however, requires addressing technical challenges, which often include the need to optimize biomass processing and invest in new technologies, issues with substrate heterogeneity, gas management and purification, digestate management, as well as infrastructure and scalability concerns. Sustainable biogas development thus requires solutions to these technical and infrastructure challenges, as well as support from policy and local communities.

This paper presents the technical and practical aspects of biogas production (mainly agricultural) and extensively discusses the anaerobic digestion (AD) process. The global development of biogas plants and the operation of the most important types of biogas plants are also discussed. In the conclusion section, the benefits of biogas technology development are provided and explained, as well as the challenges and barriers hindering the intensification of biogas plant construction despite the potential and access to adequate resources and waste materials.

Keywords: anaerobic digestion; organic waste; biogas composition; digestate properties; biogas plant operation; achievements and challenges

Introduction

Dynamic economic development contributes to a global increase in energy demand. The most widely used sources in the energy industry are conventional fuels, including coal, oil and natural gas. About 80% of the energy used in the world comes from their combustion. These raw materials belong to the group of non-renewable fuels, which means that they cannot be reused or newly obtained. According to various studies and estimates, hard coal, which is the main source of energy supply in Poland, will last for about 200 years, while in the case of oil and gas, it is determined that these raw materials can be acquired for a period of 50 years (Biernat 2018). As a result of the use of conventional fuels, over the years there has been an increase in atmospheric emissions, and consequently also environmental degradation and climate change, which are increasing in intensity with each passing year. Therefore, more and more research and technological solutions are focused on the search for alternative, more sustainable sources of energy, which include wind, solar, geothermal, hydro, as well as energy derived from various types of biofuels (ethanol, biogas, among others) (Gadirli et al. 2024).

Effective generation of energy from renewable energy sources (RES, Renewable Energy Sources) is one of the most important aspects of sustainable development, which brings positive environmental and energy consequences. The increase in the share of RES in the global energy sector has successively led to improved efficiency and savings of non-renewable raw materials, environmental improvements, as well as a significant reduction in organic waste from various industries, thanks to agricultural biogas plants that enable safe disposal of the waste and extraction of green energy (Muras 2010).

Table 1 presents the electricity yield in Poland from different generation sources in 2020–2022, according to the National Power System (KSE) 2022 report.

Table 1. Structure of installed capacity in MW, prepared on the basis of the National Power System (KSE) 2022 report

Status as of (date)	**31 December 2020**	**31 December 2021**	**31 December 2022**
Total	49,238	53,656	60,446
Commercial power plants	36,364	38,570	38,867
Hydroelectric commercial power plants	2,356	2,380	2,421
Thermal commercial power plants, of which:	34,008	36,190	36,446
hard coal-fired	22,747	24,611	24,897
lignite-fired	8,478	8,262	8,262
gas	2,782	3,317	3,288
Wind and other renewable energy power plants	10,229	15,086	21,578
Utility power plants	2,645	–	–
JWCD*	29,429	27,850	27,129
nJWCD*	19,810	25,806	33,317

* JWCD – Centrally Dispatched Power Generating Facility
* nJWCD – power of generating facilities that are not centrally dispatched by the transmission system operator

When analysing the values in Table 1, one can observe a significant dominance of commercial power plants, whose share has been increasing slightly over the years. Coal-fired power plants, which are the core of the Polish energy sector, continue to be of great importance. However, an important aspect is the huge increase in energy generation from renewable sources. In 2020, the value of installed capacity based on RES was 10,229 MW, already in 2021 this value increased by more than half, while in 2022 the amount of energy produced from this sector was 21,578 MW. Such a significant increase in the share of RES should be considered as revolutionary in relation to conditions in Poland. Therefore, one can predict that this value will grow, which is related to the increasing interest in new investment opportunities, the growing demand for electricity and the discovery and development of new efficient technologies.

Biofuels are becoming increasingly important in the renewable energy market, with the main energy source being feedstocks that are primarily distinguished by their low emissions of harmful gases into the atmosphere. These include organic waste, which remains in daily circulation, is biodegradable and does not pose a threat to the environment. Biofuels are divided into: solid (wood, straw), liquid (obtained by alcoholic fermentation – usually ethanol or esterification of vegetable oils – biodiesel) and gaseous – anaerobic digestion of so-called biogas produced from solid and liquid waste from agri-food production or in the process of biomass gasification (Rogowska, Berdechowski 2013).

Biogas is produced by anaerobic digestion (AD) from a variety of substrates, including waste from agri-food production, municipal operations and landfills. It consists mainly of methane, CH_4 (50–75%) and carbon dioxide, CO_2 (25–45%) as well as traces of other gases (hydrogen sulphide,H_2S; nitrogen, N_2; oxygen, O_2; hydrogen,H_2). Purified biogas, which is provided with the appropriate pressure and gas content percentages, becomes a fully adequate fuel that can be used in both the gas network and modern internal combustion engines (Zdebik et al. 2010). This means that its combustion does not contribute to a global increase in atmospheric carbon dioxide concentrations. Another extremely important advantage of biogas is its high calorific value of 20–26 MJ/m^3 (Colonna 2011). The process of biogas production is a biotechnological process, carried out with different groups of microorganisms decomposing organic matter in oxygen-free conditions, in biogas plants. Depending on the type of substrate undergoing fermentation, the biogas industry operates different types of plants, which are divided into agricultural, industrial, municipal, landfill and mixed.

Biogas technology, as one of the rapidly evolving forms of renewable energy, plays an important role in energy transformation and the achievement of global Sustainable Development Goals (SDGs). Aligned with climate objectives and circular economy principles, biogas integrates various economic sectors and contributes to effective resource management. Biogas production, based on the anaerobic digestion of organic waste, supports the reduction of greenhouse gas emissions, promotes sustainable waste management, and provides valuable secondary raw materials. This approach not only enables efficient waste utilization but also builds local energy resources, making biogas a key component of a sustainable energy future. It is essential to highlight that biogas is an integral part of the green energy mix, standing alongside solar, wind, and hydro power as a vital element in the energy transition. A unique feature of biogas is that its production is not dependent on weather conditions (unlike solar and wind energy), allowing it to serve as a stable and accessible energy source year-round. Research shows that biogas technology, especially in Europe with its extensive agricultural and industrial base, effectively supports the stability of energy systems transitioning toward renewable sources. North America and Asia are also increasingly investing in biogas, underscoring its international role in renewable energy systems. Biogas production naturally aligns with minimizing environmental impact, as it processes organic waste like food residues, agricultural, and municipal waste (Gadirli et al., 2024). By utilizing organic substrates, biogas closes the material loop and minimizes waste, which would otherwise need to be disposed of through landfilling or incineration. The fermentation process enables emissions-free energy generation and also reduces methane emissions – a greenhouse gas that naturally escapes from decomposing organic waste.

The AD process not only allows energy production but also generates valuable by-products. Digestate, the residual product, can be used as a natural fertilizer rich in nutrients, closing the material cycle and reducing the need for artificial chemical fertilizers. A circular economy supported by biogas production also contributes to local and regional economic development. It enables efficient use of local resources and waste, reducing the costs of transport and disposal, and provides additional income opportunities, especially for agricultural businesses. Examples from Scandinavian countries and Germany show that biogas usage within such a system not only stimulates the local economy but also boosts employment in sectors related to recycling and green technologies.

Agricultural biogas plants are a source of tangible benefits for agriculture, an opportunity to provide greater energy security (by diversifying energy sources) and improve the lives of local communities. These plants offer a number of advantages, but also face challenges that can hinder their development. Among the most common issues in the construction of new plants are high investment costs, regulations and bureaucracy, operational costs, small-scale efficiency, variable government support and emerging, albeit less frequent, problems with public acceptance. Undoubtedly, renewable energy generation from biogas, due to the high investment and operational costs of production facilities, is one of the more expensive options among all RES. Thus, the leading determinant for the development of the biogas sector appears to be the support system for renewable energy sources.

The aim of this article is to describe the process parameters of biogas production, to present the types and operation of biogas plants, and to analyse the sustainability and cost-effectiveness of biogas technologies and their place in a circular economy.

Conditions of anaerobic digestion process – technical and practical aspects

Substrates used in the anaerobic digestion

There are many types of substrates that can be used as a source or feedstock for biogas production. There are many types of substrates that can be used as a source or feedstock for biogas production. Most biodegradable organic compounds can be converted by anaerobic digestion and their biodegradability is an indicator of the extent to which this process is possible. Feedstocks for biogas production are: sewage sludge, municipal solid waste, industrial solid waste and wastewater, food waste, animal manure, plant breeding waste, catch crops, energy crops (cereals, grasses) and microalgae (Korbag, Omer 2021).

Currently, sludge from municipal wastewater treatment plants is considered the main source of organic matter for biogas production, with Sweden being a pioneering country. Wastes from wastewater treatment plants are mainly primary sludge, excess sludge and fats, oils and other products of flotation (Montusiewicz 2012). However, one of the largest substrate resources is manure and slurries from cattle, pigs, as well as poultry, fish, fur. Animal manure, mainly from pigs, cattle and poultry, is considered the main source of carbon in the AD process. The total content of solids present in animal manure consists of 90% moisture and volatile suspended solids. It proves to be an excellent substrate due to its high buffering capacity. Numerous publications have also shown that a high methane content is obtained in biogas from agricultural waste due to its significant protein and fat content (Gadirli et al. 2024). One of them is maize silage, which is distinguished by its stability and efficient biogas production, easy cultivation technology, possibility of long storage, and low price. Table 2 shows examples of substrates from agri-food industry waste and their biogas yields.

Table 2. Substrates in biogas production and their energy potential; based on (Zapałowska and Gacek 2019)

Type of substrate	Biogas efficiency ($Nm^3\ Mg^{-1}\ FM^*$)	Methane concentration (%)
Whey	30	52
Distillers grains	75	55
Expired food	120	52
Potato pulp	130	50
Beet pulp pellets	130	50
Maize silage	215	54
Maize stover	400	54

* FM – fresh matter, Nm^3 – normal cubic meters

The organic fractions of municipal waste have a nutrient deficit, low buffer capacity, high dry matter concentration, low pH and contain lignocellulosic and toxic compounds, which adversely affect the efficiency of biogas production. Despite their complexity, their composition is not stable and varies according to the season and depends on the lifestyle and habits of the inhabitants. In addition, it is different across urban and rural areas. Municipal waste fractions are 20–59% dry matter containing 53–88% organic compounds. The best subgroup of municipal waste is kitchen waste and fruit and vegetable waste from markets. They are more heavily hydrated, with dry matter accounting for 10–26%, including desirable organic matter accounting for 80–97%. These wastes have low concentrations of heavy metals and may have the disadvantages of low pH and alkalinity (Montusiewicz 2012).

Table 3 summarises the waste used as substrate in AD by source. An assessment of the susceptibility of the waste to biochemical decomposition is marked: yellow indicates very good susceptibility, green indicates good susceptibility and white indicates poor susceptibility.

Table 3. Waste substrates used in biogas production, together with their susceptibility to biochemical decomposition; based on Montusiewicz 2012.

Waste origin	Type of waste	Biogas efficiency ($Nm^3\ Mg^{-1}\ VS^*$)
Waste from wastewater treatment plants	primary sludge	250–350
	excess sludge	
	fats, oils and other products of flotation	
Agricultural waste – plant biomass	stover and other fibrous plants	200–500
	green crops, agricultural crops, grains, silages	500–990
	post-harvest residues	
Agricultural waste – animal manure	chicken manure, cattle manure	100–900
	pig manure	

	manure from other animals	
Waste from slaughterhouses, abattoirs and fish processing plants	animal fat	300–1,200
	flotation tailings	
	blood	
	intestinal or stomach contents	
	fish waste	
	poultry waste	
	animal-tissue waste	
Wastes from plants producing animal and vegetable fats and oils	deteriorated vegetable oils	600–1,600
	oilseed residues	
	greases	
	sludges from edible oil production	
	sludges from edible fats production	
Wastes from gelatine production plants	sludges from gelatine production	700–900
Wastes from potato and maize meal manufacturing plants		600–900
Wastes from yeast factories, breweries, wineries and distilleries	leachates from yeast production	300–850
	wine-making lees	
	distillers grains	
	leachates from malt houses	
	Fruit and vegetable marc (maize, potatoes)	
Waste from the dairy products industry	whey	400–900
Waste from the papermaking industry		200–800
Pharmaceutical waste	protein wastes	660–1,300
	bacterial cells, mycelium	
	residues of gelatine capsules	
Food products	expired or unfit for consumption	500–650
Municipal waste	biodegradable sorted waste	400–500
	garden and park waste	350–500
	waste from markets	500–600

* VS – volatile solids, Nm^3 – normal cubic meters

Anaerobic digestion stages and products

Obtaining biogas in anaerobic biodegradation is a complex and multi-stage process. Its main stages are hydrolysis, acidogenesis, acetanogenesis and the methanogenic (Gadirli et al. 2024). The transformations within these stages actually occur simultaneously, with different groups of bacteria working together to convert biomass into biogas. The efficiency and stability of each stage – and thus the overall biogas yield – can be optimized by carefully managing temperature and pH levels.To illustrate the process, a diagram showing the main stages of anaerobic digestion is shown below (see Figure 1).

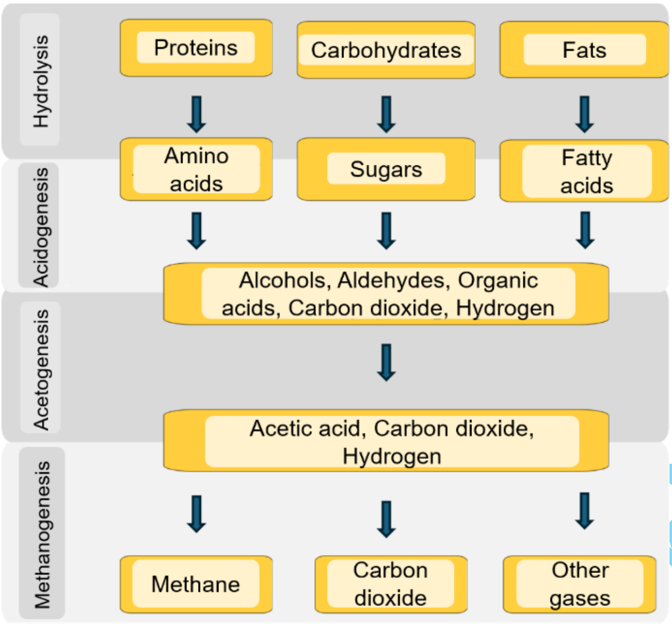

Figure 1. Anaerobic digestion process stages (author's own scheme)

According to the figure presented above, the initial reaction in the biogas production process is a hydrolysis reaction, whereby complex polymers (hydrocarbons, fats and proteins) are broken down into simple organic compounds such as amino acids, fatty acids, simple sugars and glycerin (Schattauer, Weiland 2005). This step is essential for making the organic material accessible to the bacteria involved in the subsequent stages. The decomposition of compounds is made possible by enzymes released by bacteria through biochemical reactions.

Example equation for the decomposition of sugars:

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 \text{ organic matter/glucose} \quad (1)$$

The effectiveness of hydrolysis significantly affects biogas yield, as incomplete breakdown at this stage can limit the availability of substrates for downstream processes. Slow or inefficient hydrolysis can reduce overall gas production. Optimal temperature (mesophilic: ~35°C or thermophilic: ~55°C) accelerates the hydrolysis process by enhancing enzymatic activity. Higher temperatures in the thermophilic range can improve hydrolysis rates but require careful management, as they can also increase operational energy costs. pH levels are typically maintained around neutral (6.5–7.2), as extremes can inhibit enzyme activity and microbial growth. Maintaining these conditions helps ensure efficient hydrolysis and a steady supply of substrates for acidogenesis (Chen et al. 2008, Kothari et al. 2014).

Acidogenesis is the next stage of biogas formation, in which the previously formed monomers are broken down by acetogenic bacteria into intermediate products, i.e. short-chain fatty acids (formic acid, acetic acid), alcohols (methanol, ethanol), aldehydes, as well as the gaseous products hydrogen and carbon dioxide. Some compounds formed in this stage can be used directly by methanobacteria. This stage is crucial as it transforms soluble organic compounds into intermediates that can be utilized in acetogenesis.

Example of an indirect reaction equation

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 \text{ (glucose/ethanol)} \quad (2)$$

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O \text{ (glucose/propionic acid)} \quad (3)$$

Acidogenesis contributes indirectly to biogas yield by creating VFAs and other compounds that serve as precursors in the next stages. Excessive accumulation of VFAs, however, can lower the pH, leading to system instability and inhibiting biogas production. This stage thrives in similar temperature ranges as hydrolysis, with mesophilic or thermophilic conditions enhancing microbial activity. pH control is essential here; if VFAs (volatile fatty acids) accumulate excessively, the pH may drop below the optimal range (5.5–6.5 for this stage), inhibiting further reactions (Leite et al. 2015). Buffering agents like bicarbonates may be added to stabilize pH and prevent acid accumulation, promoting smoother transition to acetogenesis.

The third stage, called acetogenic, involves the formation of acetic acid, hydrocarbon and carbon dioxide with the participation of acetic and methane bacteria. The life of these bacteria is closely intertwined, as methanogens consume hydrogen and thus contribute to providing the right conditions for acetic bacteria to live. The important reactions of this stage are:

$$CH_3CH_2OH + 2H_2O \rightarrow CH_3COO^- + 2H_2 + H^+ \text{ (ethanol/acetate)} \quad (4)$$

$$2HCO_3^- + 4H_2 + H^+ \rightarrow CH_3COO^- + 4H_2O \text{ (bicarbonate/acetate)} \quad (5)$$

Efficient acetogenesis is vital for biogas yield because acetic acid and hydrogen are directly utilized in methanogenesis, where methane is produced. Any inhibition in acetogenesis could limit the availability of these essential substrates, decreasing biogas output. It should be noted thatacetogenesis is sensitive to hydrogen accumulation, which can inhibit bacterial activity. To prevent this, hydrogen-consuming bacteria should be maintained under conditions that encourage their activity – typically neutral pH and optimal temperatures similar to those in the previous stages. Keeping pH stable supports acetogenic bacteria, while thermophilic conditions can further enhance conversion rates but may require careful monitoring to avoid energy inefficiencies (Chen et al 2008).

The final stage is the methanogenesis, which is the generation of methane by methanogenic bacteria and the reduction of carbon dioxide with hydrogen. Most of the methane is generated from acetates or alcohols; the remainder is obtained by reducing carbon dioxide with hydrogen. The individual reactions of this stage are as follows (Pilarska et al. 2019a):

$$2CH_3CH_3OH + CO_2 \rightarrow 2CH_3COOH + CH_4 \quad (6)$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (7)$$

$$CH_3OH + H_2O \rightarrow CH_4 + H_2O \quad (8)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (9)$$

Methanogenesis is the most crucial stage for biogas yield. The efficiency and stability of this step determine the final methane concentration in the biogas. Proper conditions in methanogenesis ensure maximum methane production, leading to high-quality, energy-rich biogas. Methanogenic archaea are highly sensitive to changes in temperature and pH. Optimal temperatures for methanogenesis are either in the mesophilic range (~35°C) or thermophilic range (~55°C), depending on the system setup. Methanogenesis requires a slightly alkaline environment, with an ideal pH range between 7.0 and 8.0. Fluctuations in pH or temperature can drastically reduce methane yield, so precise control is essential. Using buffering agents or adjusting substrate feeding rates can help stabilize pH and maintain a conducive environment for methanogens (Strik et al. 2006).

The above detailed descriptions and indications prove that the managing temperature and pH across each stage is essential for optimizing AD and biogas yield. Consistent temperature control – either in the mesophilic or thermophilic range – supports enzyme activity and microbial growth, with thermophilic conditions generally increasing reaction rates but also requiring more energy. On the other hand, the maintaining appropriate pH levels in each stage ensures that microbial communities function effectively, as different bacteria thrive in slightly different pH ranges. Buffering and slow adjustments can prevent the inhibitory effects of pH fluctuations (Pilarska et al 2019b).

The generation time of microorganisms varies in each stage. For the initial stages, it can be several minutes, while for methanogens, due to their slow formation and sensitivity to disturbances in environmental conditions, it ranges from tens to hundreds of hours (Schattauer, Weiland 2005). Table 4 shows the types of bacteria involved in the biogas production process and the substrates they decompose.

Table 4. Bacteria contributing to biogas formation; based on (Wang et al. 2018)

Species of bacteria	**Substrate decomposed**
Methanobacterium omelianski	H_2, ethanol, primary and secondary alcohols
Methanobacterium suboxydans	Butyrate, acetate, capronate
Methanobacterium sohngenii	acetate, butyrate
Methanobacterium propionicum	propionate
Methanobacterium formicicum	H_2, CO_2, formate
Methanococcus mazei	acetate, butyrate

Methanococcus vannielli	formate, H_2
Methanosarcina barkeri	H_2, CO, methanol, acetate
Methanosarcina methanica	acetate, butyrate

In the process of hydrolysis and acidogenesis, about 50 genera of bacteria are involved, including *Clostridium*, *Bacteroides*, *Streptococcus*. Sixty-five species have been discovered, belonging to 19 genera of methanogens, which are archaeons. This group of microorganisms includes among others *Methanobacterium*, *Methanococcus*, *Methanosarcina* (Wang et al. 2018). In summary, the bacteria involved in methane fermentation are very sensitive to variations in environmental conditions. Key conditions include lack of oxygen and light, adequate, constant temperature, proper pH, humidity and low environmental toxicity. Even slight fluctuations, as discussed in the next subsection of the paper, can slow down or inhibit bacterial activity, leading to a reduction in the amount of methane production in the biogas that is released. In extreme cases, it may even lead to a halt in the fermentation process.

Biogas, as the main product of AD, is a mixture of methane and carbon dioxide. However, it is worth noting that its composition largely depends on the type of substrate used. Table 5 presents the chemical composition of biogas generated from domestic waste, sewage sludge, waste derived from agricultural activities and waste from the food industry.

Table 5. Chemical composition of biogas obtained from different waste origins; based on (Bharathiraja et al. 2016)

Biogas component	**Unit**	**Household waste**	**Sludge from wastewater treatment plants**	**Agricultural waste**	**Waste from the agri-food industry**
CH_4	% vol.	50–60	60–75	60–75	68
CO_2		34–38	19–33	19–33	26
N_2		0–5	0–1	0–1	–
O_2		0–1	<0.5	<0.5	–
H_2O	% vol.	6	6	6	6
H_2S	Mg/m^3	100–900	1,000–4,000	3,000–10,000	100
NH_3		–	–	50–100	400
Aromatic compounds		0–200	–	–	–
Halogenated or fluorine organic compounds		–	–	–	–

However, before the biogas produced can be used as an energy source, it must be treated to increase the proportion of methane in the biogas and thus its calorific value. The process equipment that enables biogas to be properly purified and pressurised is a dehumidifier, cooler, heater, blower and carbon filter. Once the biogas has undergone the appropriate treatment stages on the aforementioned equipment, it acquires optimum parameters for energy use (high methane and carbon dioxide content, without the presence of compounds such as hydrogen sulphide or siloxanes). Biogas is most often used to produce hot water or steam for boilers, to produce electricity using generators, or in special gas engines. Alternatively, it can also be used as a fuel for vehicles (Ryckebosch et al. 2011).

Despite these numerous possibilities, the most common way of utilising biogas from the AD process is still to divert it into a high-efficiency cogeneration unit, allowing the production of both electricity and heat. The possibilities and limitations for full utilisation of the energy potential of raw materials (primary energy of substrates), was pointed out in their article by Pilarski et al. 2023.

In contrast, the digestate is a by-product of the AD process and is produced in any type of biogas plant. It is obtained in the final stage of decomposition of the organic matter that was used to produce biogas. As it is produced from different types of substrates and organic waste, its properties and nitrogen, phosphorus and potassium content may also vary. The literature indicates that the amount of digestate produced ranges from 85–95% of the mass of substrates used in the process, with the larger the flow of liquid substrates (e.g. slurry or sewage sludge) used in the process, the significantly lower the amount (Häfner et al. 2022). Basically, the composition of the digestate consists of: undigested residual organic matter, various types of minerals, as well as residual amounts of methane microorganisms. The digestate is primarily an aqueous suspension containing 2–5% dry matter, pH around 7. The total nitrogen (N) of the digestate varies between 2% and 3% of the fresh mass. Organic nitrogen is ammonified to a large extent during the AD process – so the ammoniacal nitrogen (NH_4–N) content of the by-product can be as high as 85%.

Key parameters of anaerobic digestion

Maintaining the correct progression of the AD is a fundamental task for the correct operation of a biogas plant. It is necessary to ensure the appropriate environmental conditions for parameters such as process temperature and pH level, oxidation-reduction potential, substrate fineness, concentration and type of microorganisms, as well as the content of nutrients, toxic compounds or volatile fatty acids. In addition, it is vital to adopt measures to maximise the efficiency of gas production. Excessive parameter variability can lead to inhibition of bacterial activity and acidification of the feedstock. The microorganisms involved in digestion require different environmental conditions (Worwąg et al. 2010). The following section presents the optimum values of process parameters, as well as an analysis of the impact of their variability on the digestion process.

Temperature has a very significant effect on the digestion process. As is well known, chemical reactions occur faster at higher ambient temperatures. However, when considering the biological processes of decomposition and transformation, this relationship has certain limitations. Each type of bacteria involved in these processes requires a different temperature. Exceeding these ranges can lead to inhibition or irreversible damage to the bacteria. The bacteria involved in the decomposition process can be divided according to their temperature requirements into three groups: psychrophilic, mesophilic and thermophilic.

- Psychrophiles reach an optimal growth temperature at approximately 25 °C. Although they do not require substrate heating, their decomposition efficiency and gas production are clearly inferior and limited.
- Methanogens reach their optimal growth temperature in the mesophilic range between 32 and 42 °C. Plants operating in this range are the most common, as they provide good performance and process stability.
- Thermophiles are used for processes when pathogenic bacteria need to be neutralised and a medium with a high intrinsic temperature is used. Their optimal temperature range is 50 to 57 °C, which allows high gas yields to be obtained; however, this process is more energy-intensive (Gadirli et al. 2024; Schattauer, Weiland 2005)

A 10-degree temperature change is considerable for microorganisms and can significantly disrupt methanogen populations. This results in increased volatile acids in the digester, a decrease in pH and a decrease in alkalinity. Therefore, it is necessary to insulate and heat the biodigester from the outside, especially for the growth of mesophiles and thermophiles. The temperature is closely related to the timing of the digestion process. For mesophilic bacteria, the process is slower (12–36 days). In contrast, under higher temperature conditions for thermophilic bacteria, the decomposition time for organic matter is reduced and ranges from 12–14 days.

Nutrients are another important parameter in biogas production. The proper functioning of the bacteria depends on the provision of all necessary nutrients. Although the type of feedstock plays a key role in the efficiency of gas production, one should not neglect the presence of the necessary elements, i.e. iron, nickel, cobalt selenium and tungsten. Although the content of these elements is trace, they are essential for the growth and survival of bacteria. The elements that have a significant impact on process stability are carbon and nitrogen (Schattauer, Weiland 2005). The most favourable C/N ratio for the process should be between 10:1 and 25:1. Their ratio in the feedstock must not be too high so that incomplete carbon conversion and a reduction in methane potential does not occur. On the other hand, in case of an excess of nitrogen, an excess of ammonia may be formed, leading to inhibition of bacterial growth and even destruction of the entire population.

The pH is another key parameter responsible for the stability of the operation of digesters. As with temperature changes, the bacteria present at different stages of the process have different pH requirements. Hydrolysing and acid-forming bacteria prefer a pH in the range 4.5 to 6.3. Although they can survive at slightly higher pH values, their activity will be reduced under such conditions. Acetic acid- and methane-producing bacteria, on the other hand, require a well-defined pH between 6.8 and 7.5. If the buffer capacity of carbon dioxide is depleted, the pH may drop. A drop in pH inhibits the activity of methane-producing bacteria, which leads to the concentration of acids associated with acetic fermentation. This further lowers the pH, leading to acidification of the process and inhibiting the activity of the bacteria. In order to prevent this from occurring, the substrate feed should be stopped and the methanogenes should be given time to decompose the acids, allowing the digestion process to return to proper functioning. If the pH were higher than 8.5, a toxic environmental reaction would also occur, which would have a negative impact on the growth of methanogenes (Pilarska et al., 2019b).

Inhibitors are substances that, in low concentrations, have a toxic effect on bacteria and contribute to the malfunctioning of the biogas plant. These substances can enter the biodigester with the substrates (organic compounds, heavy metals) or can be formed as intermediates in the individual stages of anaerobic digestion (ammonia, hydrogen sulphide) (Pilarska et al., 2016). It is common to distinguish between many types of inhibitors in methane fermentation. The most common are ammonia, sulphides, heavy metals, organic compounds, as well as light metal ions and compounds formed during the heat and pressure treatment of lignocellulosic substrates. For anaerobic bacteria, ammonia is an essential nutrient, but even in small concentrations it can have a detrimental effect and inhibit the fermentation process. The fermentation of urea and protein yields ammonium nitrogen (NH_4^+), the presence of which is difficult to eliminate. Two forms of this compound can be formed, such as ammonium ion, which is less toxic, and ammonia, which is more hazardous to the process. An increase in the amount of ammonium nitrogen increases the alkaline pH, which adversely affects the growth of methanogenic microorganisms and contributes to a decrease in methane production.

According to scientific studies, inadequate concentrations of ammonium nitrogen can reduce methane production by up to 50%, and the fermentation process at high ammonia concentrations is more stable for mesophiles than for thermophiles (Chen et al. 2014).

In fact, changes in the pH value, NH_4^+ and VFAs concentrations are most often indicated as the cause of destabilization of the AD process and are subject to constant monitoring. Ammonium nitrogen is a byproduct of protein degradation and is a common component in waste streams such as livestock manure and municipal wastewater. While essential for microbial growth, ammonium concentrations exceeding 400 mg/L are frequently cited as inhibitory, leading to a toxic environment for anaerobic microorganisms (Chen et al. 2008). High levels of ammonium nitrogen can shift the balance of microbial populations, specifically inhibiting methanogenic archaea responsible for methane production. According to Rajagopal, Massé et al. 2013, ammonia toxicity is attributed to its ability to penetrate cell membranes, which disrupts cellular pH balance and enzyme activities, leading to reduced methane yields. Moreover, the impact of ammonium inhibition is often exacerbated at higher pH levels, where more ammonium is present in its un-ionized, free ammonia (NH_3) form. This free ammonia form is more toxic to microbes due to its ability to diffuse freely across cell membranes, causing intracellular accumulation and metabolic disruption. Yenigün and Demirel 2013 in their article emphasize the delicate balance required to manage ammonium levels, recommending operational adjustments such as dilution and pH control to mitigate its inhibitory effects.

While VFAs are crucial precursors for methane formation, their accumulation at high concentrations can lead to acidification of the reactor environment. Excessive VFAs not only inhibit the activity of methanogens but also contribute to a drop in pH, which can critically destabilize the entire microbial ecosystem. According to Chen et al. 2008, VFAs concentrations that exceed the buffering capacity of the system can lead to pH levels falling below 6.5, a range in which methanogens become severely inhibited or inactive. This shift in pH can result in the dominance of acidogenic bacteria over methanogens, leading to a build-up of acidic intermediates and further inhibition of biogas production. The combined presence of high ammonium nitrogen and VFAs creates a challenging inhibitory environment for anaerobic digestion. Ammonium toxicity, when paired with acid accumulation from VFAs, can disrupt the microbial community structure by selectively inhibiting sensitive microbial groups. Methanogens, for instance, are particularly vulnerable to acidic conditions, which reduce their population and diversity. This scenario has a cascading effect on biogas yield, as methanogens play a critical role in converting VFAs and hydrogen into methane.

The combined presence of high ammonium nitrogen and VFAs creates a challenging inhibitory environment for anaerobic digestion. Ammonium toxicity, when paired with acid accumulation from VFAs, can disrupt the microbial community structure by selectively inhibiting sensitive microbial groups. Methanogens, for instance, are particularly vulnerable to acidic conditions, which reduce their population and diversity. This scenario has a cascading effect on biogas yield, as methanogens play a critical role in converting VFAs and hydrogen into methane.

To optimize biogas production and counteract these inhibitors, operational adjustments can be made: (i) pH control (regular monitoring and buffering of pH can help prevent acidification from excess VFAs), (ii) ammonium dilution (diluting feedstock with water or less nitrogen-rich material can help lower ammonium concentration), (iii) gradual loading increases (lowly increasing substrate loading can help acclimate microbial communities to higher concentrations of VFAs and ammonium). The indications are practical and effective in application. To sum up, effective anaerobic digestion relies on a balance between organic load and microbial health. Addressing the risks of ammonium and VFA inhibition through careful monitoring and strategic management is essential for achieving consistent, high-yield biogas production.

Benefits and problems of implementing the process

Anaerobic digestion is a biological process that allows biogas to be extracted from organic compounds due to microorganisms, which can then be converted into energy, heat or transportation fuel needed for the functioning of society. In addition to this essential benefit, this process has many other important advantages (Weiland et al. 2001, Appels et al. 2008). A selection of these are presented below:

- AD facilitates the use of RES and offers the prospect of reducing the use of depleting mine deposits, helping to reduce greenhouse gas emissions, mainly carbon dioxide and methane,
- Anaerobic digestion allows efficient biomass management, which promotes the reduction of landfill space, eliminates the problem of disposing of many troublesome wastes, i.e. sewage sludge, slaughterhouse waste and many other types of agricultural waste,
- the digestate, as a by-product of the process, is used as a fully adequate natural fertiliser; digestate is generally suitable as fertilizer when: (i) it has been tested for contaminants, and levels are within safe limits for agricultural use , (ii) nutrient levels align with the crop’s requirements, possibly with adjustments for balance, (iii) it is pathogen-free or

has undergone additional treatment to meet hygiene standards and (iv) salinity and pH are compatible with the intended soil and crop,

- codigestion enables the dilution of toxic substances that enter the process with the substrates, increases the amount of nutrients and the biodegradability of organic substances, and increases the degree of digestion and the efficiency of biogas production.

The problems and challenges of implementing the anaerobic digestion process mainly concern the following phenomena and factors (Mata-Alvarez et al. 2014):

- fermenting bacteria, especially methanogenes, are sensitive to changes in the environment, which is why the selection and monitoring of process parameters is so important,
- some substrates are periodically (seasonally) available, therefore logistical planning of the process is necessary when producing biogas,
- disruptions in the digester can occur due to inadequately (chemically) selected substrates, accidental introduction of toxic substances and contaminants, too rapid application of substrate into the reactor; chemical factors that can render co-substrates unsuitable, potentially inhibiting microbiological activity and causing process inefficiency include: carbon to nitrogen (C/N) ratio (ideal ratios range from 20:1 to 30:1), presence of inhibitory compounds in some materials, organic loading rate (OLR) and total solids content and pH and buffering capacity (e.g. co-substrates with high acidity, such as fruit waste, can decrease the pH (Mata-Alvarez et al. 2000).
- during anaerobic digestion, generated hydrogen sulfide may create engineering issues, i.e., corrosion of pipelines or fittings; another undesirable phenomenon is also the release of ammonia in the digester, excessive concentrations of which may lead to the inhibition of the process.

These are only selected issues, but it should be emphasised that the preponderance of the advantages of implementing methane fermentation prompts both researchers and practitioners to carry out continuous work on improving the possibilities of its implementation. This is based on access to reliable knowledge and information, the support of trained professionals, education, as well as the development of new, simple technologies that solve the problems mentioned. Continuous quality control of substrates, implementation of analytical methods, automation and process monitoring are also important components of success.

Fundamental issues concerning biogas plants

Development of biogas plants

Global economic development is contributing to a continuous increase in energy demand. As estimated by Żygadło and Madejski (2016), energy consumption in the European Union will increase by 25% by 2030. In contrast, a much greater increase in energy demand of at least 50% is projected, worldwide, by 2050. Extensive discussions are taking place on abandoning the use of non-renewable energy sources such as fossil fuels, which contribute to increased environmental pollution and exacerbate climate change through the emission of greenhouse gases. It is estimated that a prohibition on the use of fossil fuel boilers in all buildings will be implemented starting in 2040 across the European Union.

Referring back to the topic of biogas plant development, in Europe, countries such as Germany (11,269) are leaders in the number of biogas plants built, followed by Italy (1710), then France (890), the Czech Republic (578) and Austria (423). The first model of the European market is primarily based on a predominantly crop-based feedstock (maize silage). On the one hand, this is due to favourable conditions for the cultivation of crops for biogas plants and, on the other, to the regulations (system of incentives and subsidies) adopted by legislators and the relatively old technology used in this type of plant, which was designed for the fermentation of biomass from crops (first-generation biogas plants, so-called NaWaRo technology). The second model of national biogas markets in the European Union is based on raw material recovered from landfills. Such a structure is mainly determined by the waste management strategy adopted. The leader in this area is the United Kingdom, where the first commercial system in Europe for recovering biogas from landfill sites was established in 1982. Poland has a huge potential in biogas production, but reports indicate that only about 3% of it is used. The current number of biogas plants in Poland is 388 with a total electrical capacity of about 280 MW, of which agricultural biogas plants account for the largest share (Gadirli et al. 2024). This situation is influenced by legal, economic and social factors changing and evolving over the last decade. The state of development of the market for agricultural biogas plants in Poland is to a large extent a result of the functioning of the existing RES operating support system, i.e. the so-called certificate of origin system, as well as support for energy generation through cogeneration.

Various forms of biomass represent the third largest RES in the world. Unlike wind or solar power, biomass does not require a highly specialised infrastructure, which is a significant advantage for countries and regions with varying topography. According to the literature, the first industrial biogas plant in India was established in 1859, while in Poland, more specifically in Poznań, the first plant using sewage sludge became operational in 1928 (Kwaśny et al. 2012). The location for the development of a biogas plant is influenced by numerous factors, such as the availability of feedstock, distance to the market, location, possibility of employing workers, as well as environmental, economic, spatial, political and technical factors. Biogas plants, due to their ability to produce energy, are divided into micro-scale (CHP electrical power <15 kWe; CHP – Combined Heat and Power Plant), small-scale (15 kWe<CHP electrical power<99 kWe), medium-scale (100 kWe<CHP electrical power <299 kWe) and large-scale (CHP electrical power >300 kWe) (O'Connor et al. 2021). The efficiency of the biogas plant can be assessed on the basis of the feedstock used and the heat generated, which provides a basis for calculations, performance estimates and cost estimates for the biogas plant project (Zapałowska and Gacek 2019). The key item on the balance sheet is the biogas consumption required for the biogas plant's own use and the amount of surplus that can be sold (Szczyrba et al. 2020).

The conduct of advanced administrative, research and implementation and educational activities towards the increase of the use of renewable energy sources, including biomass – both in Europe and worldwide – is currently the only valid direction in the context of ensuring energy security and environmental protection.

Types and operation of biogas plants

A biogas plant consists of several key components that are necessary for methane fermentation and biogas production. The most important components in the construction of the plant are: a substrate/feedstock tank, a biodigester with mixer, a tank for the produced biogas, a cogeneration system, CHP (where the biogas is burned in engines, turbines or microturbines to produce electricity and heat simultaneously), a digestate tank and a biogas purification system. The cleaned biogas can be used in cogeneration systems or, after further treatment (removal of CO_2), as biomethane to feed into gas networks.It should be added that no biomethane plant is currently operating in Poland. However, when comparing the potential and possibilities of investors with the infrastructural possibilities that are in place, development is currently only hindered by legislation. Integration with the gas network, rules concerning the preparation of investments, the support system – these issues, fundamental for the renewable sources industry, are still lacking when it comes to the issue of biomethane.

The biogas plants in operation worldwide can be divided into individual groups, which are briefly characterised below.

Agricultural biogas plants, which are the most numerous group of biogas plants in the world. There are 17,662 such plants in the European Union alone, fourteen of which have an installed capacity of 9,985 MWe (O'Connor 2021). In Poland, the first agricultural biogas plant was commissioned in 2005 in Pawłówko. There are currently 218 agricultural biogas and microbial biogas plants in operation across the country. Figure 2 shows in a bar graph the dynamic growth in the number of agricultural biogas plants built in Poland. It should be noted that their number has more than doubled since 2017.

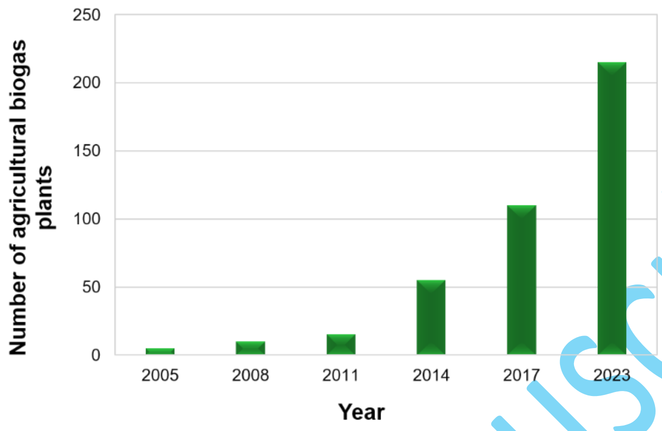

Figure 2. Development dynamics of agricultural biogas plants in Poland; partly based on Register (2018).

The feedstock for agricultural biogas plants is organic raw materials such as energy crops, maize silage, expired food from restaurants and waste from the agri-food industry. Biogas yields oscillate between 90–750 m^3 Mg^{-1} VS. Therefore, the use of waste is the cheapest and most environmentally optimal way of disposal. An additional advantage is that the digestate can be used as a fertiliser rich in nitrogen, phosphorus and potassium. Further advantages of agricultural biogas plants are energy self-sufficiency, an additional source of income for farmers, support in the restructuring and modernisation of agriculture and the creation of new jobs. Initially, biogas plants were built next to large farms, but now larger facilities are being designed next to agri-food processing plants (sugar factories, slaughterhouses). This ensures regular and low-cost sourcing of feedstock (Igliński et al. 2020). Factors influencing the profitability of an agricultural biogas plant that can be largely controlled by the investor are: a guarantee of long-term supply, the purchase price of substrates, the use of feedstock with high biogas productivity as an input, the minimisation of transport distances of feedstock to the biogas plant, the possibility of managing digestate pulp on own fields or a guarantee of collection by other entities, the possibility of obtaining support from high-efficiency cogeneration, adequate infrastructure (the shortest possible distances to the main power supply station, the heat consumer or the water and sewage system), the limitation of the size of tanks (digesters, lagoon tanks) and a long-term guarantee of the production level by the technology provider. These factors constitute an element of investment risk.

Another group consists of degassing systems for municipal landfills. Since 2005, the number of landfills in Poland has been steadily decreasing. According to data from the Statistics Poland in 2018, their number decreased from 1,000 to 286. As many as 90 % of them were equipped with degassing systems, of which only 23 had degassing systems capable of recovering thermal energy, and another 68 had systems capable of recovering electrical energy. The landfill degassing systems recovered 84,800,021 MJ of heat energy and 105,356,970 kWh of electricity (Szewczyk 2020).

Municipal landfills can be assumed to be a kind of bioreactor. It is estimated that about 50% of the landfill mass in landfills is organic waste. During the biochemical processes taking place, organic matter is transformed, resulting in the production of landfill gas, which, when directly released into the atmosphere, contributes to exacerbating the greenhouse effect. It is important to emphasise that methane has a much greater contribution to the greenhouse effect than carbon dioxide (Bąkowski 2018). Organic matter decomposes during five phases: aerobic, anaerobic, unstable methane, stable methane and quiescence. In order to obtain this type of biogas, it is necessary to build a suitable system. The system includes elements that collect gas from the waste deposit, such as vertical wells or horizontal manifolds. If it is not possible to build a degassing system, special wells are installed at the full depth of the landfill and the resulting biogas is flared. The landfill should be well isolated from its surroundings by impermeable layers of sand, clay and native soil. The vacuum pump creates negative pressure and allows the biogas to be transferred to the water separator and desulphurisation plant. On the other side of the pump, there is an overpressure, which enables the biogas to be injected into the tank, where it is then transferred further to a cogeneration unit that generates heat or electricity (Bąkowski 2018).

The third group discussed in this paper are biogas plants at wastewater treatment plants. Due to continuous urban development and the provisions in the Water Law (Dz. U. /Journal of Laws/ of 2020, item 310), the continuous expansion of the sewage network and the construction or modernisation of the number of sewage treatment plants is required. Biogas plants are the main, most favourable solution for the disposal of an increasing amount of sewage sludge (Koc-Jurczyk et al. 2020). The treatment of municipal wastewater is a complex and costly process. With the continuous increase in energy prices, and in order to be sustainable and reduce carbon dioxide elimination, wastewater treatment plants are obtaining energy from biogas plants (Lima et al. 2023). The production of biogas in biogas plants at wastewater treatment plants in Poland allows an energy recovery of about 40–200%. Currently, the greater part of water companies (around 60%), produce green energy at their treatment plants, which enables them to be partially or completely energy self-sufficient. Referring to the work of Masłoń et al. (2020), there are 2,500 wastewater treatment plants in Poland of which only 140 have systems for anaerobic digestion of sewage sludge, most of which are located in the Mazowieckie, Śląskie, Małopolskie and Podkarpackie provinces. Much of the current research and implementation work focuses on the development of optimal technological solutions for sludge-based biogas plants. The most common issues addressed are the selection of suitable cosubstrates for anaerobic digestion, the introduction of additives that neutralise or reduce the toxic effects of process inhibitors (found in sewage sludge), as well as additives that promote cell growth and activity (Pilarska 2018). It should be noted that biogas plants of this type fit into the idea of a circular economy, using anaerobic digesters and then allowing additional use of the digestate. Methane digestion is an effective method of generating energy from sewage sludge (primary sludge or excess activated sludge) generated during the treatment of municipal wastewater. Biogas production might be increased by using other wastes as cosubstrates, e.g. from agriculture, industry or municipal.

Advantages and challenges of biogas plant development – summary

Despite the fact that the development of biogas plants undoubtedly requires overcoming many challenges, mainly related to costs, infrastructure and legal regulations, their construction and the use of biogas as a renewable energy source bring many benefits, both environmental and economic. The development of biogas plants can contribute to a sustainable energy economy, especially in the context of the struggle against global warming and the need for an energy transition.

Biogas plants convert organic waste such as plant residues, slurry, biowaste or sewage sludge into biogas, reducing the problem of landfilling. Biogas produced by this means contributes to reducing the consumption of fossil fuels and reduces the emission of methane (a potent greenhouse gas), thereby reducing the carbon footprint. Biogas, as the main product of methane fermentation, can be used to produce electricity and heat, offering the possibility to power both households and industrial plants, contributing to energy efficiency. In turn, digestate (a by-product) can be used as an environmentally friendly fertiliser, which is beneficial for agriculture. Given the current geopolitical situation and the global energy crisis, the development of biogas plants provides a great opportunity to reduce dependence on traditional energy sources. The economic and political turmoil is causing energy prices to continually rise

– there is therefore a need to increase energy security, as well as to adapt legislation to the changing energy conditions in Europe. One cannot overlook the fact that investments in biogas plants stimulate the development of the local economies by creating new jobs in the area of operation and maintenance of these facilities. In addition, they provide support for so-called energy communities, the creation of which is one way of dealing with rising energy prices, balancing problems and network overload.

In addition to these benefits of biogas plant development, there are also obstacles and challenges that investors and plant owners constantly face. The situation in Poland isnot an isolated case. European countries that are less economically developed, as well as countries on other continents, including Africa – face very similar problems (Gadirli et al. 2024). The main challenges in recent years include high investment costs, public acceptance problems, legal regulations and bureaucracy, as well as changing government support and technological problems, often resulting from a lack of knowledge and unreliability of companies undertaking consultancy, design and implementation of investments concerning biogas. The construction of a biogas plant, especially on a larger scale, requires significant investment in infrastructure, which can prove a barrier for smaller investors or local governments. Although the cost of fuel may be low (when organic waste is used), the lack of a regular supply of suitable feedstock might lead to problems in maintaining biogas production at an optimal level. Ongoing and high operational costs for maintenance, plant monitoring or waste management can also be significant. Until recently, investors faced huge resistance from local communities, who mistakenly associated the construction of biogas plants with intense emissions of odours, noise or landscape alterations. Persistent dialogue and education, as well as the current geopolitical and climate conditions – including recurring natural disasters – have forced a change in thinking, making the need for energy transition an understandable and logical issue. Today, investors may rely on the cooperation of local communities, particularly in economically developed regions. In Poland, the experience of recent years has shown perfectly how complicated and time-consuming authorisation procedures for the construction and operation of biogas plants can delay the development of this sector. Likewise, unstable subsidies, tax relief or feed-in tariffs for biogas energy – unregulated, variable or unfavourable can cause a collapse in RES development, including biogas for many years. Support for biogas plants is largely dependent on state policy, which is subject to change.

Conclusions

The AD process using energy crops and other plant biomass under controlled conditions is an environmentally friendly technology. Plants that base their operation on the processing of waste from various sectors of the economy are innovative and even more preferable in terms of sustainability. They use a variety of biodegradable waste as feedstock. The waste received at the biogas plant is biodegraded using microorganisms in a methane fermentation process. The resulting biogas is a gaseous biofuel with huge potential on the energy market. The plants in question are one example of RES plants, the development of which is noticeable every year.

Biogas plants are a vital element in waste management and renewable energy production. They are a tool for sustainable agriculture and resource management. In addition to environmental and economic aspects, social aspects are also important. It is not only the investor or owner who can benefit from the construction and proper operation of these plants. Activities based on the production of biofuels have a positive impact on the development of further sectors and communities cooperating with the existing plant. Modernisation of infrastructure, job creation, possibility to establish local cooperating companies, environmental protection, waste management, production of energy in its various forms – these are only selected aspects supporting the creation and development of RES systems such as biogas plants.

Future research to optimize AD process should focus on several promising directions: (i) expanding substrate diversity – investigating new substrates, including challenging-to-degrade materials, and developing effective pretreatment methods to enhance nutrient bioavailability, (ii) optimizing process parameters – fine-tuning key parameters to maximize biogas production, with advanced monitoring and automation technologies for precise control of the digestion process, (iii) enhancing microbial stability and resilience – introducing robust microbial strains and studying microbial ecosystems within digesters to improve process stability and efficiency and (iv) reducing costs and recovering valuable resources – advancing technologies to recover nutrients (e.g., nitrogen, phosphorus) and valuable by-products like organic fertilizers from digestate, which could improve the economic viability of fermentation facilities. These research directions will support sustainable resource utilization and enhance the environmental and economic potential of anaerobic digestion as a green technology.

References

Appels, L., Baeyens, J., Degrève, J. 2008. *Principles and potential of the anaerobic digestion of waste-activated sludge. Progress in Energy and Combustion Science*, 34(6), 755–781.

Bąkowski, K. 2020. *Sieci i instalacje gazowe. Poradnik projektowania, budowy i eksploatacji. Wydawnictwo Naukowe PWN,* Warszawa, ISBN: 978-83-01-19805-3.

Biernat, K. 2010. *Biopaliwa-definicje i wymagania obowiązujące w Unii Europejskiej*. *Czysta Energia*, 10, 25–28.

Bharathiraja, B., Sudharsanaa, T., Bharghavi, A., Jayamuthunagai, J. 2016. Praveenkumar, R. *Biohydrogen and Biogas – An overview on feedstocks and enhancement process*. *Fuel*, 185, 810–828.

Chen,Y., Jay, J., Cheng, J.J., Creamer, K.S. 2008. *Inhibition of anaerobic digestion process: A review*. *Bioresource Technology*, 99, 4044–4064.

Chen, J.L., Ortiz, R., Steele, T.W.J., Stuckey, D.C. 2014. *Toxicants inhibiting anaerobic digestion: A review*. *Biotechnology Advances*, 32, 1523–1534.

Colonna, P. 2011. *Biomass, biogas and biofuels. General Nuclear Review (Revue Générale Nucléaire),* 3, 58–64

Gadirli, G., Pilarska, A.A., Dach, J., Pilarski, K., Kolasa-Więcek, A., Borowiak, K. 2024. *Fundamentals, operation and global prospects for the development of biogas plants – A Review*. *Energies*, 17, 568.

Häfner, F., Hartung, J., Möller, K. 2022. *Digestate composition afecting N fertiliser value and C mineralisation. Waste and Biomass Valorization*, 13, 3445–3462.

Igliński, B., Piechota, G., Iwański, P., Skarzatek, M., Pilarski, G. 2020. *15 Years of Polish agricultural biogas plants: their history, current status, biogas potential and perspectives. Clean Technologies and Environmental Policy*, 22(1), 281–307.

Kothari, R., Pandey, A.K., Kumar, S., Tyagi, V.V., Tyagi, S.K. 2014. *Different aspects of dry anaerobic digestion for bio-energy: An overview. Renewewable and Sustainable Energy Reviews*, 39, 174–195.

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.

Leite, A.F., Janke, L., Lv, Z., Harms, H., Richnow, H.H., Nikolausz, M. 2015. *Improved monitoring of semi-continuous anaerobic digestion of sugarcane waste: Effects of increasing organic loading rate on methanogenic community dynamics. International Journal Molecular Sciences*, 16, 23210–23226.

Lima, D., Appleyby, G., Li, L. 2023. *A scoping review of options for increasing biogas production from sewage sludge: challenges and opportunities for enhancing energy self-sufficiency in wastewater treatment plants. Energies,* 16, 2369.

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.

Mata-Alvarez, J., Dosta, J., Romero-Güiza, M.S. 2014. *A critical review on anaerobic co-digestion achievements between 2010 and 2013. Renewable and Sustainable Energy Reviews*, 36, 412–427.

Mata-Alvarez, J., Macé, S., Llabrés, P. 2000. *Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives.* Bioresource Technology, 74(1), 3–16.

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

O'Connor, S., Ehimen, E., Pillai, S.C., Black, A., Tormey, D., Barlett, J. 2021. *Biogas production from small-scale anaerobic digestion plants on European farms. Renewable and Sustainable Energy Reviews*, 139, 110580.

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., Pilarski, K., Waliszewska, B., Zborowska, M., Witaszek, K., Waliszewska, H., Kolasiński, M., Szwarc–Rzepka, K. 2019a. *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. Ecol. Chem. Eng. S*, 23, 99–115

Pilarska, A.A., Pilarski, K., Wolna-Maruwka, A., Boniecki, P., Zaborowicz, M. 2019b. *Use of confectionery waste in biogas production by the AD process. Molecules*, 24, 37.

Pilarski, K., Pilarska, A.A., Kolasa-Więcek, A., Suszanowicz, D. 2023. An agricultural biogas plant as a thermodynamic system: A study of efficiency in the transformation from primary to secondary energy. Energies, 16, 7398.

Rajagopal, R., Massé, D.I., Singh, G. 2013. *A critical review on inhibition of anaerobic digestion process by excess ammonia. Bioresource Technology*. 143, 632–641.

Register. 2018. of Energy companies producing agricultural biogas. www.kowr.gov.pl/uploads/pliki/oze/biogaz/7.%20Rejestr%20wytw%C3%B3rc%C3%B3w%20biogazu%20rolniczego%20z%20dni a%2005.01.2018%20r.pdf

Ryckebosch, E., Drouillon, M., Vervaeren, H. 2011. Techniques for transformation of biogas to biomethane. Biomass and Bioenergy, 35(5), 1633–1645.

Rogowska, D., Berdechowski, K. 2013. *Ocena wpływu sposobu alokacji emisji w procesie produkcji biopaliwa na wartość emisji gazów cieplarnianych. Nafta–Gaz*, 69(3), 226–234.

Schattauer, A., Weiland, P. 2005. *Basic knowledge of anaerobic digestion. [in] Biogas – production and use. Institut für Energetik und Umwelt, GmbH:* Leipzig, Germany, pp. 5–22.

Strik, D.P.B.T.B., Domnanovich, A.M., Holubar, P. 2006. *A pH-based control of ammonia in biogas during anaerobic digestion of artificial pig manure and maize silage. Process Biochemistry*, 41, 1235–1238.

Szczyrba, P., Masłoń, A., Czarnota, J., Olszewski, K. 2020. *Analiza gospodarki osadowej i biogazowo-energetycznej w oczyszczalni ścieków w Opolu*. *Ecological Engineering*, 21(2), 26–34.

Szewczyk, P. 2020. *Biogaz produkowany z odpadów komunalnych*. *Magazyn Biomasa*, 10(72), ISSN 2353-9321.

Wang, P., Wang, H., Qiu, Y., Ren, L., Jiang, B. 2018. *Microbial characteristics in anaerobic digestion process of food waste for methane production–A review. Bioresource Technology*, 248, 29–36.

Weiland, P., de Mes, T., Verstraete, W. 2001. *Biogas production through anaerobic digestion of biomass: The Dutch case. Biomass and Bioenergy*, 21(6), 419–428

Worwąg, M., Bień, J., Zawieja, I. 2010. *Zespoły mikroorganizmów w procesach beztlenowej stabilizacji osadów*. *Proceedings of ECOpole*, 4(2), 515–522.

Yenigün, O., Demirel, B. 2013. *A critical review on inhibition of anaerobic digestion process by excess ammonia. Bioresource Technology*, 143, 632–641.

Zapałowska, A., Gacek, T. 2019. Ekonomiczne aspekty pozyskiwania i wykorzystania biogazu. Polish Journal for Sustainable Development, 23(2), 81–89.

Zdebik, D., Głodniok, M., & Korczak, K. 2010. *Analiza możliwości wykorzystania biogazu do produkcji ciepła i energii elektrycznej na przykładzie oczyszczalni ścieków w Rybniku. Prace Naukowe GIG. Górnictwo i Środowisko/Główny Instytut Górnictwa*, 3, 87–97.

Żygadło M., Madejski R., 2016, *The conversion of biomas into energy in farm biogas plant*. *Archives of Waste Management and Environmental Protection*, 18(2), 55–66.