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Influence of the type of livestock by-products on biogas yield and composition

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Abstract. The study of the effects of various types of animal waste on the quantity and composition of biogas is significant and relevant for optimising anaerobic fermentation processes, increasing the efficiency of biogas production and adapting technologies to farm conditions. The purpose of this study was to evaluate the effects of livestock by-products,

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specifically cattle manure, pig manure, and chicken manure, on the quantity and quality of biogas produced. The methods employed in the study included statistical analysis, gas analysis, and fermentation. The study analysed the physicochemical properties of several types of raw materials for biogas production. The study found that chicken manure had the highest potential for biogas production due to its high content of volatile solids (25-30%) and the optimum ratio of methane in the biogas composition (65%). Cattle manure was characterised by a stable average biogas yield (0.15-0.18 m^3/kg volatile solids in feedstock (VT, %)), while pig manure had the lowest yield (0.12-0.14 m^3/kg volatile solids in feedstock). According to the study results, the addition of carbonaceous materials (e.g., chopped straw) improved the carbon to nitrogen ratio to optimise the fermentation process. The analysis of the organic matter content before and after fermentation revealed a significant decrease for chicken manure (51%), which indicated the effectiveness of biodegradation. The study included an assessment of the composition of biogas, including methane (50-65%), carbon dioxide (30-40%), and hydrogen sulphide (1-3%). The change in pH in all types of raw materials after fermentation indicated that the environment in the bioreactors had stabilised, providing favourable conditions for microorganisms. The findings of this study can be used in practice by ecologists, agronomists, livestock technologists, and biogas producers to create energy-independent farms through the integration of biogas plants into farms

Keywords: waste; manure; chicken manure; bioreactor; methane; carbon dioxide; fermentation

Introduction

Regular research into methods of optimising the processing of organic livestock waste is significant for ensuring energy efficiency and the long-term development of the agricultural sector of Ukraine's economy. As one of the principal problems of modern agriculture, the problem of utilisation of livestock by-products, such as chicken manure, requires research with maximum economic and environmental benefits in focus. The problem of the study is that the lack of sufficient understanding of the effects of the type of livestock by-products on the yield and composition of biogas makes complicates the optimisation of anaerobic digestion processes. According to V. Shmatenko (2024), distinct types of feedstocks significantly affect the efficiency of fermentation, which determined the quantity and quality of biogas produced. The existence of the problem is confirmed by the fact that when using feedstocks with a high content of organic matter, such as chicken manure, there was a need to adjust the carbon:nitrogen (C: N) ratio to achieve the best conditions for the biogas fermentation process.

A prominent aspect is the problem of reducing nitrogen and phosphorus emissions into the environment for pig production, as it has reduced the environmental impact of the industry and improved the efficiency of nutrient use in animal production. S. Zinoviev & M. Pushkina (2023) investigated this issue. Their study proved that the use of multiphase feeding systems and optimisation of the amino acid composition of diets can improve the efficiency of nutrient absorption by pigs. A significant issue is the need for environmentally safe disposal of organic waste (Muminova *et al.*, 2023). In this regard, Y. Palamarenko & I. Chikov (2023) investigated the effects of various methods of organic waste processing on the environment. According to their findings, the use of biogas plants for the disposal of organic waste has reduced greenhouse gas emissions. The development of biogas technologies is a topical issue for modern environmentalists. S. Tkachenko *et al.* (2020) studied the efficiency of biogas plants and their effects on the environmental situation. The researchers proposed a technology for using agricultural by-products for biogas production. Their study showed that this technological innovation has enabled the reduction of greenhouse gas emissions and contributed to the development of energy production by renewable energy facilities.

The replacement of natural gas consumption with alternative energy sources has become particularly significant due to the threat of an energy crisis caused by the military conflict and the possible termination of Russian gas supplies (Moshenskyi *et al.*, 2024; Strokal *et al.*, 2024). According to G. Geletukha *et al.* (2022), biomethane is a promising alternative to natural gas that has a wide range of applications, including energy production and raw materials for the chemical industry. Aspects of the environmental and economic assessment of the introduction of bioenergy technologies in the context of reducing anthropogenic and military risks and improving energy security of Ukraine were investigated by V. Dudin *et al.* (2024). As a result, they analysed current trends in bioenergy, modelled technological and economic parameters of biogas plants.

The problem of intensification of biogas production processes stays urgent in the context of growing demand for renewable energy sources and the need for efficient waste processing, as proved by V. Chubur *et al.* (2022). According to their findings, the combination of physical and chemical pretreatment methods, such as cavitation and electrolysis, greatly increased the efficiency of anaerobic digestion. One of the key environmental issues is the rational use of organic and mineral fertilisers, as well as the disposal of livestock waste (Kravchenko & Bykova, 2023). R. Lohosha *et al.* (2023) investigated the effects of various fertilisation systems on the yield of maize and red beet. The researchers found that the use of artificial fertilisers in combination with high doses of bio-organic fertilisers, specifically digestate, provided a considerable increase in yields. The issues related to optimising the anaerobic co-digestion of pig manure and maize stalks to increase the efficiency of biogas and methane production are still significant in the context of growing demand for renewable energy sources, the necessity of recycling organic waste and reducing greenhouse gas emissions, as proven by H. Wang *et al.* (2020). The researchers found that the addition of maize stalks to pig manure during anaerobic co-digestion increased microbial diversity.

The study of unexplored aspects of increasing the efficiency of anaerobic digestion, improving biogas purification technologies and optimising the use of various types of raw materials requires a comprehensive approach in modern conditions. K. Obileke *et al.* (2024), T. Manushkina *et al.* (2024) recommended the development of technologies aimed at reducing greenhouse gas emissions, such as the introduction of renewable energy sources and technologies for the extraction of carbon dioxide (CO_2) from industrial sources.

Studies have not paid sufficient attention to the aspects of using alternative energy sources in combination with innovative organic waste treatment technologies. The purpose of this study was to investigate the effects of types of livestock by-products on the yield and composition of biogas, considering the varying physical and chemical properties of the raw materials used. The objectives were to determine the effects of distinct types of organic livestock waste on the amount and composition of biogas; to assess the effectiveness of adding carbonaceous materials to optimise the C: N ratio in the feedstock; to analyse the effects of the physical and chemical properties of waste on the performance of the anaerobic fermentation process.

Materials and Methods

The sampling of raw materials for biogas production took place on farms specialising in cattle (Dairy Alliance Company in Kyiv region), pigs (Podilsky Bacon Farm in Khmelnytsky region) and poultry (Vinnytsia Poultry Farm in Vinnytsia region). The study was conducted in 2023-2024 in accredited laboratories of the State Service of Ukraine for Food Safety and Consumer Protection and the State Agency on Energy Efficiency and Energy Saving of Ukraine, which have the relevant permits for biogas analysis.

During the preparation of the raw materials, the livestock by-products were sieved to remove large solid inclusions. Subsequently, water was added to obtain the same dry residue (10% dry weight). After the selection of raw materials for each type of livestock by-product, the key physicochemical parameters were analysed in the laboratory: moisture content (%) was determined according to the method of drying to constant weight; volatile solids content (VT, %) was determined as a proportion of organic matter; C:N ratios were measured using a CHNS analyser. For each portion of carbonaceous materials, the weight of the additive was determined as follows (1):

$$m_{straw} = \frac{N_{initial} \times C{:}N_{desired}}{C_{straw}} - C_{initial}, \quad (1)$$

where $N_{initial}$ is the initial nitrogen content in the substrate, g/kg; $C{:}N_{desired}$ is the desired carbon to nitrogen ratio in the substrate; C_{straw} is the carbon content in straw, g/kg; $C_{initial}$ is the initial carbon content in the substrate, g/kg.

When calculating the biogas yield, the theoretical biogas yield for each type of feedstock was estimated based on the organic matter content (2):

$$V_{theoretical} = VT \times K_{degradation} \times 0.35\ m^3/kg, \quad (2)$$

where $V_{theoretical}$ is the theoretical volume of biogas, m^3; VT is the mass of volatile solids in the feedstock, kg; $K_{degradation}$ is the degradation coefficient of organic matter (0.4-0.6 for solid organic matter), 0.35 m^3/kg is the coefficient responsible for the volume of biogas produced by the decomposition of 1 kg of volatile matter.

The organic degradation factor was defined as the percentage of volatile solids decomposed (3):

$$K_{degradation} = \frac{VT_{initial} - VT_{final}}{VT_{initial}} \times 100\%, \quad (3)$$

where $K_{degradation}$ is the percentage of volatile solids decomposition; $VT_{initial}$ is the initial volatile solids content in the raw material, %; VT_{final} is the final volatile solids content after fermentation, %.

Preliminary alkaline treatment of the feedstock with sodium alkali (NaOH) solution and the use of a hydraulic shredder press to mechanically grind the materials under high pressure before fermentation can improve the efficiency of the biogas production process. A gas analyser was used to determine the biogas composition on a daily basis. The methane (CH_4) concentration in the biogas was estimated by chromatography, carbon dioxide (CO_2) – by infrared spectroscopy, and hydrogen sulphide (H_2S) – by spectrophotometry

The following equipment and facilities were used to determine the fermentation performance and evaluate the efficiency of using different types of raw materials: BioFlo laboratory anaerobic bioreactor with controlled temperature (37 °C to optimise methanogenesis) (USA), biogas collection system equipped with a gas meter and gas analyser EnviTec Biogas GmbH (Germany), Shimadzu UV-1800 spectrophotometer for biogas composition measurements (Japan), Agilent 7890A gas chromatograph (USA) for accurate analysis of CH_4, CO_2, and H_2S concentrations.

Research methods were employed to investigate the effects of the type of livestock by-products on the yield and composition of biogas, as established by legislative acts: State Standard of Ukraine (DSTU) ISO No. 11722:2004 "Solid mineral fuels. Hard coal. Determination of moisture in a sample for general analysis by the nitrogen drying method" (2005), DSTU ISO No. 5725-4:2005 "Accuracy (correctness and precision) of measurement methods and results" (2005).

The study employed the method of statistical analysis of data (analysis of variance (ANOVA)) obtained during the evaluation of the physical and chemical properties of distinct types of raw materials to compare the biogas yield and methane composition for each type of by-product. Two-way ANOVA was used in the study. To determine the statistical significance of the findings, the p-value was used, set at 0.05, meaning that $p < 0.05$ is considered statistically significant, i.e., the difference between the groups is significant.

A gas analysis and fermentation method for determining biogas yield and assessing its composition. The effect of fermentation time on gas yield was analysed by regression analysis. The average fermentation time for raw materials (organic waste, food residues, manure) was 30-45 days. For anaerobic fermentation, the optimum temperature ranged within 35-40 °C. The optimum pH for anaerobic fermentation was 6.5-7.5. Stirring was carried out 1-2 times a day or as needed to avoid sedimentation of the material. Each experiment with distinct types of raw materials was repeated 3-5 times. To ensure an optimum start of fermentation, a starter containing special anaerobic bacteria was used. The starter was obtained from previous experiments or from industrial biogas plants. 10-20% of the starter was added to 1 litre of substrate.

Results

The study described the characteristics of various types of feedstocks for biogas production, as well as the calculation of the expected biogas yield. Evaluation of the chemical and physical properties of the feedstock helped to plan the fermentation process efficiently and provide optimised conditions for the biogas plant. Carbon additives, specifically chopped straw, were used to improve the C:N ratio in the feedstock, which contributed to the optimisation of the fermentation process and increase the biogas yield (Havrysh *et al.*, 2020). Table 1 provides data on the main physical and chemical parameters of the feedstock before loading into the biogas plant for further calculations of biogas yield, as well as determining the necessary corrective measures to optimise the fermentation process.

Table 1. *Characteristics of raw materials before loading*

Indicator	Cattle manure	Pig manure	Chicken manure
Humidity (%)	75-80	70-75	60-65
Volatile solids (VT, %)	20-25	18-22	25-30
Carbon: nitrogen (C:N)	25:1	18:1	10:1

Source: compiled by the authors

The analysis of the feedstock showed that each type of waste had specific physicochemical characteristics that could affect the fermentation process: the highest moisture content (75-80%) was found in cattle manure, which required additional measures to regulate the consistency; the highest volatile solids content was observed in chicken manure (25-30%), which indicated its high potential in the biogas process; for chicken manure (10:1), an imbalance of C:N ratio was found, which negatively affected the fermentation, so carbonaceous materials such as chopped straw were added to improve this indicator (Formula 1). The desired C:N ratio is considered to be 20:1 to 30:1. For cattle manure, calculations were made using formula (1).

The initial nitrogen content ($N_{initial}$) was 1 g/kg (based on standard data for chicken manure). The desired C:N ratio ($C{:}N_{desired}$) was 20:1 (selected for optimum fermentation). The carbon content of the straw (C_{straw}) was 450 g/kg (approximate value). The initial carbon content of cattle manure ($C_{initial}$) was 250 g/kg (standard value for cattle manure). The values of formula (1) were substituted into the equation:

$$m_{straw} = \frac{1 \times 20}{450-250} = \frac{20}{200} = 0.1.$$

Therefore, to achieve the desired C:N ratio of 20:1, 0.1 kg of straw should be added for each kilogram of cattle manure. For pig manure and chicken manure, the same formula (1) was used to calculate the ratio.

The initial nitrogen content ($N_{initial}$) was 1.5 g/kg (standard value for pig manure). The desired C:N ratio ($C{:}N_{desired}$) was 20:1 (selected for optimum fermentation). The carbon content of the straw (C_{straw}) was 450 g/kg (approximate value). The initial carbon content of pig manure ($C_{initial}$) was 300 g/kg (standard value for pig manure). The values of formula (1) were substituted into the equation:

$$m_{straw} = \frac{1.5 \times 20}{450-300} = \frac{30}{150} = 0.2.$$

The calculation shows that 0.2 kg of straw should be added for every kilogram of pig manure. The initial nitrogen content ($N_{initial}$) was 1 g/kg (based on standard data for chicken manure). The desired C:N ratio ($C{:}N_{desired}$) was 20:1 (chosen for optimum fermentation). The carbon content of the straw (C_{straw}) was 450 g/kg (approximate value). The initial carbon content of the chicken manure ($C_{initial}$) was 300 g/kg (standard value for chicken). The values of formula (1) were substituted into the equation:

$$m_{straw} = \frac{1 \times 20}{450-300} = \frac{20}{150} = 0.133.$$

Thus, to achieve the desired C:N ratio of 20:1, 0.133 kg of straw should be added for each kilogram of chicken manure. Based on the analysis of the physicochemical properties of distinct types of biogas feedstocks, the expected biogas yield was calculated for each of them. These data can be used to assess the potential of different substrates in the biogas process and determine the best conditions for their use. The calculations results presented in Table 2 show the values of biogas yield depending on the type of raw material.

Table 2. *Expected biogas yields*

Raw material	Expected biogas yield (m^3/kg VT)
Cattle manure	0.15-0.18
Pig manure	0.12-0.14
Chicken manure	0.2-0.25

Note: biogas yield was calculated using the formula (2)
Source: compiled by the authors

The calculation of the expected biogas yield demonstrated the following key aspects: chicken manure provided the highest biogas yield (0.2-0.25 m^3/kg VT), and therefore this component became a promising feedstock for biogas plants. Cattle manure had an average biogas yield (0.15-0.18 m^3/kg VT), which required optimisation of fermentation conditions. Pig manure was characterised by the lowest biogas yield (0.12-0.14 m^3/kg VT), but it can be effectively used in mixed substrates. The study confirmed the expediency of factoring in the physicochemical properties of the feedstock to improve the efficiency of the biogas process.

For optimum biogas production, chicken manure should be used in combination with carbon additives (e.g., straw). To minimise the impact of H_2S, excessive use of pig manure should be avoided or adsorbents (e.g., iron oxide) should be used. For efficiency, large farms can combine several types of feedstocks for a stable C:N ratio (Havrysh *et al.*, 2019). The data on the volume of biogas produced from each type of organic feedstock after 30 days of fermentation were presented. After 30 days of fermentation in each bioreactor, the parameters listed in Tables 3, 4, 5, and 6 were evaluated.

Table 3. *Biogas yields from different types of raw materials*

Raw material	Biogas volume (m^3/kg VT)
Cattle manure	0.16
Pig manure	0.13
Chicken manure	0.23

Source: compiled by the authors

After 30 days of fermentation, chicken manure showed the highest biogas yield (0.23 m^3/kg VT), indicating its higher efficiency as a feedstock for biogas production compared to cattle manure (0.16 m^3/kg VT) and pig manure (0.13 m^3/kg VT). Table 4 shows the content of the key components of biogas collected from each type of feedstock. The results are presented in percentage terms for methane (CH_4), carbon dioxide (CO_2) and hydrogen sulphide (H_2S).

Table 4. *Composition of biogas by components*

Component	Cattle manure (%)	Pig manure (%)	Chicken manure (%)
Methane	60	55	65
Carbon dioxide	38	40	33
Hydrogen sulphide	1	3	2

Source: compiled by the authors

According to the findings of the study, chicken manure had the highest methane content (65%) and, accordingly, the feedstock demonstrated an advantage in terms of biogas energy value. Cattle manure provided an average biogas yield with the lowest H_2S content (1%), which reduced the need for additional treatment. Pig manure contained the highest level of H_2S (3%), which required additional measures to clean the biogas from impurities. Table 5 shows the dynamics of biogas yield over three 10-day fermentation periods. The data shows how the volume of biogas changed over time for each type of feedstock.

Table 5. *Dynamics of biogas yield in different fermentation periods*

Period (days)	Cattle manure (m^3/day)	Pig manure (m^3/day)	Chicken manure (m^3/day)
1-10	0.04	0.03	0.05
10-20	0.07	0.05	0.09
20-30	0.05	0.04	0.07

Source: compiled by the authors

The highest average daily biogas yield was observed for chicken manure during all days of fermentation, with a maximum in the second period (0.09 m^3/day). Cattle manure showed an average level of dynamics, while pig manure had the lowest biogas yields, especially in the first period (0.03 m^3/day). Table 6 presents the volatile solids before and after fermentation, as well as the calculated organic matter degradation factor for each type of feedstock.

Table 6. *Degradation factor of organic matter (volatile solids, VT)*

Raw material	VT before fermentation (%)	VT after fermentation (%)	Degradation rate (%)
Cattle manure	25	11	55
Pig manure	22	11	50
Chicken manure	30	12	60

Note: organic degradation factor was determined by the established formula (3)
Source: compiled by the authors

Chicken manure showed the highest organic matter degradation rate (60%), indicating its high biodegradability. Cattle manure had an average degradation factor (55%), while pig manure had the lowest (50%), which could affect the efficiency of processing. Chicken manure showed the highest biogas yield and methane content due to its high organic matter content, optimum C:N ratio and high organic matter degradation factor. Pig manure had the lowest yield due to its high sulphur content, which contributed to the formation of the H_2S component. Cattle manure provided a stable average gas yield but required balancing to improve the methane ratio. Removal of H_2S is necessary to protect equipment and reduce emissions. Chicken manure could cause ammonia accumulation, which required adjustment of the substrate concentration. Biogas production from chicken manure is the most cost-effective due to the high methane yield. Cattle manure has proved to be a suitable feedstock for biogas production and economically viable for farms with large livestock.

Table 7. *Distribution of organic matter before and after fermentation*

Raw material	Organic matter before fermentation (%)	Organic matter after fermentation (%)	Difference (%)
Cattle manure	80	36	44
Pig manure	78	39	39
Chicken manure	85	34	51

Source: compiled by the authors

Prior to the biofermentation process, it is vital to assess the organic matter content of distinct types of feedstocks, as this is a key indicator for the efficiency of the biogas process. After fermentation, the organic matter is partially decomposed and some of it is converted into biogas. Table 7 shows the changes in the organic matter content of the feedstock types under study before and after fermentation.

Changes in organic matter content after fermentation are significant for all types of feedstocks. The largest decrease in organic matter was observed in chicken manure (51%), suggesting a high level of decomposition of organic compounds during fermentation. For effective fermentation, it is vital to understand changes in the chemical composition of the substrate, specifically pH and C:N ratio. These parameters affect the activity of microorganisms that decompose organic matter, as well as the final quality and quantity of biogas. Table 8 shows the changes in pH and C:N ratio before and after fermentation for each type of feedstock.

Table 8. Chemical characteristics of the substrate before and after fermentation for three types of raw materials

Raw material	pH before fermentation	pH after fermentation	C:N before fermentation	C:N after fermentation
Cattle manure	7.2	7.8	25:1	15:1
Pig manure	7	7.5	18:1	12:1
Chicken manure	6.8	7.4	10:1	7:1

Source: compiled by the authors

The increase in pH after fermentation indicated the stabilisation of the substrate, which reduces the risk of developing an acidic environment in the biogas plant. Changes in the C:N ratio showed an improvement in the conditions for microorganisms responsible for the decomposition of organic matter, which may contribute to a better activity of the microbiological process. The energy efficiency of biogas depended on the amount of methane produced during fermentation and its calorific value. As methane is the principal energy component of biogas, its amount directly affected the energy yield. Table 9 shows the energy efficiency of biogas from distinct feedstock types based on the amount of methane and its calorific value.

Table 9. Energy efficiency of biogas

Raw material	Volume of methane (CH_4) m^3/kg VT	Calorific value (kWh/m^3 CH_4)	Energy output (kWh/kg VT)
Cattle manure	0.1	9.94	0.994
Pig manure	0.07	9.94	0.696
Chicken manure	0.15	9.94	1.491

Source: compiled by the authors

Chicken manure demonstrated the highest energy yield (1.491 kWh/kg VT), and therefore it should be considered as the most efficient feedstock for biogas plants among the types under study. Components in biogas, such as H_2S and ammonia (NH_3), can be harmful to health and to biogas plant equipment. It is therefore crucial to monitor their content during the fermentation process and in the final biogas. Table 10 shows the level of harmful components in biogas produced from distinct types of raw material.

Table 10. Environmental indicators (content of harmful components in biogas)

Component	Cattle manure (%)	Pig manure (%)	Chicken manure (%)	Permissible level (%)
H_2S	1	3	2	⩽1
NH_3	0.8	1.5	2.1	⩽1

Source: compiled by the authors

The level of harmful components in biogas varied depending on the type of feedstock. Pig manure had the highest level of H_2S – 3%, which required additional biogas treatment to reduce its negative effects, while cattle manure and chicken manure had lower levels of harmful components in biogas. Temperature is one of the most significant factors affecting the speed of biological fermentation processes. Since temperature conditions change the activity of microorganisms, this can substantially affect the amount and composition of biogas. Table 11 shows the dependence of biogas yield on fermentation temperature for each type of feedstock.

Table 11. *Biogas yield depending on the fermentation temperature*

Temperature (°C)	Cattle manure (m^3/kg VT)	Pig manure (m^3/kg VT)	Chicken manure (m^3/kg VT)
25	0.14	0.11	0.2
30	0.16	0.13	0.23
35	0.18	0.14	0.25
40	0.17	0.13	0.24

Source: compiled by the authors

The temperature of 35 °C is optimal for fermentation of all types of feedstocks, providing maximum biogas yield. Increasing the temperature to 40 °C resulted in a decrease in biogas volumes, probably due to the inhibition of microbial activity. The biogas yield from chicken manure was the highest among the studied feedstock types at all mentioned temperatures. The CH_4 and CO_2 content in biogas is a significant indicator, since methane is the principal energy component, while carbon dioxide is a product of decomposition of organic matter. The ratio of these gases can give an indication of the efficiency of the methanogenesis process. Table 12 shows the ratio of methane:carbon dioxide (CH_4:CO_2) in biogas produced from distinct types of raw material.

Table 12. *CH_4:CO_2 ratio in biogas*

Raw material	CH_4:CO_2 ratio
Cattle manure	1:0.6
Pig manure	1:0.7
Chicken manure	1:0.5
Optimal ratio	1:0.6 or higher

Source: compiled by the authors

Chicken manure showed the highest methane content compared to other feedstocks, making it the most efficient source of biogas. The high CO_2 content of biogas from pig manure may require additional treatment to improve energy efficiency. The time to reach the maximum biogas yield is another significant factor that determines the efficiency of the fermentation process. The time required to reach the highest level of biogas yield can vary depending on the type of feedstock under study. Table 13 shows the time to reach the maximum biogas yield depending on the type of feedstock used.

Table 13. *Time to reach the maximum biogas yield*

Raw material	Time to maximum biogas yield (days)
Cattle manure	22
Pig manure	18
Chicken manure	20

Source: compiled by the authors

Pig manure provided the fastest achievement of the maximum biogas yield in 18 days, which positively affected the efficiency of fast biogas processes. According to the study results, cattle manure and chicken manure showed a longer fermentation period, which may affect the overall efficiency of biogas production. The effect of mechanical shredding or chemical treatment on biogas yield is vital for process optimisation. Table 14 shows the effects of raw material pretreatment on biogas yield.

Table 14. *Effects of raw material pretreatment on biogas yield*

Raw material	No treatment (m^3/kg VT)	After mechanical shredding with a hydraulic shredder press device (m^3/kg VT)	After chemical treatment with NaOH solution (m^3/kg VT)
Cattle manure	0.16	0.18	0.19
Pig manure	0.13	0.14	0.15
Chicken manure	0.23	0.26	0.28

Source: compiled by the authors

Pretreatment with NaOH solution significantly increased biogas yields for all feedstock types. Chicken manure showed the largest increase in biogas yield after mechanical grinding (13% increase) and chemical treatment (22% increase). These data confirmed the significance of pretreatment to increase the efficiency of the fermentation process. The fermentation temperature directly affected the biogas yield. The highest yield was observed at 35 °C, after which the fermentation efficiency began to decrease. For all feedstock types, the CH_4:CO_2 ratio varied, with the highest methane content in the biogas produced from chicken manure. Pig manure reached the maximum biogas yield in 18 days, indicating an acceleration of the fermentation process compared to other feedstocks. Mechanical and chemical treatment of the feedstock significantly increased the biogas yield, which is essential for increasing the efficiency of biogas plants.

Discussion

According to the findings of this study, chicken manure is the most promising raw material for biogas production due to its high methane yield, optimum carbon to nitrogen (C:N) ratio (ensured by the addition of carbonaceous materials), and high degradation coefficient of organic matter. One of the most pressing problems is the formation of undesirable impurities such as H_2S. Adjustment of the substrate composition, maintenance of the optimum pH level and control of the C:N ratio are possible with the combined use of such raw materials as chicken manure with the addition of straw or cattle manure. It was found that pig manure had high levels of hydrogen sulphide, which required additional measures aimed at treating the biogas to reduce its harmful effects. K. Akamati *et al*. (2022) raised an analogous issue. The researchers found that rational changes in feed composition reduced the H_2S content of biogas, and effective management of manure treatment systems, including aeration or the use of chemical inhibitors, significantly reduced the level of hydrogen sulphide and greenhouse gas emissions, contributing to a reduction in impact. This statement can be agreed with, as the concentration of H_2S in biogas can actually depend on the composition of feed and animal housing conditions. Changes in the diet can genuinely affect the metabolic processes in the animal body, altering the chemical composition of the manure and the level of H_2S in the biogas (Golub *et al*., 2020).

The present study noted that each type of biogas feedstock had unique physical and chemical characteristics that significantly affected the biogas yield and composition. Specifically, chicken manure demonstrated the highest biogas yield and optimum methane content due to the high level of decomposed organic material. A. Uwizeye *et al*. (2019) investigated an analogous issue. The researchers found that the overall level of methane emissions in major pig meat-producing countries fluctuated depending on changes in livestock production methods and management, with an increase in methane emissions from enteric fermentation in Spain. The findings obtained in the present study differed from the conclusions presented by A. Uwizeye *et al*. (2019), since the present study focused on the physicochemical characteristics of the feedstock that determine biogas yield, which was distinct from the approaches proposed by researchers in analysing methane emissions in the context of specific livestock production methods. The authors' study focused on factors related to livestock management and agricultural practices.

Chicken manure proved to be the most promising feedstock for biogas production due to its high methane yield and organic matter degradation factor, making it an economically viable and energy-efficient source for biogas plants. S. Singh *et al*. (2024) covered this subject in their study, showing that methanogenic bacteria in anaerobic mull, cattle rumen and manure played a significant role in the decomposition of organic matter and methane production. The present study reached analogous conclusions, as the findings revealed that methanogenic bacteria are essential for the breakdown of organic matter, which confirmed the feasibility of using anaerobic methanogenesis for the treatment of organic waste.

According to the findings of the present study, it is known that chicken manure has become the best feedstock for biogas production due to its high content of volatile solids and high methane yield, which ensured the highest biogas production. S. Chozhavendhan *et al*. (2020) also studied this problem. The researchers found that biogas production technology proved to be effective in converting renewable energy sources such as agricultural, livestock, industrial, and municipal waste into a clean form of energy. Their study confirmed that biogas technology can reduce greenhouse gas emissions and promote development by efficiently utilising renewable resources and reducing dependence on fossil fuels.

It was noted that the physicochemical properties of distinct types of raw material, specifically moisture content, volatile solids content, and C:N ratio, positively affected the biogas fermentation process. C. Mutate *et al*. (2023) found that feedstocks with an optimum C:N ratio, as well as high levels of organic matter, provided the best fermentation results and biogas yields. This statement can be agreed with, as a high content of organic matter provides sufficient energy for microorganisms, which stimulates anaerobic fermentation and leads to a high biogas yield (Kucher *et al*., 2022).

It was found that temperature fluctuations and the type of feedstock positively affect the methane production, which was significant for the efficiency of biogas technologies. N. Lovanh *et al*. (2023) pointed to the efficiency of using livestock waste, specifically wastewater from poultry and dairy manure processing, for biogas production, including methane. N. Lovanh *et al*. (2023) focused on the efficiency of agricultural waste processing for biogas production, while the present study covered three principal types of biogas feedstocks and compared their efficiency in terms of physical and chemical characteristics.

Cattle manure showed an average level of biogas yield, but it was necessary to correct its moisture content and C:N ratio to increase fermentation efficiency. L. Dong *et al*. (2019) found that the plunger reactor provided stable production of high-quality biogas under conditions of waste disposal with hydraulic retention for 25 days, temperature conditions of 37-40°C, and a 7-10% concentration of solids in the substrate. The statement of L. Dong *et al*. (2019) can be agreed with, as the researchers confirmed the effectiveness of large-scale bioreactors for the treatment of organic waste, specifically cattle manure, which led to an increase in biogas and methane production under optimum conditions of hydraulic retention and temperature.

After mechanical grinding and chemical treatment of chicken manure, an increase in biogas yield was found (by 13% and 22%, respectively). I. Mahmoud *et al*. (2022) found that the co-digestion of sludge and raw chicken manure increased the total biogas production and improved the sludge treatment process. The findings of the present study showed an increase in biogas yield after pretreatment and grinding of the feedstock, while I. Mahmoud *et al*. (2022) employed another technology and accordingly indicated that the increase in biogas yield was achieved through co-digestion of sludge and chicken manure.

It is recommended to use chicken manure in combination with carbon additives (straw), which is necessary to obtain maximum biogas yield. E. Orhorhoro & O. Oghoghorie (2024) concluded that the highest level of biogas yield was observed when chicken manure was co-digested with seaweed. The present study obtained partially analogous findings to those of E. Orhorhoro & O. Oghoghorie (2024), which showed that the use of an organic additive in the form of seaweed was effective in increasing biogas productivity. However, in the present study, the greatest effect was observed when chicken manure was combined with various additives, including carbon-rich straw, which created favourable conditions for microbial activity and optimisation of the carbon to nitrogen ratio.

This study found that the use of chicken manure produced the highest proportion of methane compared to other types of raw materials, making it the most efficient source of biogas. J. Di Mario *et al*. (2024) found that the use of untreated olive mill wastewater for biogas production led to an increase in biogas yield. The statement of J. Di Mario *et al.* (2024) can be agreed with, because according to scientific data, wastewater contains organic compounds that can be broken down by microorganisms during anaerobic fermentation, which leads to an increase in the content of methane and other biogas components.

Chicken manure has the highest proportion of methane compared to other types of raw materials. M. Ajao *et al.* (2024) showed that the addition of silica nanosupplementation increased the amount of methane in cow and sheep manure biogas. The statement of M. Ajao *et al.* (2024) can be agreed with, because according to scientific data, the added nanosupplement can have a catalytic effect, stimulating biochemical reactions that increase the amount of methane yield in biogas systems.

It was found that chicken manure showed the highest biogas yield after 30 days of fermentation, which indicated its greater efficiency as a feedstock for biogas production compared to cattle manure and pig manure. O. Ojo (2022) presented the results, according to which poultry manure was the most effective feedstock for biogas production compared to cow and pig manure, as it provided the highest volume of biogas production and high level of gas production. The findings of O. Ojo's (2022) work can be agreed upon, as analogous studies confirm that poultry manure has a high potential for biogas fermentation due to its high content of easily digestible organic compounds such as proteins and fats. This is why better gas production rates were achieved compared to the other two types of manure studied, which contain a high amount of cellulose and are more difficult to break down during fermentation.

The study of the content of harmful components in biogas revealed that cattle manure and chicken manure had a lower content of harmful components in biogas compared to pig manure contaminated with hydrogen sulphide, which contributed to the reduction of anthropogenic emissions. Z. Akyürek (2023) found that the use of livestock waste for biogas production helped reduce greenhouse gas emissions. The researchers' conclusions should be accepted, as the use of livestock waste for biogas production does have benefits for reducing harmful emissions, including greenhouse gases such as methane and hydrogen sulphide.

The highest pH level was found in cattle manure. S. Ejiko *et al*. (2024) noted that a high pH was recorded in pig waste, which affected the speed and quality of anaerobic digestion. It is possible to agree with the opinion of S. Ejiko *et al*. (2024), since high pH in pig manure does reduce the efficiency of the process, since an acidic environment is optimal for anaerobic bacteria.

Compared to other types of raw materials, pig manure showed the highest level of carbon dioxide (CO_2), which contributed to the decomposition of organic compounds. B. Žalys *et al*. (2023) showed that pretreatment of cow, pig, and chicken manure with CO_2 gas led to an increase in biomethane yield compared to untreated manure. The findings of B. Žalys *et al*. (2023) should be agreed with, as pretreatment with CO_2 gas does indeed increase biomethane yields and reduces the amounts of harmful gases, specifically hydrogen sulphide, during the biogasification process.

According to the obtained indicators, the average biogas yield with the lowest hydrogen sulphide content was obtained from cattle manure compared to other types of raw materials, which reduced the need for additional stages of biogas purification before its use. A. Ogunkeyede *et al*. (2024) found that cow belching and manure sludge produced high levels of biogas, which helped to reduce the amount of organic waste while contributing to energy production. The conclusions of A. Ogunkeyede *et al*. (2024) should be agreed with, since the use of the types of raw materials under study actually enables not only the reduction of organic waste, but also their use for energy production.

It was found that an elevated level of biogas yield from cattle manure was achieved at pH 7.8 after fermentation. M. Mohammed *et al*. (2022) found that the highest biogas yield was achieved at pH 7, while the use of an isolated digester greatly increased the volume of biogas produced compared to a transparent digester. This statement can be agreed with, as the optimum pH level for the activity of methanogenic microorganisms is within the range of neutral or slightly alkaline environment.

The study found that the use of the technology of preliminary chemical treatment of biomass (solutions of sodium alkali or potassium hydroxide were used for alkaline treatment), which consisted of chicken manure, improved the biogas yield. K. Venslauskas *et al*. (2024) found that biogas production was improved in untreated straw, specifically by applying a biological pretreatment method using microorganisms, namely *Trichoderma* species. The conclusions of K. Venslauskas *et al*. (2024) can be agreed with, as the scientific data confirms that biomass pretreatment using a biological method can contribute to the efficient decomposition of structural carbohydrates, thus increasing the availability of fermentable sugars for microorganisms, and improving biogas yields.

Conclusions

The study revealed that the greatest biogas yield was recorded when using chicken manure (0.23 m^3/kg VT), due to the high content of organic matter and the optimum C:N ratio. Pig manure provided the lowest biogas yield (0.13 m^3/kg VT) due to the high H_2S content, and therefore additional measures for biogas treatment were required. Cattle manure demonstrated an average biogas yield (0.16 m^3/kg VT) but required optimisation of fermentation conditions to improve performance. Chicken manure showed the highest biogas yield during all fermentation periods, reaching a maximum (0.09 m^3/day) in the second period, and therefore the use of this substrate is effective for biogas plants.

According to the observations, chicken manure had the highest organic degradation rate (60%), indicating the high efficiency of its biological decomposition, while cattle manure and pig manure had degradation rates of 55% and 50%, respectively. Chicken manure, with its high organic matter degradation factor and high methane content of 65%, proved to be the most energetically valuable feedstock for biogas production. Considering the energy efficiency of this substrate, its use is beneficial for biogas plants. Reduction of H_2S emissions from pig manure is possible with limited use of pig manure, addition of adsorbents, or combination of various types of feedstocks, which will achieve a stable C:N ratio and reduce the effects of the harmful component. The findings of the study of the physical and chemical properties of the feedstock revealed that the highest moisture content (75-80%) was observed in cattle manure, which required additional consistency adjustment, while the highest content of volatile solids (25-30%) was found in chicken manure, which emphasised its high energy quality. The C:N ratio of the chicken manure (10:1) was too low, and therefore carbonaceous materials, such as straw, were added to improve the optimum biogas yield.

Areas for further research may include the introduction of a comprehensive approach to analysing the effects of seasonal changes in temperature and humidity on fermentation processes and biogas yields to assess the optimum conditions for the operation of biogas plants using animal by-products and their effects on biogas production.

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Conflict of Interest

None.

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Вплив типу побічних продуктів тваринництва на вихід і склад біогазу

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Анотація. Дослідження впливу різних видів відходів тваринного походження на кількість та склад біогазу є важливим і актуальним для оптимізації процесів анаеробного бродіння, підвищення ефективності виробництва біогазу та адаптації технологій до умов господарств. Метою роботи була оцінка впливу побічних продуктів тваринництва, зокрема гною великої рогатої худоби, свинячого гною та курячого посліду на кількість і якість отриманого біогазу. В ході дослідження застосовувалися методи: статистичний аналіз, метод газоаналізу і ферментації. Під час проведення дослідження проаналізовані фізико-хімічні властивості різних видів сировини для виробництва біогазу. Встановлено, що курячий послід мав найвищий потенціал для утворення біогазу через високий вміст летких твердих речовин (25-30 %) і оптимальне співвідношення метану в складі біогазу (65 %). Також виявлено, що гній великої рогатої худоби характеризувався стабільним середнім рівнем виходу біогазу (0.15-0.18 м3/кг маса летких твердих речовин у сировині (VT, %)), тоді як свинячий гній мав найнижчий вихід (0.12-0.14 м3/кг маса летких твердих речовин у сировині). Згідно з результатами дослідження продемонстровано, що додавання вуглецевих матеріалів (наприклад, подрібненої соломи) сприяло покращенню співвідношення вуглецю до азоту для оптимізації ферментаційного процесу. Проведений аналіз вмісту органічної речовини до та після ферментації показав значне її зниження для курячого посліду (51 %), що свідчило про ефективність біологічного розкладу. Дослідження включало оцінку складу біогазу, зокрема метану (50-65 %), вуглекислого газу (30-40 %) і сірководню (1-3 %). Зміна показників pH у всіх типах сировини після ферментації вказувала на стабілізацію середовища в біореакторах, що забезпечило сприятливі умови для мікроорганізмів. Результати дослідження можуть бути використані на практиці екологами, агрономами, технологами тваринництва і виробниками біогазу з метою створення енергетично незалежних господарств через інтеграцію біогазових установок у фермерські господарства

Ключові слова: відходи; гній; курячий послід; біореактор; метан; вуглекислий газ; ферментація