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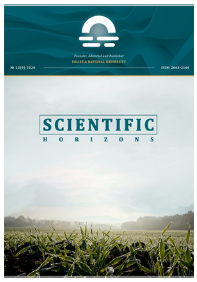

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Bioconversion of livestock by-products into biogas: Experimental study of optimal fermentation conditions

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Abstract. The bioconversion of organic waste into biogas is a substantial part of the company's strategy for sustainable development and reducing its environmental impact. The key factors affecting the efficiency of this process are fermentation temperature, carbon-to-nitrogen (C/N) ratio and substrate type. The study aimed to

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investigate the effect of temperature conditions, C/N ratio and different types of organic waste on biogas yield, particularly methane concentration, during anaerobic fermentation. Two temperature conditions were compared in the experiment: mesophilic (35°C) and thermophilic (55°C), using three types of organic waste: poultry manure, cattle manure and pig manure. The optimal C/N ratio was also studied to improve the energy efficiency of the process. Under thermophilic conditions, an increase in biogas yield by 20-28% and an increase in methane concentration by 5-10% were recorded compared to the mesophilic regime. The highest biogas yield (0.42 m^3/kg of organic dry matter (OSR)) and methane concentration (70%) were achieved with poultry manure. In the thermophilic regime, the time to achieve stable gas production was also reduced to 7-8 days, which confirmed the effectiveness of this approach for industrial use. The thermophilic fermentation mode is more efficient for biogas production and increases the energy efficiency of the process. Optimisation of the C/N ratio and co-fermentation of different substrates further improved the efficiency. Poultry manure proved to be the most efficient substrate for bioconversion, which opens prospects for its use on an industrial scale. The results of the study can be used to optimise biogas fermentation technologies to improve the performance of biogas plants and reduce energy costs

Keywords: renewable energy sources; organic waste; methane; anaerobic fermentation; thermophilic mode; mesophilic mode

INTRODUCTION

The growing demand for renewable energy sources is driving the development of innovative technologies aimed at the efficient use of organic waste. One of the most promising areas is the bioconversion of livestock by-products into biogas through anaerobic fermentation. This process produces methane, a valuable energy resource while reducing the amount of organic waste and related environmental problems. An important factor affecting the efficiency of the biogas fermentation process is the temperature regime, which significantly changes the speed and quality of biogas fermentation (Danylyshyn & Koval, 2023). Mesophilic and thermophilic fermentation regimes have their advantages and disadvantages depending on the type of substrate (Kovtun & Merzlov, 2023). In this regard, research on the effect of temperature on the bioconversion of organic waste is relevant. For instance, C. Morales-Polo *et al.* (2021) noted that temperature changes can significantly alter the energy and environmental potential of bioconversion using the example of barley residues processing into biogas in Spain. Such studies determined the mechanisms that affect the efficiency of these processes in greater detail.

Despite numerous scientific developments, there is a lack of research on specific substrates and conditions that ensure maximum biogas yields at different temperature conditions. The problem of biogas fermentation efficiency depending on the type of substrate, is understudied. N. Yahmed *et al.* (2021) consider the processing of date palm waste into biogas, biohydrogen, and date syrup, noting the high potential of such waste, but without specific conclusions on the optimal fermentation conditions. The study by M. Djaafri *et al.* (2019) adds important information on the biogas fermentation of date palm leaves under anaerobic digestion conditions but does not consider the effect of temperature. Expanded use of agro-industrial waste, in particular poultry manure and cattle manure, which are promising substrates for biogas plants, is emphasised. G. Leni *et al.* (2021) underline the importance of new opportunities for the utilisation of agricultural waste, in particular through the use of insects that can process organic waste into biogas. However, there is no generalised data yet on how temperature affects these types of substrates. Other studies, such as the work of V. Kumar *et al.* (2022), focus on bioinoculants for organic waste biodegradation and agricultural waste bioconversion, which indicates the importance of optimising fermentation processes to achieve high efficiency.

One of the key issues requiring further study is the optimisation of the biogas fermentation process for different types of organic waste. A. Rashwan *et al.* (2023) demonstrated the importance of food and agricultural waste processing to combat climate change, highlighting the need to optimise technologies to maximise the efficiency of these processes. According to their study, the use of agricultural waste for biogas production can substantially reduce greenhouse gas emissions. F. Ranjbar *et al.* (2022) studied the use of wheat straw in anaerobic cofermentation with cattle manure, which increases biogas yields and reduces the need for additional energy. The study highlighted that such a combination of substrates can be more efficient than using each type of waste separately, especially in conditions of limited resources. The study by N. Mahato *et al.* (2021) focuses on the bioconversion of citrus waste into biofuels and valuable compounds through fermentation, which can be an important component in the introduction of alternative energy sources. The authors noted that waste such as orange peels can be a significant source for biogas production, rendering the process even more cost-effective. The use of agricultural waste is not limited to biogas production (Donchak & Shkvaruk, 2024). J. Tuly *et al.* (2022) demonstrated the possibility of processing agricultural waste into valuable peptides through solid-state fermentation of *Bacillus* sp.

mutant, which is also a promising area for extracting additional value from agricultural waste. However, this requires further research into the fermentation conditions and specific characteristics of different types of waste. The study of anaerobic digestion technologies used for agro-industrial waste remains an important stage of development. A. Neri *et al.* (2023) provide an overview of anaerobic fermentation for biomethane production from agricultural and food waste, highlighting the importance of optimising these processes to increase productivity and energy efficiency.

These studies indicated the significant potential of biogas technologies and the existence of gaps in knowledge regarding the interaction of temperature regimes and substrate types in biogas plants. The study aimed to determine the optimal fermentation conditions for maximising the yield of biogas with a high methane content using different types of livestock by-products.

MATERIALS AND METHODS

The study was conducted between February and July 2024. The sample consisted of three main types of livestock by-products that are widely used in the biogas industry: cattle manure – collected from the Elita farm in Poltava region. This farm specialises in the production of agricultural products and has a stable record of high-quality by-products. Pig manure was sourced from the commercial pig farm Podillya-Agroprodukt, located in the Vinnytsia region. The poultry manure was collected from the Yasensvit poultry farm located in the Kyiv region. This enterprise is one of the leaders in the production of chicken eggs and poultry by-products in Ukraine.

The criterion for inclusion in the sample was a high content of organic matter – at least 70% of dry weight. Measurements were made using an organic matter analyser (Shimadzu TOC-L, Japan); absence of foreign impurities – substrates should not contain bedding materials (straw, sawdust), sand, stones or other insoluble inclusions. This was checked by visual inspection and sieving through a 2 mm mesh. Exclusion criteria: Preservatives – samples should not be treated with chemicals (formaldehyde, urea, etc.) for long-term storage. Information about the methods of substrate treatment was verified by interviewing suppliers. Treatment of materials with chemicals – samples that were exposed to pesticides, herbicides or other pollutants were excluded from the study. Before being loaded into the bioreactors, all samples were pretreated by drying at 105°C for 24 hours, grinding to a fraction of less than 2 mm, and standardising the dry matter content (8%). This drying temperature and duration are commonly used as a baseline in laboratory practice to prepare samples for further experiments and to obtain stable and reproducible results.

Several methods were used in the study to determine the biogas yield and methane concentration. The biogas yield was determined by collecting the gas produced during fermentation and measuring its volume under normal pressure and temperature (Nm^3/t). The experiment was carried out in laboratory anaerobic bioreactors Biostat B (Sartorius, Germany) with a volume of 10 litres (working volume – 8 litres). The bioreactors were equipped with temperature, pH, and gas pressure control systems, as well as gas outlet systems for biogas collection. The substrates were loaded into the bioreactors, adding water to achieve an optimal consistency (8% dry solids). Each substrate was tested at two temperature conditions: mesophilic (35°C) and thermophilic (55°C), which are standard and common for many microbiological and biotechnological processes such as composting, anaerobic digestion and fermentation, as well as under normal conditions (temperature: 0°C (273.15 K), pressure: 101.325 kPa (1 atmosphere)). The thermophilic mode, at 55°C, provides a significantly higher biogas yield and reduces the time to reach stable gas production.

The fermentation process lasted 30 days for each type of substrate. The control parameters included biogas volume, methane concentration and time to reach a stable gas yield. To determine the effect of the carbon to nitrogen (C/N) ratio, each substrate was tested at three values: 20:1, 25:1, and 30:1. The ratio was adjusted by adding corn silage or ammonium nitrate. The volume of biogas was recorded using gas meters connected to the bioreactor systems. The methane concentration was determined by gas chromatography using an Agilent 7890A instrument with a thermocouple detector. The fermentation time was determined by the achievement of stable gas production (the daily gas volume changed by no more than 5%). The collected data were processed using SPSS v.27 software. Analysis of variance was used to compare the groups. In addition to the Biostat B-Plus bioreactors (Sartorius, Germany), the study used an Agilent 7890A gas chromatograph (Agilent Technologies, USA) to analyse the composition of biogas, an automatic pH meter Mettler Toledo SevenCompact (Mettler Toledo, Switzerland) to monitor acidity, and a laboratory balance Radwag AS 220.X2 (Radwag, Poland) for accurate dosing of components.

RESULTS

The study obtained comprehensive data on the effect of fermentation temperature, substrate type and C/N ratio on biogas yield and its quality composition. The influence of temperature on the bioconversion of organic waste. Temperature is a critical factor that determines the efficiency of fermentation processes in biogas plants. The study compared two temperature regimes – mesophilic (35°C) and thermophilic (55°C) – to determine how temperature affects biogas yield and quality composition depending on the type of substrate. The mesophilic regime (35°C) of fermentation ensures stable gas production 10-12 days after the start of the process. The following results were obtained for different types of substrates: for poultry manure, the biogas yield was 0.35 m^3/kg of organic dry matter (OSR), which is the highest among the substrates studied (Fig. 1). The methane concentration in the biogas was 60-65%. The biogas yield from cattle manure was 0.28 m^3/kg OSR, while the methane content in biogas reached 60%, which is slightly lower than in poultry manure. For pig manure, the biogas yield was 0.25 m^3/kg OSR, which is the lowest among all the substrates studied in the mesophilic regime. However, despite this, the methane concentration in the biogas reached 62%, which is a significant indicator for this type of organic matter. Along with the highest biogas yield, poultry manure showed a good methane concentration, which indicates its potential for use in biogas plants due to its high nitrogen content, which contributes to greater methane production with an appropriate C/N ratio adjustment.

In the thermophilic regime (55°C), the results are as follows: biogas yield from poultry manure increased to 0.42 m^3/kg OSR, which is 20% more than in the mesophilic regime. The methane concentration in the biogas increased to 70%. This indicates the high potential of such a substrate in the thermophilic regime, especially given its high amount of organic matter and optimal C/N ratio. In the study of cattle manure, the biogas yield was 0.36 m^3/kg OSR, which is 28% higher compared to the mesophilic regime. The methane concentration reached 68%, which is a significant improvement compared to the mesophilic regime. Pig manure at thermophilic temperature demonstrates an increase in biogas yield of 0.31 m^3/kg OSR. The methane concentration in biogas from cattle manure increased to 65%, which is the optimal value for energy-efficient biogas production. Reducing the time to achieve stable gas production to 7-8 days in the thermophilic mode is another significant result, as it reduces the overall cost of the fermentation process and increases the overall efficiency of the biogas plant.

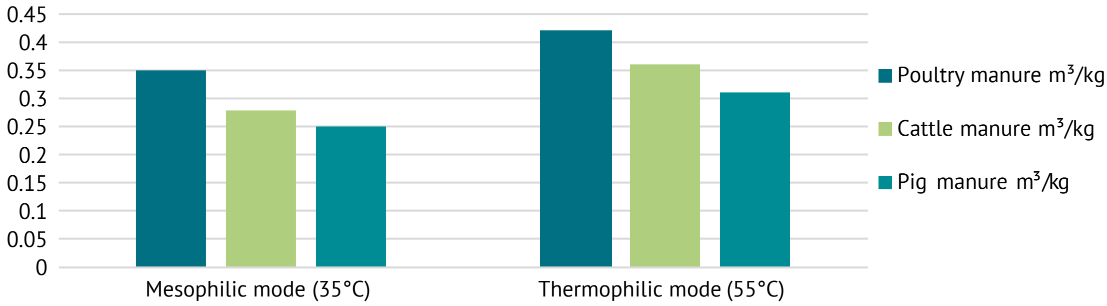

***Figure 1**. Indicators of biogas yield from the studied substrates*
***Source:** compiled by the authors*

The results of the analysis of variance showed that the thermophilic regime has a statistically significant effect on increasing biogas yield and methane concentration compared to the mesophilic regime ($p < 0.05$). Poultry manure showed the highest results, biogas yield increased by 20% and methane concentration by 10%, which confirms the advantages of using this substrate in the thermophilic mode. Cattle manure and pig manure also showed a significant improvement in indicators, but less pronounced than poultry manure. The type of substrate is one of the main factors determining the efficiency of the bioconversion of organic waste into biogas. Different types of manure have different characteristics that affect the biogas and methane yields, as well as the overall energy efficiency of the process (Kucher *et al.*, 2022). The study examines the efficiency of the main types of substrates, namely poultry manure, cattle manure and pig manure.

Poultry manure demonstrated the highest performance among all the substrates tested. The average biogas yield from poultry manure was 140 Nm^3/t of substrate, and the methane yield was 90 Nm^3/t of substrate. These indicators indicate the high efficiency of poultry manure in the biogas fermentation process, which is explained by the high nitrogen content, which contributes to the formation of methane in the process of anaerobic decomposition. In addition, poultry manure has an optimal C/N ratio, which achieves higher methane concentrations in biogas, especially under thermophilic fermentation conditions (55°C), where its potential is fully revealed. Cattle manure is the second most efficient substrate among the tested substrates. The average biogas yield from this substrate was 80 Nm^3/t of substrate, and the methane yield was 34 Nm^3/t of substrate. Due to its high organic matter content and more balanced C/N ratio (approximately 25:1), cattle manure demonstrates high biogas and methane yields and, therefore an effective substrate for fermentation processes in both mesophilic and thermophilic fermentation modes.

Pig manure demonstrated the lowest biogas, and methane yields of all the substrates studied. The average biogas yield from pig manure was 28 Nm^3/t of substrate, and the methane yield was 17 Nm^3/t of substrate. This is attributed to the lower level of organic matter in pig manure and the less-than-optimal C/N ratio. However, pig manure, if the C/N ratio is optimised (e.g., with corn silage or ammonium nitrate), can show a significant improvement in biogas yield by 15-20%, making it more efficient in fermentation processes than poultry manure with an incorrect ratio. The C/N ratio is a critical factor for efficient biogas fermentation, as it affects the activity of the microorganisms in the bioconversion process. The balance between C/N in the organic substrate determines the rate of decomposition and the amount of biogas produced, as well as its composition, particularly the methane content. Correction of the C/N ratio is an important factor in improving biogas yield and methane concentration when using different types of manure in biogas plants. The optimal C/N ratio varies depending on the type of substrate, and correcting this parameter by adding corn silage or ammonium nitrate to the substrate significantly increases the fermentation efficiency (Table 1).

***Table 1**. Biogas yield and methane concentration before and after C/N correction for different types of manure*

Type of substrate	C/N ratio	Biogas yield before correction (m^3/kg OSR)	Methane concentration before correction (%)	Biogas yield after correction (m^3/kg OSR)	Methane concentration after correction (%)
Cattle manure	25:1	0.36	68	0.46	72
Pig manure	25:1	0.31	65	0.37	68
Poultry manure	30:1	0.42	70	0.5	74

***Source:** compiled by the authors*

For cattle manure, the optimal C/N ratio was 25:1. By adding corn silage or ammonium nitrate to correct the C/N ratio, the biogas yield increased by 28%, yielding 0.46 m^3/kg OSR. The methane concentration also increased to 72%, which increases the energy efficiency of the process. The optimal C/N ratio for pig manure was 25:1. When the C/N ratio was adjusted with the addition of corn silage or ammonium nitrate, the biogas yield increased by 20%, resulting in a result of 0.37 m^3/kg OSR. The methane concentration increased to 68%, which improves the overall fermentation efficiency. For poultry manure, the optimal C/N ratio was 30:1. The experiment showed that the correction of C/N in poultry manure leads to a 20% increase in biogas yield, which gives 0.5 m^3/kg OSR. The methane concentration increases to 74%, which ensures the maximum yield of energy-efficient biogas. Thus, the study showed that adjusting the C/N ratio significantly improves the efficiency of biogas fermentation. This is especially important for substrates with an uneven C/N ratio, such as pig manure or poultry manure. The addition of organic materials such as corn silage or ammonium nitrate balances the C/N ratio, which can increase the biogas yield by 15-20% for all types of substrates. This improves both the quantity and quality of biogas, particularly the methane concentration.

C/N adjustment has also been shown to improve the stability of the fermentation process by avoiding problems associated with too high or low nitrogen levels. The increase in methane concentration and decrease in carbon dioxide emissions as a result of the C/N ratio adjustment contributes to the energy efficiency of biogas plants and reduces the cost of the fermentation process (Pryshliak *et al.*, 2021). Biogas is an important source of renewable energy, and its composition depends on various factors, such as the type of substrate, fermentation conditions, and the technology used to produce it. According to the results of the Agilent 7890A gas chromatograph, biogas produced by the anaerobic decomposition of organic materials consisted mainly of methane (CH_4) and carbon dioxide (CO_2), with smaller amounts of hydrogen sulphide (H_2S) and traces of other gases. Methane (CH_4) is the main component of biogas responsible for its energy value. Depending on the type of substrate and fermentation conditions, the methane content ranges from 50% to 70% of the total biogas composition (Pryshliak *et al.*, 2021). Methane has a high calorific value, which makes it an ideal energy source for further use in generators or boilers to produce electricity and heat. Importantly, the higher the methane content, the more efficient the energy production process.

Carbon dioxide is the second main component of biogas, with a content ranging from 25% to 30%. CO_2 is the result of the anaerobic decomposition of organic materials, but it has no energy value as it cannot be used for energy production. However, its presence in biogas is a natural and unavoidable part of the process. To increase the energy efficiency of biogas, it is important to reduce the CO_2 content, as this allows for an increase in the methane concentration (Golub *et al.*, 2020). Hydrogen sulphide is a harmful component of biogas that is produced during the fermentation of organic materials containing sulphur, such as manure, poultry manure or food waste. Biogas typically contains up to 2% hydrogen sulphide. This gas is highly corrosive and can damage equipment, so its concentration must be monitored. A high H_2S content can also reduce the efficiency of biogas use for energy needs, as sulphur can contaminate engines and generators (Golub *et al.*, 2017). Therefore, additional methods are often used to purify biogas from hydrogen sulphide to reduce its content to a safe level.

Biogas may also contain other gases in trace amounts, such as ammonia (NH_3), nitrogen (N_2), water vapour and other volatile organic compounds. Their amount is usually minimal, but they can affect the overall composition of the gas and its quality. Thermophilic conditions, maintained at 55°C, can significantly improve the composition of biogas, by reducing impurities such as CO_2 and H_2S. Under thermophilic conditions, anaerobic microorganisms are more active, which accelerates the decomposition of organic materials and improves methanogenesis. Compared to mesophilic conditions, thermophilic conditions contribute to a reduction in CO_2 content – due to the more active activity of methanogenic microorganisms, the CO_2 content can be reduced in thermophilic conditions, which contributes to an increase in the methane concentration in biogas. An increase in methane concentration – 55°C provides better conditions for methanogenic archaea, which increases methane yield. As a result, the methane content in biogas can increase by up to 70%, which is a significant improvement compared to mesophilic conditions. Reduced hydrogen sulphide (H_2S) content – higher temperatures can reduce the concentration of hydrogen sulphide in biogas due to faster decomposition of sulphur-containing compounds or their absorption in other phases of the fermentation process (Skliar *et al.*, 2019).

The thermophilic regime also reduces the time to reach stable gas production, which is an important factor in increasing the overall efficiency of biogas plants. The analysis of the biogas composition shows that thermophilic operation is an effective way to improve the quality of biogas to reduce the content of impurities and increase the concentration of methane. This improves energy efficiency and reduces operating costs for gas treatment. As a result, thermophilic operation makes biogas plants more cost-effective and provides greater stability in energy production. The fermentation process is much faster in the thermophilic regime. Experimental results show that the time to achieve stable gas production is usually 7-8 days compared to 10-12 days in the mesophilic regime. As such, under thermophilic conditions, gas production stabilises twice as fast, which is an important factor for industrial biogas plants, where increasing the process speed can significantly increase productivity. Reducing the time to stable gas production allows for an increase in the number of substrates treated per unit of time. This is relevant in industrial biogas plants where biogas production is a continuous process. Increasing productivity by reducing the fermentation time increases the overall energy production efficiency, as the plant moves to the next fermentation cycle faster.

Reduced energy and resource costs are also achieved by shortening the fermentation time, as the process is faster, and less time is required to maintain the optimum temperature at all times. This also reduces the cost of heating the fermentation tanks, making the technology more economical. Reduction in the fermentation time also impacts the composition of the biogas. Thermophilic microorganisms that operate at high temperatures are more active and can decompose organic materials faster, leading to an increase in methane content and a decrease in impurities such as carbon dioxide and hydrogen sulphide. As a result, biogas becomes more energy efficient. In addition, high temperatures reduce the risk of pathogenic microorganisms, which can be a problem in mesophilic conditions where the likelihood of contamination increases. This ensures more stable and predictable biogas production (Skliar *et al.*, 2019).

Recommendations on the use of livestock by-products to improve the energy efficiency of the bioconversion process. To improve the energy efficiency of the bioconversion process using livestock by-products, several key aspects need to be considered. The selection of appropriate substrate types is important for increasing the efficiency of biogas plants. However, it is necessary to choose the right type of substrate for different fermentation conditions. Correction of the C/N ratio is also important for increasing biogas yields, and it is necessary to maintain an optimal C/N ratio in the substrates. This can be achieved by adding organic additives, such as corn silage or ammonium nitrate, which improves the decomposition of organic matter and promotes active methanogenesis. The use of thermophilic conditions (55°C) promotes faster and more efficient decomposition of organic matter, which can significantly reduce the fermentation time and increase the efficiency of the process.

The use of by-products with high carbon content can be realised by adding silicate materials such as straw or chopped plant residues, which in turn can be useful for correcting the C/N ratio, especially for substrates with high nitrogen content such as pig manure. Residues from grain processing, such as wheat bran or corn stover, can also be added to increase the carbon content of the substrates, which increases the biogas yield. Improving the efficiency of the fermentation process through inoculation can be done by using special microbiological additives, such as methanogenic bacteria cultures or enzymes, which can accelerate the fermentation of organic matter. This can be particularly useful for substrates that are difficult to anaerobically degrade. The implementation of waste-free technologies is based on the creation of biogas plants, which makes it possible to reduce the amount of waste and generate energy at the same time. Given the large amount of waste generated on farms, using it in biogas plants can significantly reduce the negative environmental impact. The study demonstrated the importance of optimising parameters such as temperature, humidity, pH and stirring speed in the reactors to achieve maximum biogas fermentation efficiency. The use of automated control systems for these parameters can significantly improve the process.

DISCUSSION

The results of the study confirm the importance of temperature conditions for the efficiency of the biogas fermentation process. In particular, the thermophilic regime (55°C) demonstrated a significant increase in biogas yield (by 20-28%) and an increase in methane concentration (by 5-10%) compared to the mesophilic regime (35°C). These findings correlate with previous studies, particularly the work of N. Pryshliak *et al.* (2021), which also confirmed the importance of optimising temperature conditions to improve the efficiency of biogas plants. The authors noted that temperature has a significant impact on the fermentation rate and overall biogas yield, which is critical for the industrial use of such technologies. The study confirms the conclusions of O.G. Skliar *et al.* (2019), who presented a programme and methodology for experimental research at a laboratory biogas plant, which allows for a detailed analysis of the impact of various factors on biogas yield. The application of this methodology confirms the feasibility of the chosen approach for analysing temperature conditions and choosing substrates since the data obtained show similar trends in improving the efficiency of biogas plants.

V.S. Chubur (2023) also emphasised the importance of selecting a suitable substrate for biogas plants. In the present study, poultry manure showed the best results as a substrate, which confirms its high efficiency, in contrast to cattle manure and pig manure. The results also correlate with the research of other international scientists, such as O. Alghoul *et al.* (2019), who conducted experimental studies on biogas production from food waste. The study also emphasised that the right choice of substrate and optimisation of fermentation conditions are key to achieving the high performance of biogas plants. In particular, the use of a thermophilic process in this experiment demonstrates the advantage of this approach compared to a mesophilic one, which can significantly reduce the time to achieve stable gas production. Another important aspect is the impact of optimising the C/N ratio, which, according to A. Nsair *et al.* (2020), are also critical for improving the energy efficiency of the process. However, in this work, the authors did not conduct separate experiments to study this variable, which is a promising area for further research.

The results of this study demonstrated the importance of optimising key fermentation parameters, which is consistent with previous studies, in particular, with a study by M. Zhou *et al.* (2018), which determined that increasing the temperature to the thermophilic range significantly increases the efficiency of methanogenesis. Similar conclusions were made by E. Liu and S. Liu (2017), who demonstrated that the use of a mixture of duck manure and straw under optimised fermentation conditions allows for maximum biogas yields. The study confirms the effectiveness of combining different types of organic feedstock to increase methane yield. The optimisation of the C/N ratio in this study is consistent with the analysis of M. Safari *et al.* (2018). Using the response surface methodology in their study, the study determined that the optimal C/N ratio is a key factor for increasing biogas yield. Similarly, S. Djimtoingar *et al.* (2022) confirmed the effectiveness of this methodology for predicting and optimising fermentation parameters.

This study correlates with the research of W. Romaniuk *et al.* (2022), which determined that the fermentation of molasses bards at high temperatures significantly improves the performance of biogas plants due to the increased availability of organic matter for methanogenesis. The study also points out the importance of substrate preparation, which is in line with the findings of J. Sun *et al.* (2024), who emphasise the importance of pre-treating plant residues such as corn stalks with microbial agents to increase biogas yields. This proves that the combination of substrate preparation and the choice of the optimal temperature regime can significantly improve the overall performance of the plants. The quality and composition of the biogas produced were emphasised. The study by Y. Chen *et al.* (2021) demonstrated that biogas enrichment technologies, such as pressure adsorption, can significantly improve its quality characteristics, which can be used in the future to improve existing biogas plant systems. This correlates with the conclusion on the importance of not only increasing the production volume but also improving the composition of the biogas produced. The results confirm the potential of alternative substrates for co-fermentation. This coincides with the data of P. Gupta and A. Gupta (2014), who noted that even unconventional materials such as coal can be used in anaerobic fermentation processes, although the main focus should be on biologically active waste.

The results of this study correlate with the findings of P. Dobre *et al.* (2014), stating that the main factors affecting biogas production are temperature, pH, C/N ratio and substrate composition. Their analysis shows that the optimal fermentation conditions depend on the combination of these parameters. The data also confirms the importance of selecting the type of waste, especially those with a high nitrogen content, such as poultry manure. This correlates with the research of Z. Recebli *et al.* (2015), concluding that cattle manure and pig manure provide lower biogas yields compared to more concentrated organic waste. The study demonstrated the importance of an integrated approach to the selection of substrates, temperature conditions and biogas enrichment. One of the main limitations of the study is the narrow specialisation in certain types of organic waste, which may not fully reflect the diversity of the raw material base for biogas plants. In addition, the experimental conditions on a laboratory scale may not consider all possible technical and economic challenges when scaling up the process to an industrial level. Further research should focus on the development of efficient methods for pretreating substrates and the integration of the latest biogas treatment technologies to increase their energy value.

CONCLUSIONS

Comparison of the mesophilic (35°C) and thermophilic (55°C) modes showed significant advantages of the latter. In the thermophilic mode, biogas yield increased by 20-28%, and methane concentration increased by 5-10%. Poultry manure reached 0.42 m^3/kg OSR of biogas with a methane concentration of 70%, which is the best result among the substrates studied. Reducing the time to stable gas production to 7-8 days confirms the feasibility of using the thermophilic regime in industrial conditions. Correction of the C/N ratio for different substrates increased the biogas yield by 20-28% and increased the methane concentration by up to 74%. Cattle manure, pig manure and poultry manure demonstrated increased energy efficiency after optimising the C/N ratio.

The highest quantitative and qualitative indicators were recorded for poultry manure, which is determined by its high nitrogen content. This substrate proved to be the most promising to produce energy-efficient biogas. The results of the study confirm the significant potential of livestock by-products for bioconversion, especially if key fermentation parameters are optimised. Practical recommendations include the use of thermophilic conditions, correction of the C/N ratio, and the introduction of co-fermentation to increase biogas yields. Despite achieving the goal, the study has limitations, including the dependence of the results on precise control of parameters and substrate specificity. Further research should analyse the optimisation of fermentation technologies, studying mixed substrates and the impact of microbial additives to maximise biogas yield and process efficiency.

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CONFLICT OF INTEREST

None.

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Біоконверсія побічних продуктів тваринництва в біогаз: експериментальне дослідження оптимальних умов ферментації

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Анотація. Біоконверсія органічних відходів у біогаз є важливою складовою стратегії сталого розвитку та зменшення впливу на довкілля. Ключовими факторами, що впливають на ефективність цього процесу, є температура ферментації, співвідношення вуглецю до азоту (C/N) та тип субстрату. Метою цієї роботи було дослідження впливу температурних режимів, співвідношення C/N та різних типів органічних відходів на вихід біогазу, зокрема концентрацію метану, при анаеробній ферментації. У експерименті порівнювались два температурні режими: мезофільний (35°C) та термофільний (55°C), із застосуванням трьох типів органічних відходів: пташиного посліду, гною великої рогатої худоби та свинячого гною. Вивчалося також оптимальне співвідношення C/N для покращення енергоефективності процесу. В умовах термофільного режиму було зафіксовано збільшення виходу біогазу на 20-28 % та зростання концентрації метану на 5-10 % у порівнянні з мезофільним режимом. Найвищий вихід біогазу (0.42 $м^3$/кг органічної сухої речовини (OSR)) і концентрація метану (70 %) були досягнуті при використанні пташиного посліду. У термофільному режимі також було зафіксовано скорочення часу досягнення стабільного газовиділення до 7-8 днів, що підтвердило ефективність цього підходу для промислового використання. Термофільний режим ферментації є більш ефективним для виробництва біогазу та підвищує енергоефективність процесу. Оптимізація співвідношення C/N та ко-ферментація різних субстратів додатково покращили ефективність. Пташиний послід виявився найбільш ефективним субстратом для біоконверсії, що відкриває перспективи для його використання в промислових масштабах. Результати роботи можуть бути використані для оптимізації технологій біогазової ферментації, зокрема для поліпшення продуктивності біогазових установок та зменшення витрат на енергозабезпечення

Ключові слова: відновлювані джерела енергії; органічні відходи; метан; анаеробне бродіння; термофільний режим; мезофільний режим