EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(12), 352–361
https://doi.org/10.12912/27197050/214483
ISSN 2719–7050, License CC-BY 4.0

Received: 2025.10.22
Accepted: 2025.11.15
Published: 2025.12.01

The potential of biogas from animal manure – the role of biogas plants in reducing emissions from Polish agriculture

Alina Kowalczyk-Juśko[1*], Patrycja Pochwatka[2], Andrzej Mazur[2]

[1] Department Environmental Engineering, University of Life Sciences in Lublin, Leszczyńskiego 7, 20-069 Lublin, Poland
[2] Department of Geodesy and Spatial Information, University of Life Sciences in Lublin, Leszczyńskiego 7, 20-069 Lublin, Poland
* Corresponding author's e-mail: alina.jusko@up.edu.pl

ABSTRACT

The aim of this study was to determine the current role of slurry, manure, and poultry droppings in the mix of Polish agricultural biogas plants and their biogas potential. Statistical data on biogas production in Poland from 2011 to 2024 and the consumption of substrates from various sources, with particular emphasis on livestock manure, were analyzed. Biogas efficiency analyses were performed for five types of animal manure in a specialized laboratory. The advantages of biogas production were identified in terms of energy production, reduced air pollutant emissions, and the use of digestate from biogas plants as fertilizers. The current number of agricultural biogas plants in Poland is less than 200, and the amount of electricity they produce is approximately 1000 GWh. Biogas plants primarily use processing waste, while only slurry plays a significant role, accounting for approximately 15% of the total substrate mass. Manure and poultry manure are of marginal importance, accounting for 3% and 0.8% of the substrate mass, respectively. Laboratory test results indicate that all types of animal manure are valuable materials for anaerobic digestion, with liquid manure playing an important role in diluting the chamber contents, and cow, pig, and poultry manure having high biogas yields of 264.37, 205.18, and 276.54 m^3/Mg ODM, respectively, with biomethane content >60%. It is rational to encourage farmers to build biogas plants and micro-biogas plants and users of existing installations to use animal faces more, which will contribute to the increase in renewable energy production and improvement of the environment.

Keywords: biogas plant, anaerobic digestion, manure, slurry, emission reduction.

INTRODUCTION

The development of biogas plants in Poland faces a number of challenges. Although the first agricultural biogas plant was launched in 2005, fewer than 200 have been built in the past 20 years (KOWR, 2025). Existing biogas plants primarily utilize waste from agricultural and food processing, substrates from targeted crops (primarily maize silage), expired food, and plant and animal by-products generated on farms (Kowalczyk-Juśko et al., 2022; Pochwatka et al., 2025). The latter group includes animal feaces: manure, slurry, and poultry droppings (Czekała et al., 2023; Białobrzewski et al., 2024). Their role in the biogas plant substrate mix is highly diverse. At the same time, a significant amount of feaces is identified in Poland as being used to fertilize fields without prior treatment, which poses a risk of nutrient contamination of surface and groundwater (Męcik et al., 2023; Krupka et al., 2024). Polish legislation specifies the precise doses and timing of natural fertilizer applications (Act, 2007), but farmers do not always adhere to these regulations. Another problem is the storage of manure when its removal to the fields is impossible for agricultural or legal reasons.

According to estimates prepared by the Poznań University of Life Sciences (Kozłowski et al., 2019), over 70 million tons of cattle and pig manure are produced annually in Poland. Poland is also a significant poultry producer (Dróżdż et al., 2020; Olejnik et al., 2022). Poland is a leading European country in terms of livestock production (Ziętara et al., 2024). Since 2012, it has been the largest European poultry producer, and dairy farming is also developing rapidly. A consequence of this developed livestock production is the production of large quantities of animal manure (Wawrzyniak et al., 2021; Łukomska et al., 2025). In Western Europe, slurry production predominates, as raising animals on slats requires less labor (Gaworski and Kic, 2024; Silva et al., 2025). Meanwhile, in Poland, litter-based farming predominates, resulting in manure production approximately four times greater than slurry production. This is unfavorable in terms of greenhouse gas emissions from animal manure (Pilvere et al., 2025; Symeon et al., 2025). Stored manure tends to self-heat, and as a result, a pile of this fertilizer stored in anaerobic conditions at temperatures between 30 and 50 °C becomes a natural biogas plant, emitting large amounts of methane, many times greater than stored slurry (Nowak et al., 2024). Furthermore, both types of fertilizers also emit nitrous oxide – a gas with a greenhouse gas impact 273 times more potent than CO_2 (Haider et al., 2025). These emissions will become a huge financial burden for the livestock sector starting in 2027, when the ETS2 and ETS3 greenhouse gas taxation systems are likely to be introduced. In the case of ETS3, which directly addresses greenhouse gas emissions from agriculture, farmers will be exempt from fees provided that animal feaces are sent directly from the farm for processing in biogas plants (Verschuuren et al., 2024; Prandecki and Wrzaszcz 2025). The electricity, heat, or biomethane produced from them will then have a negative carbon footprint, as this will avoid greenhouse gas emissions generated during landfill (Bórawski et al., 2024).

MATERIALS AND METHODS

Statistical data

This study uses information on the number of biogas plants in Poland, the energy they produced, and the consumption of individual substrates between 2011 and 2024. Data were obtained from The National Support Centre for Agriculture (KOWR), the institution supervising agricultural biogas plants, which are a separate category in Polish law, distinguishing them from biogas plants at sewage treatment plants and landfills (Act, 2015). Based on statistical data, trends in the use of individual types of animal manure were determined.

Laboratory tests

Laboratory tests of biogas yield included five types of animal manure: cattle and pig manure (animal manure with straw), cattle and pig slurry (animal manure only), and poultry manure. Fresh matter (FM) samples delivered from farms, after averaging and homogenization, were subjected to basic tests: pH (PN-EN ISO 10523:2012), dry matter content (DM) using the gravimetric method (PN-EN ISO 18134-2:2017-03), and organic dry matter content (ODM) using the gravimetric combustion method (PN-EN ISO 18122:2023-05). The samples were subjected to batch testing of biogas yield, according to DIN 38 414-S 8 (2012), in 1-liter reactors under mesophilic conditions (39±1 °C). The inoculum was the liquid fraction of digestate from an agricultural biogas plant, obtained through the separation of the solid fraction. During fermentation, gas production and composition were measured daily (CH_4, CO_2, O_2, H_2S, NH_3), using a Geotech GA5000 gas analyzer. Fermentation studies were terminated when daily biogas production was less than 1% of the total biogas volume produced up to that time, in accordance with the DIN standard. All studies were performed in triplicate, and arithmetic means of the results were then calculated.

RESULTS AND DISCUSSION

Results from the statistical data

The current situation of biogas plants in Poland

The number of agricultural biogas plants in Poland is slowly growing (Table 1). The first agricultural biogas plant was commissioned in 2005, and for 20 years their number has been less than 200. This slow growth, compared to other European countries e.g. Italy, Germany, Great Britain, Denmark (IRENA, 2025) is due to many reasons: an unstable support system for renewable energy sources (RES), complicated legal procedures, and low public acceptance due to low social awareness (Lisiak-Zielińska et al., 2023).

Currently, most biogas is burned in cogeneration (CHP) units, generating electricity and heat in combination. In 2024, the total electricity generated in agricultural biogas plants exceeded 1.000 GWh (Table 1). Several plants use biogas to generate heat for various processing plants (drying plant, distillery). Heat from cogeneration is sometimes not applicable, particularly in biogas plants located far from densely built-up areas or businesses with a heat demand. The first biomethane plant in Poland was built in 2025 and is not included in the summary due to the current reporting year. This is a very large plant, with a biogas production equivalent of 45 MW, primarily using sugar beet pulp.

Substrates used in biogas plants

The total amount of substrates used in agricultural biogas plants in 2024 exceeded 7.5 million Mg (Table 1). Reports submitted by agricultural biogas producers to the supervisory authority – The National Support Centre for Agriculture, provide detailed information about the substrates and their origin, including waste codes, if applicable. For the purposes of this article, they have been grouped into three groups (Figure 1), depending on their origin: animal (animal manure, slaughterhouse residues, digestive tract contents), biomass from targeted crops (silage from maize, grass, cereals, and other plants grown for biogas plants), and waste and by-products from agri-food processing (from distilleries, breweries, sugar refineries, olefin processing plants, fruit and vegetable processing plants, etc.).

The first biogas plants primarily used animal waste (approximately 60% of the substrate mass) and maize silage (approximately 25%), with by-products accounting for a dozen or so percent of the mass. Due to the high cost of dedicated substrates, the importance of silage declined, replaced by waste and by-products from agriculture and food processing. The importance of animal-derived substrates also declined, as the growing number of biogas plants, and the resulting increase in demand for substrates, led biogas plants to widely utilize other liquid substrates: distiller's stock and whey, and more recently, expired food products, which, after appropriate preparation, are delivered to the biogas plant in liquid form.

There is a steady upward trend in the quantitative use of slurry for biogas production (Figure 2), associated with the increasing number of biogas plants. However, its importance, expressed as a percentage of the substrate mass, is decreasing. In the first years analyzed, slurry parted at almost 60% of the mass of all substrates and was the first or second largest (after stillage). This is due to the fact that it is one of the few substrates that dilutes the feedstock. Most agricultural biogas plants operate using wet technology, maintaining the dry matter content in the chamber at an average level of <15%, which allows for pumping the chamber contents between individual tanks (acidification chamber – fermenter – digestate tank). Gradually, the importance of slurry decreased, and in 2024, it accounted for 15.8% of the fermented mass. Manure is a minor substrate in Polish biogas plants:

Table 1. Data on agricultural biogas plants in Poland

Year	Number of enterprises	Number of biogas plants	Amount of biogas production [mln m^3]	Amount of electricity [GWh]	Amount of substrates [Mg]
2011	4	8	36.646	73.433	469,416
2012	10	16	73.152	141.804	917,122
2013	21	28	112.412	227.89	1574,179
2014	35	42	174.253	354.978	2,126,378
2015	50	58	206.236	429.4	2,484,500
2016	69	78	250.325	524.532	3,231,760
2017	84	94	292.036	608.27	3,796,930
2018	86	96	304.475	638.51	4,000,157
2019	85	96	307.337	646.355	3,957,804
2020	93	103	328.174	689.713	4,411,965
2021	99	116	343.07	732.882	4,913,469
2022	109	128	375.003	796.675	5,696,274
2023	119	143	430.08	919.277	6,775,626
2024	136	162	468.517	1,012.18	7,551,052

Note: KOWR 2025.

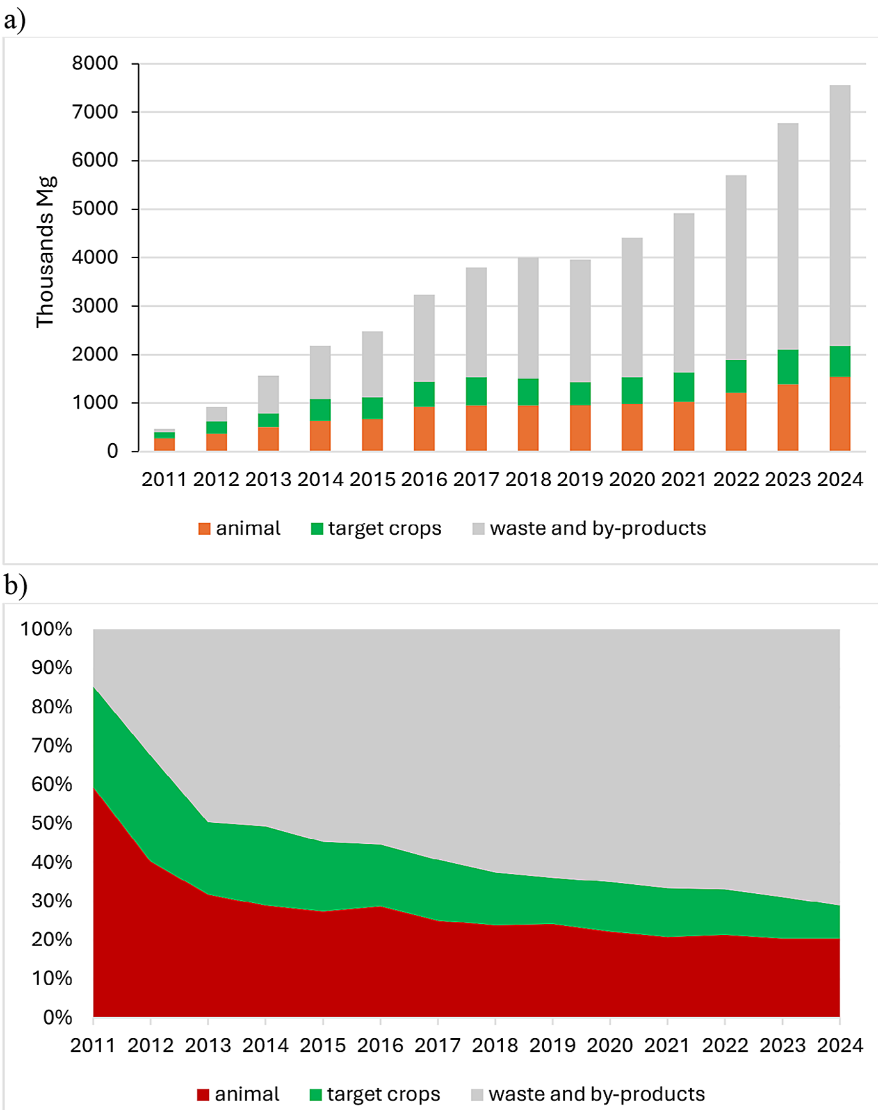


Figure 1. Quantity (a) and structure (b) of substrate groups used in agricultural biogas plants in Poland in 2011–2024 (source: KOWR, 2025)

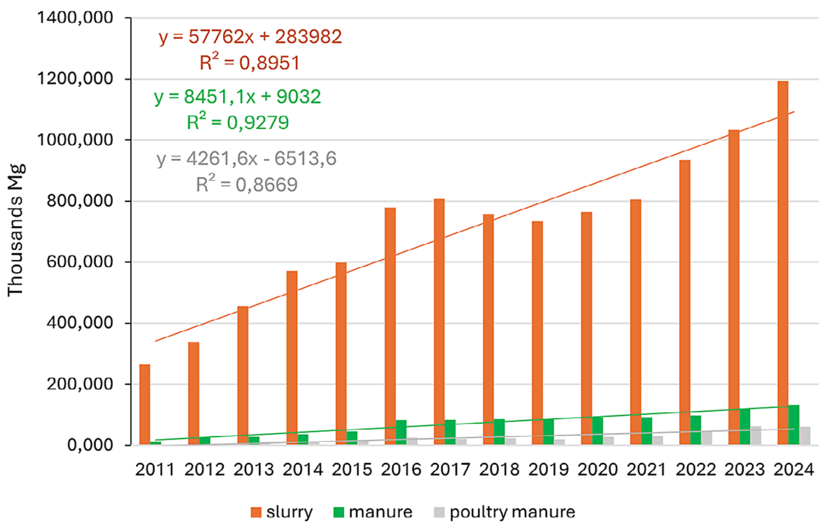


Figure 2. Trends in the use of animal manure for agricultural biogas production in 2011–2024 (own calculations based on: KOWR, 2025)

its share during the analyzed period was less than 3% of the total substrate mass, although the trend in its use is increasing (Figure 2). The low interest in manure is due to several reasons. The first is that manure is often produced on smaller animal farms that raise animals on straw. Therefore, it is a dispersed substrate requiring transport from various locations, and the costs of transporting substrates is a significant item in the economic balance of biogas plants. Furthermore, the straw present in manure takes a long time to decompose as a lignocellulosic raw material. Long straw fibers can wrap around agitators (in the case of mechanical mixing systems) and can float and form a skin on the surface of the fermenting mass, complicating biogas plant operation.

Poultry manure is also insignificant in the substrate mix, it was a part of only 0.2–0.8% of all substrate stream, despite the very large supply of this form of manure in agriculture. Poultry manure is a difficult substrate because it contains large amounts of ammonia, which, at high concentrations, becomes an inhibitor of the anaerobic digestion process. Furthermore, poultry manure contains a large mineral fraction (sand), which sinks to the bottom of the fermentation chamber, and the resulting sludge reduces its working volume and requires disposal.

In Poland, the problems associated with animal feaces management differ from those associated with its use in biogas plants. Manure poses a greater environmental problem than slurry. It is estimated (IPCC, 2006), that greenhouse gas emissions from manure are on average level of 0.41 Mg CO_2eq/Mg fresh matter, which is higher compared to emissions from slurry, which is 0.31 Mg CO_2eq/Mg fresh matter. This is mainly due to the method of storage: on farms, slurry is collected in closed tanks, often underground, while manure is stored on manure pads, and sometimes even in fields. Manure pads protect the ground from leachate seeping into the soil and water. Unfortunately, natural fermentation and aerobic decomposition cause the products of these processes to migrate freely into the atmosphere. These products include methane and nitrous oxide, potent greenhouse gases (Yasmin et al., 2022; San Martin Ruiz et al., 2022).

Results of the experimental test

Biogas yield from animal manure

Laboratory studies have shown that farm animal feaces differs significantly in physical state (Table 2). The lowest dry matter content was found in cattle and pig slurry, at 8.41% and 1.73%, respectively. The very low dry matter content in pig slurry was likely due to the animal housing method and frequent flushing of animal housing. Slurry, due to its low dry matter content, is used in biogas plants as a diluting substrate, while also containing anaerobic fermentation bacteria, particularly in the case of ruminant slurry – cattle and sheep (Wang et al., 2023). The highest dry matter content (42.30%) was found in poultry manure, which has a solid consistency and is spread on fields using manure spreaders in agricultural practice. Large differences in biogas yield and composition were found (Table 2). The largest amounts of biogas were obtained from poultry manure – 458.60 m^3/Mg ODM, however, due to the higher content of biomethane, cattle slurry proved to be more efficient, giving more than 300 m^3/Mg ODM biomethane. The smallest amount of biogas and biomethane was obtained from the fermentation of pig manure: respectively 332.54 and 205.18 m^3/Mg ODM.

The rate of anaerobic decomposition of individual types of animal feaces turned out to be significantly different. Poultry manure fermented the fastest – 17 days (Figure 3e) and pig slurry – 22 days (Figure 3c). In turn, substrates containing

Table 2. Biogas yield from tested farm animal feaces

Substrate	pH	Dry matter [%]	Organic dry matter [% D.M.]	Methane content [%]	Cumulative production			
					From fresh mass [m^3/Mg FM]		From organic dry matter [m^3/Mg ODM]	
					CH_4	biogas	CH_4	biogas
Cattle manure	8.19	28.98	89.80	58.6	68.80	117.41	264.37	451.14
Cattle slurry	7.41	8.41	70.95	68.5	18.40	26.86	308.37	450.17
Pig slurry	7.59	1.73	63.51	71.4	2.78	3.89	253.41	354.79
Pig manure	7.79	17.10	89.21	61.7	31.30	50.73	205.18	332.54
Poultry manure	6.62	42.30	84.12	60.3	98.40	163.18	276.54	458.60

straw took the longest to decompose: cattle manure – 27 days (Figure 3a) and pig manure – 29 days (Figure 3d). Until recently, straw was not considered a substrate for biogas plants, but for several years there has been a growing interest in this raw material throughout Europe (Alamia et al., 2024; Vaskina et al., 2025). Most often, straw is pre-treated before being fed to the digester, e.g., by mechanical shredding, steam explosion, or extrusion (Kupyaniuk et al., 2020; Orth et al., 2025).

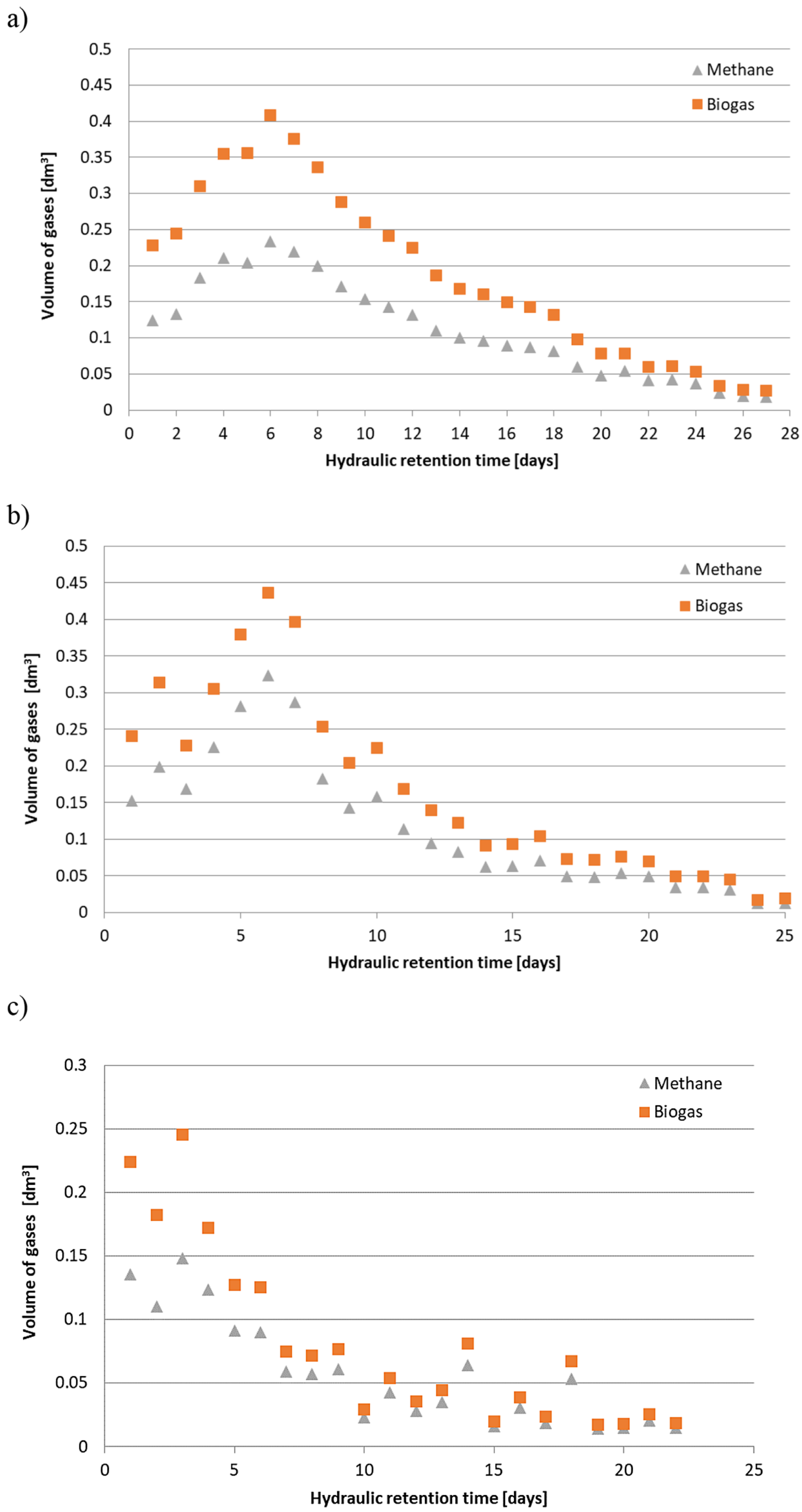
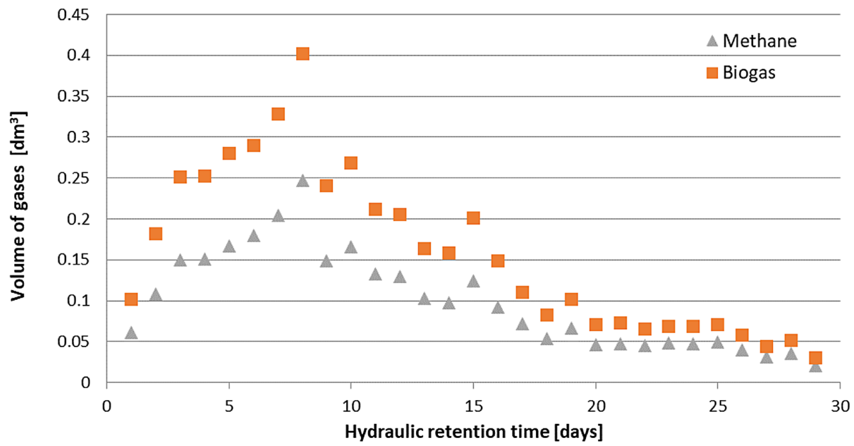


Figure 3. Fermentation rate and efficiency of cattle manure (a), cattle slurry (b), pig slurry (c), pig manure (d), poultry manure (e)

d)



e)

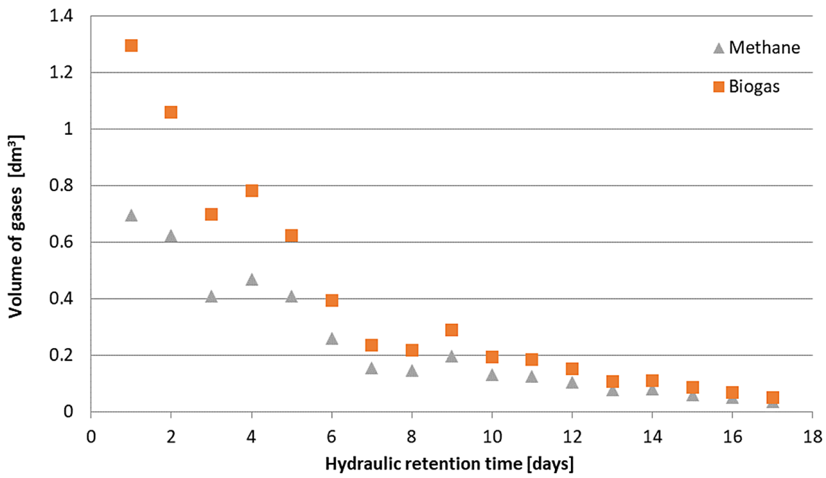


Figure 3. Cont. Fermentation rate and efficiency of cattle manure (a), cattle slurry (b), pig slurry (c), pig manure (d), poultry manure (e)

The decomposition time of individual substrates is a very important parameter used to calculate the hydraulic retention time (HRT) in order to select the appropriate size of fermentation chambers depending on the co-substrate recipe (Lee and Dulany, 2025; Oladunni et al., 2025).

The importance of biogas plants for the environment

The extension of the emissions trading system to agriculture (EU ETS3) will involve the introduction of fees for emissions of other greenhouse gases, after CO_2, including methane produced in agriculture. Research shows that in laboratory conditions, 1 Mg of manure (with straw) can emit 31.30–68.80 m^3 of methane, and 1 Mg of slurry – 2.78–18.40 m^3 of methane, depending on the animal species. Assuming a methane density of 0.72 kg/m^3 (Koonaphapdeelert et al., 2020), this amount is 22.54–49.54 kg CH_4/Mg of fresh manure and 2.00–13.25 kg CH_4/Mg of slurry. In a functioning biogas plant, and especially under natural conditions during manure storage, these values are lower. The net total methane emissions during storage of untreated cattle slurry were found to be 4045.7 g CH_4/m^3 slurry in an open storage (Dumont et al., 2013). In the study by Petersen et al. (2016), methane production rates in pig and cattle slurry were 0.030 and 0.011 kg CH_4/kg ODM within 24 h, respectively. In farm conditions, significant changes in methane emissions from animal excrements are observed in different seasons. The experiment (Cardenas et al., 2021) showed that the methane emissions from manure stored in summer were considerably higher than those from manure stored in winter. CH_4 production started after approximately one month, reaching values of 0.061 kg CH_4/kg ODM and achieving high total emissions of 0.148 kg CH_4/kg ODM. In winter, the highest emissions level was 0.0011 kg CH_4/kg ODM. An important factor influencing methane emissions from animal excrements is the storage temperature (Hilgert et al., 2022). Annual average CH_4 emission per kg ODM excrected on dairy and finishing pig farms with liquid manure management as calculated with an empirical model using daily time steps were 10.0 and 36.2 g/kg ODM/yr, respectively (Petersen et al., 2024). However, rising CO_2, emission prices, as well as the fact that in the case of methane, the conversion factor to the equivalent amount of CO_2 is 27 over a 100-year period (IEA, 2025) – the methane tax burden would become a significant cost for farmers. In addition to methane, manure storage also generates nitrous oxide emissions, for which the equivalent CO_2 is 273 (IEA, 2025). Decomposition of some of the organic matter contained in animal feaces in controlled conditions of fermentation tanks significantly reduces their emission intensity, which will be taken into account when designing fees for agricultural emissions. The cumulative contribution of methane from farm manure management is significant and there are considerable benefits from acting sooner rather than later to curb emissions. As well as the justification in terms of reduced GHG emissions in the short term, the realisable economic value of this alternative fuel source would be a welcome contribution to the increasingly challenging farm business economics in the animal production sector (Ward et al., 2024).

CONCLUSIONS

Animal production is associated with the production of feaces, which emits air pollutants such as methane and nitrous oxide. Manure, consisting of animal feaces and bedding, in particular, emits significant amounts of pollutants. The construction of biogas plants, which produce energy fuel under controlled, anaerobic conditions, can alleviate this problem and provide economic benefits for animal farmers. The development of agricultural biogas plants in Poland is slow, especially given the high potential of substrates from agriculture and the agri-food processing industry. Current use of animal feaces, particularly manure and poultry manure, is negligible. The results obtained in our research indicate varying biogas yields from different types of feaces, ranging 332.54–458.60 m^3/Mg ODM. The construction of a biogas plant, with the rational selection of co-substrates, can bring numerous environmental and economic benefits to farms.

Acknowledgments

Cofounded by Regional Fund for Environmental Protection and Water Management in Lublin, 108/2025/D/EE.

REFERENCES

1. Act of 10 July 2007 on fertilizers and fertilization (Journal of Polish Laws of 2007 No. 147 item 1033, as amended).
2. Act of 20 February 2015 on renewable energy sources (Journal of Polish Laws, item 478, as amended).
3. Alamia, A., Partoon, B., Rattigan, E., Bruun Andresen, G. (2024). Optimizing hydrogen and e-methanol production through Power-to-X integration in biogas plants. *Energy Conversion and Management, 322*, 119175. https://doi.org/10.1016/J.ENCONMAN.2024.119175
4. Białobrzewski, I., Waszkielis, K., Bułkowska, K. (2024). The application of Anaerobic Digestion Model No. 1 for the optimization of biogas production from maize silage, pig manure, cattle manure, and digestate in a full-scale biogas plant. *Fuel, 357*, 129789. https://doi.org/10.1016/J.FUEL.2023.129789
5. Bórawski, P., Bełdycka-Bórawska, A., Kapsdorferová, Z., Rokicki, T., Parzonko, A., Holden, L. (2024). Perspectives of electricity production from biogas in the European Union. *Energies 17*(5), 1169. https://doi.org/10.3390/EN17051169
6. Cárdenas, A., Ammon, C., Schumacher, B., Stinner, W., Herrmann, C., Schneider, M., Weinrich, S., Fischer, P., Amon, T., Amon, B. (2021). Methane emissions from the storage of liquid dairy manure: Influences of season, temperature and storage duration. *Waste Management, 121*, 393–402. https://doi.org/10.1016/j.wasman.2020.12.026
7. Czekała, W., Jasiński, T., Dach, J. (2023). Profitability of the agricultural biogas plants operation in Poland, depending on the substrate use model. *Energy Reports, 9*, 196–203. https://doi.org/10.1016/J.EGYR.2023.05.175
8. DIN 38 414-S8. 2012. German standard methods for the examination of water, waste water and sludge.
9. Dróżdż, D., Wystalska, K., Malińska, K., Grosser, A., Grobelak, A., Kacprzak, M. (2020). Management

of poultry manure in Poland – Current state and future perspectives. *Journal of Environmental Management, 264*, 110327. https://doi.org/10.1016/J.JENVMAN.2020.110327

10. Dumont, M., Luning, L., Yildiz, I., Koop, K. (2013). Methane emissions in biogas production. The Biogas Handbook: Science, Production and Applications. *Woodhead Publishing Series in Energy,* 248–266. https://doi.org/10.1533/9780857097415.2.248
11. Gaworski, M., Kic, P. (2024). Assessment of production technologies on dairy farms in terms of animal welfare. *Applied Sciences, 14*, 6086. https://doi.org/10.3390/APP14146086
12. Haider, S., Song, J., Bai, J., Wang, X., Ren, G., Bai, Y., Huang, Y., Shah, T., Feng, Y. (2025). Toward low-emission agriculture: Synergistic contribution of inorganic nitrogen and organic fertilizers to GHG emissions and strategies for mitigation. *Plants, 14*(10), 1551. https://doi.org/10.3390/PLANTS14101551
13. Hilgert, J.E., Amon, B., Amon, T., Belik, V., Dragoni, F., Ammon, C., Cárdenas, A., Petersen, S.O., Herrmann, C. (2022). Methane emissions from livestock slurry: Effects of storage temperature and changes in chemical composition. *Sustainability, 14*, 9934. https://doi.org/10.3390/su14169934
14. IEA, International Energy Agency (2025). Emission Factors 2025 edition. Database documentation.
15. IPCC, Intergovernmental Panel on Climate Change (2006). *Guidelines for National Greenhouse Gas Inventories.* Chapter 10: Emissions from livestock and manure management.
16. IRENA, 2025, *Renewable Energy Statistics 2025*, International Renewable Energy Agency, Abu Dhabi.
17. Koonaphapdeelert, S., Aggarangsi, P., Moran, J. (2020). *Biomethane: Production and applications.*
18. Green Energy and Technology, Springer Singapore; Singapore. https://doi.org/10.1007/978-981-13-8307-6
19. Kowalczyk-Juśko, A., Mazur, A., Pochwatka, P., Janczak, D., Dach, J. (2022). Evaluation of the effects of using the giant miscanthus (*Miscanthus x giganteus*) Biomass in Various Energy Conversion Processes. Energies, 15(10), 3486. https://doi.org/10.3390/EN15103486
20. KOWR, (2025). https://www.gov.pl/web/kowr/dane-dotyczace-dzialalnosci-wytworcow-biogazu-rolniczego.
21. Kozłowski, K., Dach, J., Lewicki, A., Malińska, K., do Carmo, I.E.P., Czekała, W. (2019). Potential of biogas production from animal manure in Poland. *Archives of Environmental Protection, 45*(3), 99–108. https://doi.org/10.24425/AEP.2019.128646
22. Krupka, M., Olkowska, E., Klimkowicz-Pawlas, A., Łęczyński, L., Tankiewicz, M., Michalczyk, D. J., Wolska, L., Piotrowicz-Cieślak, A. I. (2023). The impact of soil and water pollutants released from poultry farming on the growth and development of two plant species. *Agriculture, 14*(1), 87. https://doi.org/10.3390/AGRICULTURE14010087
23. Kupryaniuk, K., Oniszczuk, T., Combrzyński, M., Czekała, W., Matwijczuk, A. (2020). The influence of corn straw extrusion pretreatment parameters on methane fermentation performance. *Materials, 13*(13), 3003. https://doi.org/10.3390/ma13133003
24. Lee, H. G., Dulany, Z. (2025). Biogas and hydrogen production from waste biomass via dark fermentation evaluating VFAs, COD, and HRT for process optimization. *Biomass, 5*(3), 57. https://doi.org/10.3390/BIOMASS5030057
25. Lisiak-Zielińska, M., Jałoszyńska, S., Borowiak, K., Budka, A., Dach, J. (2023). Perception of biogas plants: A public awareness and preference - A case study for the agricultural landscape. *Renewable Energy, 217*, 119212. https://doi.org/10.1016/J.RENENE.2023.119212
26. Łukomska, A., Witaszek, K., Dach, J. (2025). Current state of development of demand-driven biogas plants in Poland. *Processes, 13*(8), 2369. https://doi.org/10.3390/PR13082369
27. Męcik, M., Buta-Hubeny, M., Paukszto, L., Maździarz, M., Wolak, I., Harnisz, M., Korzeniewska, E. (2023). Poultry manure-derived microorganisms as a reservoir and source of antibiotic resistance genes transferred to soil autochthonous microorganisms. *Journal of Environmental Management, 348*, 119303. https://doi.org/10.1016/J.JENVMAN.2023.119303
28. Nowak, M., Czekała, W., Bojarski, W., Dach, J. (2024). Research on a new method of water recovery from biogas plant digestate. *Energies, 17*(21), 5505. https://doi.org/10.3390/EN17215505
29. Oladunni, A. A., Oladeji, D., Orhadahwe, T. A. (2025). European Journal of Sustainable Development Research Effect of hydraulic retention time and substrate-to-inoculum ratio on batch anaerobic digestion of goat manure and response surface methodology optimization. *European Journal of Sustainable Development Research, 9*(3), 295. https://doi.org/10.29333/ejosdr/16337
30. Orth, F., Hülsemann, B., Kriswantoro, J. A., Ko, T. W., Chu, C. Y. (2025). Bioeconomic potential of lignocellulosic by-products: Steam explosion-based fractionation into solid and liquid phases for fiber and methane production. *Bioresource Technology, 433*, 132723. https://doi.org/10.1016/J.BIORTECH.2025.132723
31. Petersen, S.O., Ma, C., Hilgert, J.E., Mjöfors, K., Sefeedpari, P., Amon, B., Aarnink, A., Francó, B., Dragoni, F., Groenestein, K., Gyldenkærne, S., Herrmann, C., Hutchings, N.J., Kristensen, I.S., Liu,

J., Olesen, J.E., Rodhe, L. (2024). In-vitro method and model to estimate methane emissions from liquid manure management on pig and dairy farms in four countries. *Journal of Environmental Management, 353*, 120233. https://doi.org/10.1016/j.jenvman.2024.120233

32. Petersen, S.O., Olsen, A.B., Elsgaard, L., Triolo, J.M., Sommer, S.G. (2016). Estimation of Methane Emissions from Slurry Pits below Pig and Cattle Confinements. *PLoS ONE 11*(8): e0160968. https://doi.org/10.1371/journal.pone.0160968
33. Pilvere, I., Krievina, A., Upite, I., Nipers, A. (2025). Manure production projections for latvia: challenges and potential for reducing greenhouse gas emissions. *Agriculture, 15*(19), 2080. https://doi.org/10.3390/AGRICULTURE15192080
34. PN-EN ISO 18134-2:2017-03 Solid biofuels – Determination of moisture content.
35. PN-EN ISO 18122:2023-05 Solid biofuels – Determination of ash content.
36. PN-EN ISO 10523:2012 Water quality – Determination of pH.
37. Pochwatka, P., Kowalczyk-Juśko, A., Pituła, M., Mazur, A., Vaskina, I., Dach, J. (2025). Energetic potential of tobacco waste within combustion or anaerobic digestion. *Energies, 18*(4), 762. https://doi.org/10.3390/EN18040762
38. Prandecki, K., Wrzaszcz, W. (2025). Farm greenhouse gas emissions as a determinant of sustainable development in agriculture—methodological and practical approach. *Sustainability, 17*(14), 6452. https://doi.org/10.3390/SU17146452
39. San Martin Ruiz, M., González Puelles, J. E., Herra Bogantes, J., Rivera-Méndez, W., Reiser, M., Kranert, M. (2022). Methane, nitrous oxide, and ammonia emissions on dairy farms in spain with or without bio-activator treatment. *Atmosphere, 13*(6), 893. https://doi.org/10.3390/ATMOS13060893
40. Silva, M. J., Zainol, I., Tanoeiro, J. R., Sitowski, A., Major, I., Murphy, E. J., Fehrenbach, G. W. (2025). Livestock slurry and sustainable pasture management: microbial roles, environmental impacts, and regulatory perspectives in Ireland and Europe. *Microorganisms, 13*(4), 788. https://doi.org/10.3390/MICROORGANISMS13040788
41. Symeon, G. K., Akamati, K., Dotas, V., Karatosidi, D., Bizelis, I., Laliotis, G. P. (2025). Manure management as a potential mitigation tool to eliminate greenhouse gas emissions in livestock systems. *Sustainability, 17*(2), 586. https://doi.org/10.3390/SU17020586
42. Vaskina, I., Pochwatka, P., Vaskin, R., Adamski, M., Nowak, M., Dach, J. (2025). Ukraine's biogas potential: a comprehensive assessment of energy yields and of feedstock availability. *Sustainable Energy Technologies and Assessments, 81*, 104412. https://doi.org/10.1016/J.SETA.2025.104412
43. Verschuuren, J., Fleurke, F., Leach, M. C. (2024). Integrating agricultural emissions into the european union emissions trading system: legal design considerations. *Sustainability, 16*(12), 5091. https://doi.org/10.3390/SU16125091
44. Wang, R., Gu, J., Wang, Q., Jiang, S., Wu, Z., Wang, J., Li, G., Gong, X. (2023). Enhancing methane production in dry anaerobic digestion of ruminant manures through substrates ratio regulation for strengthened microbial interactions. *Environmental Technology & Innovation, 32*, 103389. https://doi.org/10.1016/J.ETI.2023.103389
45. Ward, N., Atkins, A., Atkins, P. (2024). Estimating methane emissions from manure: a suitable case for treatment? *Environmental Research: Food System, 1*, 025003. https://doi.org/10.1088/2976-601X/ad64d7
46. Wawrzyniak, A., Lewicki, A., Pochwatka, P., Sołowiej, P., Czekała, W. (2021). Database System for Estimating the Biogas Potential of Cattle and Swine Feces in Poland. *Journal of Ecological Engineering, 22*(3), 111–120. https://doi.org/10.12911/22998993/132426
47. Yasmin, N., Jamuda, M., Panda, A. K., Samal, K., Nayak, J. K. (2022). Emission of greenhouse gases (GHGs) during composting and vermicomposting: Measurement, mitigation, and perspectives. *Energy Nexus, 7*, 100092. https://doi.org/10.1016/J.NEXUS.2022.100092
48. Ziętara, W., Pietrzak, M., Malak-Rawlikowska, A. (2024). Polish dairy farm transformations and competitiveness 20 years after Poland's accession to the European Union. *Animals, 14*(13), 2013. https://doi.org/10.3390/ANI14132013