PAN POLSKA AKADEMIA NAUK

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

ITP-PIB

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2024.149127
2024, No. 61 (IV–VI): 55–61

# Analysis of opportunities for performance improvement based on data from agricultural mono substrate biogas plant

Edyta Wrzesińska-Jędrusiak[1], Michał Czarnecki[1], Szymon Szufa*[2], Grzegorz Maj[3], Iveta Čabalová[4], Marianna Grześkowiak[1]

[1] Institute of Technology and Life Sciences – National Research Institute, Falenty, Hrabska Ave., 3, 05-090 Raszyn, Poland

[2] Lodz University of Technology, Faculty of Process and Environmental Engineering, 90-924, Żeromskiego St, 116, Łódź, Poland

[3] University of Life Sciences in Lublin, Department of Power Engineering and Transportation, Głęboka St, 28, Lublin, 20-612, Poland

[4] Technical University in Zvolen, Faculty of Wood Sciences and Technology, Department of Chemistry and Chemical Technologies, T.G. Masaryka St, 24, 960 01 Zvolen, Slovak Republic

* Corresponding author

RECEIVED 12.05.2023 ACCEPTED 18.02.2024 AVAILABLE ONLINE 10.05.2024

**Abstract:** Anaerobic digestion is a demanding process, due to the large number of process and environmental factors that affect it. Many years of research of the various parameters have made it possible to optimise the process to obtain the maximum amount of biogas and methane contained in it, and this provides energy and environmental benefits. The article deals extensively with the operation of agricultural biogas plants, using the example of a plant that faces numerous operational problems. In order to identify the negative effects on energy yield and the equipment operating in the system, the substrate was examined, the data on its operation analysed, and solutions were proposed that should be taken into account in the further operation of the biogas plant. The analysis showed a good biogas yield from beet pulp of 563 $dm^3 \cdot kg^{-1}$ of TS (total solid) and an average methane yield of 58%. With the analysis presented, it was possible to identify some operational problems. The biogas yield study also highlighted some errors made at the plant design stage. The most important of these is the use of an inappropriate organic matter loading factor for the digester, which leads to acidification of the contents and degradation of the methanogenic microorganism cultures.

**Keywords:** biogas plant, biomass, combined heat and power (CHP), waste, waste management

## INTRODUCTION

The anaerobic digestion process is a chemical process that requires the right conditions to be met for it to operate effectively. The most important process parameters for the operation of such systems are pH, temperature, FOS/TAC ratio. FOS is a measure of the volatile organic acids measured in mg $CH_3COOH \cdot dm^{-3}$ and TAC is a measure of the total inorganic carbon, carbon/nitrogen (C/N) ratio, water content, feedstock fraction and hydraulic retention time (*HRT*) (Kryvoruchko *et al.*, 2009; Vijayakumar *et al.*, 2022). These parameters have a very strong influence on the quantity and composition of the biogas obtained, and this translates into revenues for the energy company. Ensuring the continuity of the process under laboratory conditions is relatively straightforward whereas on a technical scale it is much more difficult. Therefore, biogas plants require specialised equipment, continuous laboratory monitoring of the substrate and technical monitoring of the equipment (Steyer *et al.*, 1999; Lardon, Punal and Steyer, 2004; Ghouali, Sari and Harmand, 2015).

As one of the most important renewable fuels, which is derived from biomass, biogas is an environmentally friendly, clean, inexpensive and versatile fuel especially for rural areas (Böhringer *et al.*, 2017). Biogas is exploited worldwide for heating purposes and for cogeneration of electricity. The preferred method of extracting energy from biomass in terms of the ratio of output to input energy is anaerobic digestion. As a result of such fermentation, methane production is preferable to bioethanol production due to the fact that a greater proportion of the compounds in the biomass are converted into simple compounds, which produce $CH_4$ and $CO_2$ (Fugol *et al.*, 2023).

The biogas yield of the organic material has a key impact on the economic effect of the plant. The set of measuring devices is usually supervised by a customised process monitoring IT system. It collects output data from the measuring instruments, displays process messages, transmits appropriate signals to the actuators and collects and stores historical data. Control of the fermentation process in a biogas plant is necessary because disturbances in methane fermentation, can lead to either temporary or permanent destabilisation of biogas and methane production, resulting in a decrease in electricity production and financial losses for the biogas plant. Most of the disturbances in biogas production (>60%) are due to technical failures or malfunctions of equipment installed at the biogas plant. Disturbances due to the properties of the dosed substrates and mistakes made by biogas plant operators account for about 35–40%. (Olesienkiewicz, 2019).

Biogas plants are systems that allow the production of gaseous biofuel. The operation of these systems is a very complex issue. In addition to the above-mentioned parameters related to the anaerobic methane fermentation process in the digesters, there are also many factors that determine the operation of the plant in the electricity system or the influence of external factors (Rizwan *et al.*, 2020). On this basis, it can be concluded that biogas plants are also high-risk systems (Szymańska and Wieteska, 2017). In the vast majority of cases, the economic viability of a biogas plant is the deciding factor for its construction (Olesienkiewicz, 2022), while its profitability is determined primarily by the cost of its construction, the costs and opportunities associated with obtaining the substrate, the possibility of external financing and the anticipated revenue (Szymańska and Wieteska, 2017).

The operation of a biogas plant is not only about aspects related to the processing of organic material in the digesters and the fuel produced. The proper operation of a biogas plant also includes obtaining material with the right parameters, transporting it as cheaply as possible, storing the organic material and processing it into more efficient forms in terms of the biogas yield of the material. Many biogas plants do not carry out laboratory monitoring of the substrate and therefore it is much more difficult to locate the cause of the lower biogas yields (Kryvoruchko *et al.*, 2009). However, the most detailed testing of the substrate should be done before the biogas plant is built. This will allow the process to be modelled (Jabłoński *et al.*, 2014), the system to be customised to run the anaerobic digestion process and the investment to be more profitable. Biogas plants on farmland are an effective solution for the beneficial and inexpensive treatment of organic waste and the provision of electricity and heat in municipalities and agro-industrial sectors (Fugol *et al.*, 2023). A special case of agricultural biogas plants are agricultural microbiogas plants. These are systems designed and adapted for small-scale biogas production, usually fed only with substrate from the owner's farm. As described in the study (Enitan *et al.*, 2016), an 8.1 kWh biogas plant can also be profitable, despite the wide range of waste use. Animal manure, maize silage and household organic waste are directed to the digester. Unfortunately, many contractors installing agricultural biogas plants do not adapt the technology or infrastructure specifically for organic substrate, and investors are unaware of the possibility of solutions with a shorter return on investment. An analysis to determine the boundary conditions of investment profitability was presented in a study based on three different case studies (Czekała *et al.*, 2017). However, this is a very complex, individual issue, related, among other things, to local and legal conditions within the country. The possibility of treating the substrate before fermentation is also rarely analysed. And this is a solution that can bring tangible benefits. The impact of different substrate pre-treatment methods has been described in many publications (Mahajan *et al.*, 2020; Skibko *et al.*, 2021; Bandgar, Jain and Panwar, 2022). It is also worth considering the possibility of using an appropriately sized pre-treatment of the substrate and building smaller fermenters. It is then possible to reduce the retention time of the organic input and to obtain a higher yield of biogas (often also with a higher methane content). The aim of this study is to show the complexity of the operation of agricultural biogas plants, also in the case of mono substrate biogas plants. The data required for the analysis were obtained from an agricultural biogas plant that processes beet pulp for fertiliser and also for energy purposes. The plant in question is generating lower revenues from electricity sales than initially expected. For this purpose, both the substrate and the operation of the measurement, control and enforcement equipment were analysed.

## MATERIAL AND METHODS

### INTRODUCTION TO THE ISSUE OF BEET PULP MANAGEMENT

The development of technology for the production of biogas from biomass, derived from agricultural sources makes it possible to manage waste biomass and convert it to energy and agricultural fertiliser. Biogas production depends primarily on the type, quantity and quality of the feedstock. The choice of substrate is made mostly on the basis of its availability to the biotechnology plant (Wrzesińska-Jędrusiak *et al.*, 2022).

The main feedstock in the agricultural biogas plant under study is beet pulp. Those are the residue from the sugar beet pulping process, which is carried out to obtain sugar. According to Commission Decision (2000), beet pulp are classified as vegetable agricultural waste or waste from the food industry using the term "vegetable tissue waste" (code 02 01 03) or "materials unsuitable for consumption or processing" (code 02 03 04) in the definition, and specifically "waste from the sugar industry" (code 02 04 01). Usually beet pulp is the sole substrate for biogas plants. Four samples of the substrate were analysed. Samples designated 1 and 2 were drained. Samples 3 and 4 were left unchanged. According to the laboratory's procedure, the collected material was described on the basis of an organoleptic test method of determining the quality of the product using standard human senses, that is, visual, olfactory and tactile.

In order to compare substrates for biogas plants, a list of the different substrates, used in biogas plants, and their parameters is presented in Table 1.

### GOAL OF ESTIMATE THE POTENTIAL OF THE RESULTING SUBSTRATE USED IN THE BIOGAS PLANT

The main objectives of this study are: to estimate the potential of the resulting substrate used in the methane fermentation process to analyse the composition of the biogas, including the

**Table 1.** The parameters of substrates

| Substrate | General solids (%) | Volatility solids (% of GS) | Biogas yield ($dm^3 \cdot kg^{-1}$) | Biogas yield ($dm^3 \cdot kg^{-1}$ of TS) | Methane content (%) |
|---|---|---|---|---|---|
| Cattle slurry | 8–11 | 75–82 | 200–500 | 20–30 | 60 |
| Pig slurry | 7 | 75–86 | 300–700 | 20–35 | 60–70 |
| Cattle manure | 25 | 68–76 | 250–450 | 70–90 | 60 |
| Pig manure | 20–25 | 75–80 | 270–450 | 55–65 | 60 |
| Corn silage | 2–35 | 85–95 | 450–700 | 170–200 | 50–55 |
| Sugar beets | 23 | 90–95 | 800–860 | 170–180 | 53–54 |
| Potato decoction | 6–7 | 85–95 | 400–700 | 36–42 | 58–65 |
| Brewery waste | 20–25 | 70–80 | 580–750 | 105–130 | 59–60 |

Explanations: GS = general solids, TS = total solids.
Source: own elaboration based on: Myczko (2011).

determination of methane concentration, in order to obtain information on the efficiency of this process.

A site visit was carried out at the study site to locate the occurrence of possible sources of operational problems.

## BIOGAS PLANT SYSTEM DESCRIPTION

The research was carried out at an agricultural biogas plant located in the eastern part of central Poland The installation is located near an agri-food processing plant and was constructed to further process waste from the plant. The resulting gaseous fuel is used to power a co-generator. Electricity and heat is partly consumed to keep the anaerobic digestion process running, while its surplus is sent to the electricity grid and the external heating network. The heat is put to use for the food processing company.

The substrate is supplied throughout the year in concrete open silos. There, the pulp is stored for a period of approximately six weeks for ensiling under cover (so-called heap) and loading. This reaction enables the breakdown of sugars, mainly glucose, into lactic acid, and then, with the help of several stages, the creation of biogas, which is shown in the diagram (Fig. 1). In the first stage of “hydrolysis”, the complex compounds of the starting material are decomposed into simple organic compounds, e.g. sugar, amino acids, fatty acids. Bacteria that participate in the process release enzymes that break down the material through biochemical reactions. The intermediate products formed in this way with the participation of acid-forming bacteria are decomposed in the so-called “acidification phase” into fatty acids (acetic, propic and butyric acid) as well as carbon dioxide and hydrogen, but also small amounts of lactic acid and alcohol are formed. In the next phase of “creation of acetic acid” with the participation of bacteria, these products turn into substances that precede the formation of biogas (acetic acid, hydrogen and carbon dioxide). Due to the harmful effect of too high hydrogen content on acetic bacteria, they must cooperate with methane bacteria. They consume hydrogen in the formation of methane and, as a result, provide suitable conditions for the life of acetic bacteria. In the next phase of “methanogenesis”, the last stage of biogas formation, methane is produced from the products of acetogenesis (Schattauer and Weiland, 2005).

The change in substrate composition results in more efficient decomposition by methane fermentation and inhibits

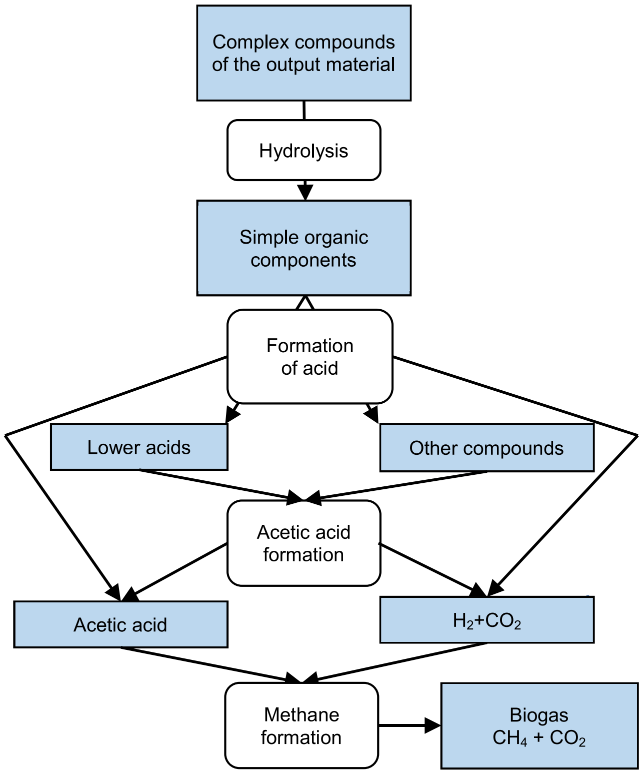


**Fig. 1.** Diagram of the process of biogas formation; source: own elaboration

the growth of putrefactive and butyric bacteria (PN-EN 12880:2007). The material is then placed in a dosing station, from where a pumping system transfers it to the fermenters. The fermentation process is carried out in three tanks: two digester tanks and one secondary digester tank. A highly sophisticated hydraulic system allows the mass for maceration to be properly distributed and directed to the appropriate fermenter as required. The total capacity of the fermenters is approx. 2500 $m^3$. The transport of methanogenic bacteria is ensured by high-speed mechanical stirrers inside the fermenter. The digestion pulp is partially returned to the start of the pumping system for mixing with fresh substrate. After the process, the material is pumped out of the tanks into the centrifuge and then stored in dry form in closed tanks (Fig. 2).

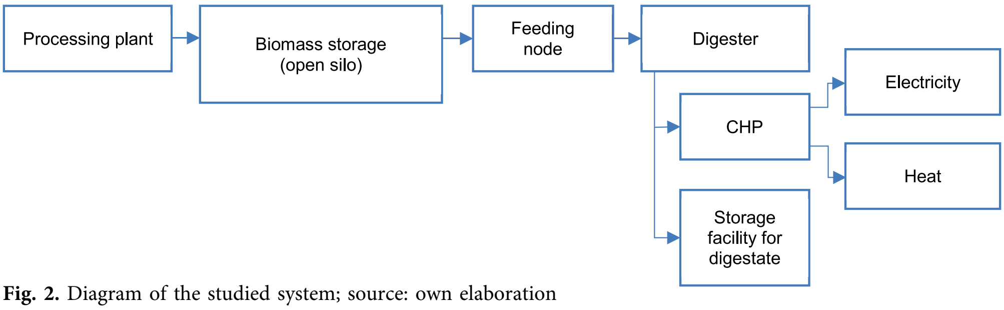


**Fig. 2.** Diagram of the studied system; source: own elaboration

The produced biogas is cleaned of hydrogen sulphide in a desulphurisation plant. Biogas storage in the upper part of the fermenters is possible up to a pressure of approximately 0.13 MPa absolute pressure. The gaseous biofuel is then routed to a compressor and to a gas engine, where it is combusted. An emergency flare has also been prepared in case the combined heat and power (CHP) unit fails and the gas space of the fermenters fills up (Tab. 2).

**Table 2.** The parameters of biogas plant

| Technical parameter | | Value | Unit |
|---|---|---|---|
| Generating unit capacity | | 1560<br>~2500 | kW (electric)<br>kW (heat) |
| Volume of tanks (active) | | 2500 | $m^3$ |
| Hydraulic retention time | | 28 | days |
| Biogas efficiency | | 763 | $m^3 \cdot h^{-1}$ |
| Biogas composition | $CH_4$ | 54.3 | % |
| | $CO_2$ | 44 | % |
| | $O_2$ | <1 | % |
| | $H_2S$ | 3 | ppm |
| Temperature of the fermentation process | | ~38.5 | °C |

Source: own study.

The biogas plant was commissioned in the second decade of the 21st century. Its operation has been subjected to an in-depth analysis due to the many problems reported with the efficiency of its operation, as well as its high operating expenses. This article is based on site visits to the biogas plant, substrate testing, own experience, literature review and information provided by technologists.

The biogas plant was commissioned in the second decade of the 21st century. Its operation has been subjected to an in-depth analysis due to the many problems reported with the efficiency of its operation, as well as its high operating expenses. This article is based on site visits to the biogas plant, substrate testing, own experience, literature review and information provided by technologists.

## RESULTS AND DISCUSSION

### SUBSTRATE ANALYSIS

According to the laboratory's procedure, the collected material was described on the basis of an organoleptic test method of determining the quality of the product using standard human senses, that is, visual, olfactory and tactile. The beet pulp labelled "1" as well as that labelled "2" was assessed organoleptically in a very similar way. It is a fraction of up to 10 mm in size, shiny and visibly moist. The colour of the material is beige/light brown. Occasional fragments of fibres are noted, probably the roots of the plant. After prolonged contact with oxygen, the material darkens and a rather rapid development of fungi, moulds was observed on the surface. The smell was determined to be characteristic, acidic. The crushing creasing of the material results incauses an outflow of water and a slight staining, which is definitely an undesirable phenomenon First, general solids and volatility solids tests were performed for individual samples (Tab. 3).

**Table 3.** Results of the primary analysis of samples

| Sample number | General solids (%) | Water content (%) | Volatility solids (% of GS) |
|---|---|---|---|
| 1 | 11.10 ±2.2 | 88.90 ±1.8 | 93.20 ±2.1 |
| 2 | 14.20 ±2.2 | 85.80 ±1.7 | 86.90 ±2.1 |
| 3 | 15.30 ±2.2 | 84.70 ±1.6 | 86.20 ±2.0 |
| 4 | 12.90 ±2.2 | 87.10 ±1.8 | 88.10 ±2.1 |

Explanations: GS = general solids.
Source: own study.

The tests confirmed that the water content (*WC*) of the pulp is within the pumpability limit of the material as declared by the manufacturer of the pumps used in the plant. A sufficiently high substrate *WC* also allows for the effective transport of methanogenic bacteria colonies when aided by mechanical stirrers. No signs of fungus may be indicative of the freshness of the samples taken. For the value of general solids (GS), the standard deviation has a high value.

A detailed evaluation of the biogas yield of the substrate using the static method takes into account the other relevant parameters of the test material for the anaerobic digestion process. The resulting loading of the digestion mixture with the test material sample was between 3.6%. The aim of the baseline tests carried out was to identify possible abnormalities (e.g. the presence of inhibitory factors) associated with the substrate (Tab. 4).

Biogas yield studies were also carried out using a dynamic method, on a semi-technical scale. These tests were designed to assess the behaviour of the substrate under conditions closely resembling those of an agricultural biogas plant. The plant allows many other factors to be taken into account that cannot be observed in the static method.

**Table 4.** Results of a study on the static biogas yield assessment of samples

| Sample number | Reaction pH (–) | Dissolved oxygen ($mg \cdot dm^{-3}$) | FOS/TAC (–) | Hydraulic retention time (days) | Biogas yield[1)] ($dm^3 \cdot kg^{-1}$ of TS) | Content of methane (%) |
|---|---|---|---|---|---|---|
| 1 | 7.75 ±0.1 | 0.03 | 0.82 | 24 | 515.32 | 59.7 |
| 2 | 7.80 ±0.1 | 0.11 | 0.80 | 21 | 624.64 | 54.2 |
| 3 | 7.76 ±0.1 | 0.07 | 1.25 | 27 | 438.56 | 56.5 |
| 4 | 7.90 ±0.1 | 0.08 | 1.33 | 21 | 675.97 | 61.0 |

[1)] Volume of biogas yield is expressed in $dm^3$ measured in 20°C and atmospheric pressure 1,013.25 hPa).
Explanations: FOS = volatile organic acids measured in mg $CH_3COOH \cdot dm^{-3}$, TAC = total carbon present in water in the form of inorganic compounds.
Source: own study.

**Table 5.** Results of a study on the dynamic biogas yield assessment of samples

| Sample number | Hydraulic retention time (days) | Biogas yield[1)] ($dm^3 \cdot kg^{-1}$) | Biogas yield[1)] ($dm^3 \cdot kg^{-1}$ of GS) | Content of methane (%) | Content of hydrogen sulphide (ppm) |
|---|---|---|---|---|---|
| 1 | 28 | 62.4 | 572.47 | 54.0 | 3,824 |
| 2 | 28 | 76.1 | 535.91 | 52.2 | >5,000 |
| 3 | 28 | 60.9 | 398.03 | 65.3 | 3,998 |
| 4 | 28 | 67.3 | 521.71 | 56.2 | >5,000 |

[1)] Volume of biogas yield is expressed in $dm^3$ measured in 20°C and atmospheric pressure 1,013.25 hPa).
Explanations: GS = general soilds.
Source: own study.

For the dynamic analysis, the digestion mixture was loaded with the substrate sample to a level of ~4% (Tab. 5). The highest biogas yield value was obtained for the sample with the highest value of general solids. A difference of more than 24% in biogas yield between the different samples and a difference of more than 13 percentage points in the methane content of the biogas was also observed. This may be indicative of uneven ensiling of the substrate, resulting from ensiling under a pile and substrate sampling from locations with different water content and access to oxygen.

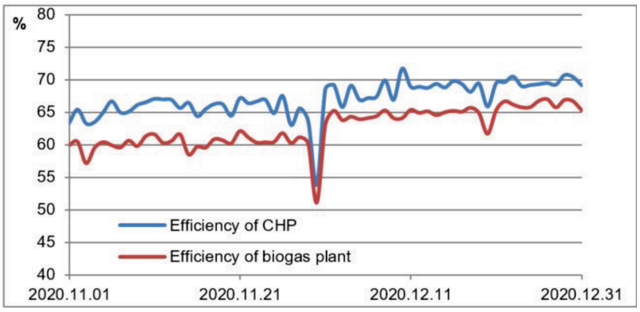


**Fig. 3.** An efficiency of energy generation during the period 01.11.2020–31.12.2020; CHP = combined heat and power; source: own study

## OPERATION OF THE BIOGAS PLANT

A functioning biogas plant can struggle with a number of operational problems. Problems can include a clogged pumping system and ballast build-up inside the fermenters. This is a source of a significant increase in operating expenses and more frequent downtime. Insufficient biogas production to feed the CHP and frequent process interruptions during operation result in unstable CHP operation and low efficiency operation. In order to limit the impact of "major" failures (e.g. of the pumping system or the CHP) on the results obtained, the period analysed was limited to two months.

The authors obtained CHP efficiency data from the biogas plant operator and sufficient data to calculate efficiency based on biogas yield and methane content, as well as electricity and heat generation. The difference between the values obtained from the SCADA program and those calculated was at most 0.3%. The results of the assessment of the efficiency of energy production from beet pulp methane fermentation are shown in Figure 3.

During the period under review, there were two cases where biogas had to be diverted to a flare for safety reasons. As the biogas was consumed without any energy benefit, the efficiency of its generation on the day in question dropped. Modern gas engines operating as cogenerators under rated conditions achieve an overall efficiency of 85%. As the installed unit is already somewhat run down, its maximum efficiency in the period under review reached a value of 77%. Taking into account the biogas plant's own needs (heat and electricity), the record efficiency was 69.26%. This is not a very high value, but it should be noted that most of the time the system operates at an efficiency level of 50–60%.

## ANALYSIS OF OPTIONS FOR IMPROVING THE PERFORMANCE OF BIOGAS PLANTS

During the field reconnaissance and after reviewing the biogas plant's computer monitoring data, technical problems were identified due to the permeability of the batch node and the high frequency of cleaning the digesters from sand (at least once a year). An analysis was carried out on how to improve the operation of the biogas plant and the biogas yield.

It is difficult to clearly indicate at which stage any fine impurities enter the substrate. Pump and screw systems are very fragile systems. They are designed to transport materials with certain properties. If even a small element with different properties (especially hard or flexible) enters the system, it can plug the system again. It is likely that after the desludging process, the solid fraction is mixed with the water that was used to wash the beet. This would be very detrimental to the subsequent fermentation process and also to the equipment being operated. If this is indeed the case, a possible solution is to install appropriate filters before mixing the two substances. In order to reduce the amount of contamination in the substrate, it is also advisable to set up a cleaning station for the wheels and, above all, the loading elements of the vehicle using basic equipment such as brushes and pressure washers.

Maintaining the temperature inside the fermenters is one of the most important parameters. A temperature drop of 3–5°C can almost completely stop the biogas production process. According to the data presented, there were significant temperature fluctuations in the process tank. Temperature fluctuations could also be related to low-efficiency mixing or due to faults in the measuring apparatus as well as the operation of the calculation automation.

According to studies, long-term substrate storage has a negative effect on the subsequent fermentation process if there is a high water content in the substrate (Wiącek and Tys, 2015). Other substrates intended as feedstock for biogas plants can be stored in the air or under cover without significant losses in process efficiency. This is a particularly important issue in winter, as freezing and thawing of the substrate causes intracellular damage and changes in substance composition (sucrose decomposition) (Połeć *et al.*, 2013). Storage of compressed pulp in sleeves may be a solution to this problem. A study by Vervaeren *et al.* (2010) showed a 15% improvement in biogas yield, for methane fermentation of maize silage, compared to unfermented feedstock, especially when ensiled in foil sleeves.

Continuous monitoring of the feedstock is also recommended – a proper anaerobic digestation process must be carried out with stable feedstock. The most convenient form is biotechnological monitoring, which allows data to be correctly interpreted by a team of experienced biotechnologists in the event of operational problems. Performing a physic-chemical analysis also identifies the source of low biogas yield problems at the microbial level.

Regarding the hydraulic retention time to be used for beet pulp, the scientific literature is not in agreement. Some authors point to a 20-day fermentation period for beet pulp (Połeć *et al.*, 2013), while others show in empirical studies that the retention time for this substrate should be 25 days or more (Demirel and Scherer, 2008). This is especially true for large-scale biogas plants (Fugol *et al.*, 2023). The best solution will be to determine independently, experimentally, which retention time brings better benefits and keeps the equipment in rated operating states.

## CONCLUSIONS

The tests conducted showed a large variation in the biogas yield of the substrate. In the case of static analysis, there was a 50% difference in biogas yield between samples, while in dynamic conditions it was only 22%. According to the provided measurement data of the biogas plant monitoring system, the efficiency of the biogas plant is in the range of 64–71%. The value of electricity generated by the system is stabilised, the value of heat produced fluctuates quite a bit. The main problems associated with the operation of the system are low reliability, low efficiency and operation of the co-generator under unstable conditions. As part of the prepared work, a number of solutions were presented to improve the energy performance of the biogas plant. Particular attention was paid to the biotechnological analysis of the organic substrate, which is the post-production residue from the beet pulping process. To date, biotechnological supervision of the system has been inadequate, biotechnological conditions inside the fermenters have been unstable. It was recommended that the substrate be analysed for inhibitors (chemicals and methanogenic bacteria content).

## AUTHOR CONTRIBUTIONS

1st Author and 2nd Author: study design, data collection, statistical analysis, data interpretation, manuscript preparation, literature search, 3rd Author: study design, data collection, literature search, 4th, 5th Author and 6th Author: manuscript preparation, literature search.

## CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

## REFERENCES

Bandgar, P.S., Jain, S. and Panwar, N.L. (2022) "A comprehensive review on optimization of anaerobic digestion technologies for lignocellulosic biomass available in India," *Biomass and Bioenergy*, 161, 106479. Available at: https://doi.org/10.1016/j.biombioe.2022.106479.

Böhringer, C. *et al.* (2017) "The impact of the German feed-in tariff scheme on innovation: Evidence based on patent filings in renewable energy technologies," *Energy Economics*, 67, pp. 545–553. Available at: https://doi.org/10.1016/j.eneco.2017.09.001.

Commission Decision (2000) "2000/532/EC: Commission Decision of 3 May 2000 replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 75/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of Council Directive 91/689/EEC on hazardous waste (notified under document number C(2000) 1147) (Text with EEA relevance)," *Official Journal*, L 226, 6.9.2000. Available at: https://eur-lex.europa.eu/eli/dec/2000/532/oj (Accessed: December 12, 2023).

Czekała, W. *et al.* (2017) "The possibility of functioning microbiogas plant in selected farm," *Journal of Water and Land Development*, 35, pp. 19–25. Available at: https://doi.org/10.1515/jwld-2017-0064.

Demirel, P. and Scherer, P. (2008) "Production of methane from sugar beet silage without manure addition by a single-stage anaerobic digestion process," *Biomass and Bioenergy*, 32 (3), pp. 203–209. Available at: https://doi.org/10.1016/j.biombioe.2007.09.011.

DIN 38414. *German standard methods for the examination of water, waste water and sludge. Sludge and sediments (group S), Determination of the amenability to anaerobic digestation (S8).* June 1985.

Enitan, A.M. *et al.* (2016) "Optimization of biogas generation using anaerobic digestion models and computational intelligence approaches," *Reviews in Chemical Engineering*, 33(3), pp. 309–335. Available at: https://doi.org/10.1515/revce-2015-0057.

Fugol, M. *et al.* (2023) "Improving the energetic efficiency of biogas plants using enzymatic additives to anaerobic digestion," *Energies*, 16(4), 1845. Available at: https://doi.org/10.3390/en16041845.

Ghouali, A., Sari, T. and Harmand, J. (2015) "Maximizing biogas production from the anaerobic digestion," *Journal of Process Control*, 36, pp. 79–88. Available at: https://doi.org/10.1016/j.jprocont.2015.09.007.

Jabłoński, S. *et al.* (2014) *Monitoring i sterowanie procesem technologicznym biogazowni [Monitoring and control of the biogas plant technological process]*. Wrocław: Politechnika Wrocławska.

Kryvoruchko, V. *et al.* (2009) "Anaerobic digestion of by-products of sugar beet and starch potato processing," *Biomass and Bioenergy*, 33, pp. 620–627. Available at: https://doi.org/10.1016/j.biombioe.2008.10.003.

Lardon, L., Punal, A. and Steyer, J.P. (2004) "On-line diagnosis and uncertainty management using evidence theory – experimental illustration to anaerobic digestion processes," *Journal of Process Control*, 14, pp. 747–763. Available at: https://doi.org/10.1016/j.jprocont.2003.12.007.

Mahajan, R. *et al.* (2020) "Effect of pretreatments on cellulosic composition and morphology of pine needle for possible utilization as substrate for anaerobic digestion," *Biomass and Bioenergy*, 141, 105705. Available at: https://doi.org/10.1016/j.biombioe.2020.105705.

Myczko, A. *et al.* (2011) *Budowa i eksploatacja biogazowni rolniczych. Poradnik dla inwestorów zainteresowanych budową biogazowni rolniczych [Construction and operation of agricultural biogas plants. A guide for investors interested in building agricultural biogas plants]*. Warszawa–Poznań: ITP.

Olesienkiewicz, A. (2019) "Monitoring biotechnologiczny biogazowni, czyli jak okiełznać procesy fermentacji [Biotechnological monitoring of biogas plants, or how to control fermentation processes]," *Teraz Środowisko*, 23th October, Available at https://www.teraz-srodowisko.pl/aktualnosci/monitoring-biotechnologiczny-biogazownia-proces-fermentacji-substraty-7802.html (Accessed: December 12, 2023).

PN-EN 12176:2007. *Charakterystyka osadów ściekowych. Oznaczanie wartości pH [Characterization of sewage sludge. Determination of pH values]*. Warszawa: Polski Komitet Normalizacyjny.

PN-EN 12879:2007. *Charakterystyka osadów ściekowych. Oznaczanie straty przy prażeniu suchej masy osadu [Characterization of sewage sludge. Determination of the loss on roasting of sludge dry matter]*. Warszawa: Polski Komitet Normalizacyjny.

PN-EN 12880:2007. *Charakterystyka osadów ściekowych. Oznaczanie suchej pozostałości i zawartości wody [Characterization of sewage sludge. Determination of dry residue and water content]*. Warszawa: Polski Komitet Normalizacyjny.

Połeć, B. *et al.* (2013) "Wpływ preparatu bakteryjno-enzymatycznego LACTACEL-W na procesy zakiszania i fermentacji metanowej wysłodków buraczanych [The influence of the bacterial-enzymatic preparation LACTACEL-W on the ensiling and methane fermentation processes of beet pulp]," *Postępy Nauki i Przemysłu Rolno-Spożywczego*, 68(2), pp. 46–69. Available at: https://www.ibprs.pl/wp-content/uploads/2018/08/PNiTPRS-2013-2-Rozdzia%C5%82-V.pdf (Accessed: December 12, 2023).

Rizwan, R. *et al.* (2020) "An industrial scale testing and analysis of waste-to-energy production from various substrates by employing a modern anaerobic digestion plant," *Biomass and Bioenergy*, 138, 105571. Available at: https://doi.org/10.1016/j.biombioe.2020.105571.

Schattauer, A. and Weiland, P. (2005) *Biogaz. Produkcja. Wykorzystanie [Biogas-production and use]*. Leipzig: Institut für Energetik Und Umwelt GmbH.

Skibko, Z. *et al.* (2021) "Use of pellets from agricultural biogas plants in fertilisation of oxytrees in Podlasie," *Journal of Water and Land Development*, 51, pp. 124–128. Available at: https://doi.org/10.24425/jwld.2021.139022.

Steyer, J.P. *et al.* (1999) "Advanced control of anerobic digestion proces through disturbances monitoring," *Water Research*, 33, pp. 2059–2068. Available at: https://doi.org/10.1016/S0043-1354(98)00430-8.

Szymańska, A. and Wieteska, S. (2017) "Ocena ryzyka eksploatacji biogazowni rolniczych w Polsce na potrzeby ubezpieczeń od wybranych zdarzeń losowych [The risk assessment of biogas plants operation in Poland for the insurance from some random events]," *Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu*, 500, pp. 162–174. Available at: https://doi.org/10.15611/pn.2017.500.14.

Vervaeren, H. *et al.* (2010) "Biological ensilage additives as pretreatment for maize to increase the biogas production," *Renewable Energy*, 35(9), pp. 2089–2093. Available at: https://doi.org/10.1016/j.renene.2010.02.010.

Vijayakumar, P. *et al.* (2022) "Current technologies of biochemical conversion of food waste into biogas production: A review," *Fuel*, 323, 124321. Available at: https://doi.org/10.1016/j.fuel.2022.124321.

Wiącek, D. and Tys, J. (2015) Biogaz – wytwarzanie i możliwości jego wykorzystania [Biogas – Production and possibilities of its use]," *Acta Agrophysica. Monographiae*, 1. Lublin: Instytut Agrofizyki im. Bohdana Dobrzańskiego PAN. Available at: http://www.acta-agrophysica.org/Biogaz-wytwarzanie-i-mozliwosci-jego-wykorzystania,147345,0,2.html (Accessed: March 22, 2022).

Wrzesińska-Jędrusiak, E. *et al.* (2022) "Environmental performance of the innovative, patented mixing system in an agricultural biogas plant based on LCA approach," *Journal of Cleaner Production*, 349, 131420. Available at: https://doi.org/10.1016/j.jclepro.2022.131420.