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Reduction of Greenhouse Gas Emissions by Replacing Fertilizers with Digestate

Alina Kowalczyk-Juśko[1*], Patrycja Pochwatka[1], Jakub Mazurkiewicz[2], Jakub Pulka[2], Barbara Kępowicz[1], Damian Janczak[2], Jacek Dach[2]

[1] Department Environmental Engineering and Geodesy, University of Life Sciences in Lublin, Leszczynskiego 7, 20-069 Lublin, Poland

[2] Department of Biosystems Engineering, Poznan University of Life Sciences, Wojska Polskiego 50, 60-627 Poznan, Poland

* Corresponding author's e-mail: alina.jusko@up.lublin.pl

ABSTRACT

Digestate from a biogas plant can be a valuable organic and mineral fertilizer. Quantitative proportions of co-substrates used in three agricultural biogas plants in Poland were analyzed. The composition of digestates was examined and large differences in the content of macronutrients were found, especially N and K. On the basis of the factors used to calculate emissions from the production and use of artificial fertilizers, the greenhouse gas (GHG) reduction resulting from replacing mineral fertilizers with digestate was calculated. In terms of 1 Mg of fresh digestate, this reduction may not seem large, as it amounts to 27.9–61.6 kg of CO_2 eq, but it should be taken into account that digestate contains little dry matter. The annual amount of digestate used on an area of 1 ha allows avoiding GHG emissions of 25.8–44.5 Mg CO_2 eq.

Keywords: biogas plant, anaerobic digestion, digestate, fertilizing, emission reduction.

INTRODUCTION

Following the European Climate Law (2021) and the related principles of climate neutrality – including the reduction of greenhouse gas (GHG) emissions to at least 55% by 2030, EU countries are required to achieve national targets (European Green Deal 2021, EU Regulation 2018). In the years 2005-2020, the level of GHG emissions from agriculture in the EU remained at a similar level; however, trends varied widely at the national level. In Poland, these emissions have increased by nearly 10%, and by 2030 their decrease is estimated at 5% compared to the level in 2020 (European Council 2020). In the EU, 80% of GHG emissions in agriculture are the CH_4 emissions from enteric fermentation and the N_2O emissions from soils, while around 10% is responsible for manure management and related CH_4 emissions (EEA 2022, Fagodiya et al. 2022). Ruminants are animals whose digestive tracts produce large amounts of methane (Pochwatka et al. 2020). Researchers and breeders are looking for the ways to reduce these emissions, as they are associated with the lower milk yield of cows (Gislon et al. 2020). In the future, these activities may be related to the taxation of such emissions (Rybak et al. 2022). However, the appropriate management of livestock manure has much greater potential in reducing GHG emissions (Dalby et al. 2021, Awasthi et al. 2019). It should be noted that the systems of keeping animals, and especially cattle, are different in individual EU countries (Guyomard et al. 2021, Linden et al. 2020). In Poland, the leading cattle-keeping system is free-stall barns with deep bedding (made of straw); hence, the side effect is manure with a dry matter higher than slurry and methane efficiency (Piszcz et al. 2022, Mazur et al. 2021). In Western Europe, sites are mainly in the bedding-free form; hence, the side effect is diluted manure collected in tanks (Hilgert et al. 2022). Non-compacted manure, stored in piles – like in Poland is a source of strong methane and NH_3 emissions (Piechota and Iglinski 2021). Thus, one of the solutions to reduce manure gas emissions is to use it as a substrate for biogas plants (Mazurkiewicz 2022). However, the European Climate Law emphasizes that this is one of the correct solutions for reducing gas emissions, mainly methane (2021).

In turn, the production, transport as well as use of mineral fertilizers contribute directly and indirectly to GHG emissions, in particular carbon dioxide and nitrous oxide (Menegat et al. 2022). However, fertilizers increase agricultural productivity and stimulate CO_2 uptake by plants and cause sequestration in the soil (Tiefenbacher et al. 2021). This avoids GHG emissions related to land use change, which account for approximately 10% of global GHG emissions. Depending on the type of fertilizer, their carbon footprint varies (Wu et al. 2021). In the case of ammonium nitrate, more CO_2 is emitted during production than when used (Dattamudi et al. 2019). This is most often associated with the need to process conventional raw materials to obtain the hydrogen necessary for production (Ghavam et al. 2021). In the case of urea, it is the opposite, higher emissions are recorded after its use in the field. Urea production and use are also associated with higher N_2O emissions (Dong et al. 2022). In addition, fertilizers produce significant amounts of NH_3, which is emitted into the atmosphere and is formed from the decomposition of substances containing protein and urea (Dari and Rogers 2021). In the EU, agriculture is responsible for about 92% of its emissions into the atmosphere, of which 17% is the production of mineral fertilizers, and the rest is animal production (Murawska and Prus 2021).

Fertilizer production is energy intensive (Adiansyah et al. 2021). It is estimated that 40–60% of the energy used in agriculture is spent on the production of fertilizers (Ahrens et al. 2022). The production of nitrogen fertilizers is characterized by the highest energy consumption (Sastre et al. 2021). Natural gas is a key material used in the production of ammonia, which is the basis of nitrogen fertilizers (Amhamed et al. 2022). After Russia's aggression against Ukraine in early 2022 and the related increases in natural gas prices, reaching EUR 280 per MWh (a 10-fold increase), some companies producing mineral fertilizers in Poland reduced or stopped production altogether (Czekała et al. 2022, European Parliament 2022). This affected the market prices of mineral fertilizers, especially nitrogen fertilizers, as well as their availability (Schnitkey et al. 2022). Hence, farmers' interest in alternative methods of plant fertilization has increased. One of them is the use of digestate from biogas plants (Petraityte et al. 2022).

Digestate is a byproduct obtained in the process of anaerobic digestion (Dach et al. 2020). For many biogas plants, it is waste, the management of which involves costs, e.g. transport (Proskynitopoulou et al. 2022). Under the current geopolitical and economic conditions, it can be a significant source of income for the owner of a biogas plant (Jurgutis et al. 2021). Digestate is an alternative to mineral, natural (manure, slurry), and organic (compost) fertilizers because it is a source of valuable minerals for plants (Fernández-Rodríguez et al. 2022). Its low dry matter comparable to liquid manure, neutral, alkaline pH, relatively high content of organic matter, and high NPK content are just some of the few parameters that speak in favor of using this byproduct as a fertilizer (Chojnacka et al. 2020, Czekała et al. 2020). Its properties and composition depend on the substrates used in the biogas plant, as well as on the technology of the biogas installation (Czekała et al. 2022). The use of unprocessed digestate does not involve any major additional costs (Feiz et al. 2022). Digestate is also used more and more often for creating compost, biochar or digestate granulates – especially in the case of more demanding plants (Cavali et al. 2022). The use of digestate as a fertilizer can also contribute to reducing gaseous emissions (Tilvikiene et al. 2020). The aim of the research was to assess the reduction of greenhouse gas emissions that can be obtained by replacing mineral fertilizers with the digestate from agricultural biogas plants using various cosubstrates.

MATERIALS AND METHODS

Research objects

The research material consisted of the digestate from three agricultural biogas plants located in Poland. The economic analysis of digestate management in these facilities and selected information are included in the article (Czekała et al. 2020). All anaerobic digestion installations carried out a mesophilic process, with quasi-continuous filling of the chamber, in liquid fermentation

Table 1. Biogas plant characteristic

Biogas plant designation	Kind of substrates	Amount of substrates [Mg/year]	Amount of digestate [Mg/year]	CHP power [MW]
A	Maize silage, cow manure, cow slurry, beet pulp	23,500	20,000	1.0
B	Meat waste, industrial sewage sludge, digestate	94,000	80,000	1.8
C	Grain distillery stock, food waste	60,000	50,000	1.2

(with 12-15% dry matter content in the chamber). In all examined biogas plants, biogas after drying and initial desulfurization was burned in cogeneration engines (CHP). The installations differed in the content and the amount of substrates used, and thus – the amount of biogas produced as well as the power of the cogeneration engine varied. The characteristics of biogas plants, the types of substrates used in them and the amount of digestate produced are included in Table 1.

Analytical methods

The physical and chemical properties of substrates and digested pulp were determined using certified laboratory procedures. The pH was measured in the digestate with a pH meter. Dry matter (DM) was determined by drying the samples in an oven at 105 °C for 24 h, according to PN-EN ISO 18134-3:2015-11. Organic dry matter (ODM) was measured by loss on ignition in a muffle furnace at a temperature of 550 °C for at least 3 h, according to PN-EN 15935:2013-02. The tests of biogas efficiency from individual substrates were carried out in accordance with the DIN 38 414 standard. To assess the fertilization value of the digestate, the levels of nitrogen (N), phosphorus (as P_2O_5) and potassium (as K_2O), were determined. Total nitrogen was determined using the Kjeldahl method, whereas phosphorus and potassium with using ICP-OES.

Evaluation of the reduction of pollutant emissions

In order to assess the reduction of pollutant emissions that can be achieved by replacing mineral fertilizers with digestate, the emission factors (Table 2) arising from the production and use of mineral fertilizers, determined for Central Europe (Kool et al. 2012), were used.

RESULTS AND DISCUSSION

Characteristics of the substrates

In all the examined biogas plants, substrates were used which, according to the law in force in Poland (Renewable..., 2015), are allowed for use in agricultural biogas plants. These were substrates from dedicated energy crops (maize silage), animal production (manure and cattle slurry), and agri-food processing (beet pulp from the sugar factory, meat waste from the slaughterhouse, industrial sewage sludge, grain distillery stock, food waste). Each biogas plant used a different substrate recipe (Table 3), and the common feature was to maintain the concentration of dry matter in the fermentation chamber at the level of approx. 12-15%. This is a necessary condition in wet fermentation, mainly due to allowing the co-substrates to be pumpable. For this reason, in biogas plant B, digestate was used as a process liquid to dilute the co-substrate mixture and maintain an appropriate dry matter content.

Characteristics of digestate

Laboratory analysis of the digestate from the studied biogas plants showed significant differences in its composition (Table 4). The digestate from biogas plant A contained the most dry matter (6.62%) and it was almost twice as much compared to the other two installations. The high content of DM in digestate A could be the result of

Table 2. The carbon footprint of N, P_2O_5 and K_2O fertilizer

Kind of fertilizer	N-fertilizer	P_2O_5 fertilizer	K_2O fertilizer
Designation	kg CO_2 eq/kg N	kg CO_2 eq/kg P_2O_5	kg CO_2 eq/kg K_2O
Coefficient	5.62	1.47	1.36

Table 3. Characteristic of substrates in biogas plants

Parameter	DM [%]	ODM [% in DM]	Biogas yield [m^3/Mg ODM]	Amount of substrate [Mg/year]	Percentage in feedstock [%]
Biogas plant A					
Maize silage	33	89	560	10,281	43.75
Cow manure	18	73	286	8,813	37.50
Beet pulp	22	94	579	736	3.13
Cow slurry	1	85	233	3,670	15.62
Biogas plant B					
Meat waste	30	82	450	51,700	55.0
Industrial sewage sludge	6	75	316	17,860	19.0
Digestate	3.7	61	107	24,400	26.0
Biogas plant C					
Grain distillery stock	6	94	620	45,000	75.0
Food waste	14	82	475	15,000	25.0

using the co-substrates with a high content of lignocellulose: maize silage and manure containing straw. The highest content of ODM in DM found in the digestate from biogas plant A indicates that the dissolution of the substrates used was the lowest. This indicates the need for a longer hydraulic retention time (HRT) for cellulosic co-substrates. From the fertilization point of view, a high content of ODM is beneficial because it increases the content of organic matter in the soil (Crolla et al. 2013, Doyeni et al. 2021). The pH of all digestates was alkaline (pH from 8.10 in biogas plant C to 9.40 in biogas plant B) and was typical of digestates in various studies (Tiwary et al. 2015, Koszel et al. 2020). The amount of individual fertilizer components in the fresh matter (FM) was different and depended on the selection of co-substrates (Table 4). Noteworthy is the particularly high K_2O content in the digestate from biogas plant C, which may be the result of using stillage from the distillery as a co-substrate. This argument is confirmed in other studies (Czekała et al. 2020, Szymańska et al. 2015).

Emission reduction

The presence of a significant amount of nutrients in the post-fermentation mass from a biogas plant means that it can be a valuable agricultural fertilizer. Such use of digestates, especially from agricultural biogas plants, is common (Crolla et al. 2013, Janczak et al. 2019, Koszel et al. 2020). Owing to the use of natural fermentation products, based on the substrates from agriculture and crop processing, the amount of chemical fertilizers used on the fields can be reduced. This, in turn, is associated with a reduction in pollutant emissions that are associated with the production

Table 4. Parameters of digestate

Biogas plant	DM [%]	ODM [% DM]	pH	N_{tot}		P_2O_5		K_2O	
				[kg/Mg FM]	[Mg/a]	[kg/Mg FM]	[Mg/a]	[kg/Mg FM]	[Mg/a]
A	6.62	76.47	8.19	3.82	76.4	1.08	21.6	4.08	81.6
B	3.70	60.96	9.40	4.00	320.0	2.50	200.0	1.30	104.0
C	3.21	63.00	8.10	6.58	329.0	1.64	82.0	16.30	815.0

Table 5. Reduction of emissions obtained by replacing mineral fertilizers with digestate from the tested biogas plants

Biogas plant	N_{tot} [Mg CO_2 eq/a]	P_2O_5 [Mg CO_2 eq/a]	K_2O [Mg CO_2 eq/a]	Total [Mg CO_2 eq/a]
A	429.4	31.8	110.9	572.1
B	1798.4	294.0	141.4	2233.8
C	1849.0	120.5	1108.4	3077.9

Table 6. The maximum dose of digestate, area of land needed for its development and reduction of emissions

Parameter	Unit	Biogas plant		
		A	B	C
Reduction of GHG emissions by using 1 Mg of digestate	kg CO_2 eq/Mg	28.6	27.9	61.6
Amount of digestate per 1 ha	Mg/ha	44.5	42.5	25.8
Area needed to apply digestate	ha/a	449.4	1882.4	1935.3
Reduction of GHG emissions by using the permissible dose of digestate	kg CO_2 eq	1272.7	1185.6	1589.3
Reduction of GHG emissions by using 30 Mg digestate per 1 ha	kg CO_2 eq	858	837	1848

of fertilizers and their use in the fields. In order to calculate the theoretical amount of this reduction, indices (Table 2) were used and they were related to individual nutrients contained in the digestate.

Annual replacement of mineral fertilizers with digestate of the same fertilizing values, coming from biogas plants A, B and C, allows to reduce the amount of pollutants emitted by 572.1, 2233.8 and 3077.9 Mg CO_2 eq, respectively (Table 5).

The use of 1 ton of digestate from biogas plants A, B and C in place of mineral fertilizers reduces emissions by 28.6, 27.9 and 61.6 kg CO_2 eq, respectively (Table 6). Zeshan and Visvanathan (2014) calculated that the reduction of GHG emissions due to the use of digestate may amount to more than 130 kg CO_2/Mg, and the differences in the calculations may result from different characteristics of digestates and different methodologies used in the research.

Taking into account the fact that an average of 30 tons of digestate is used per 1 ha, it can be calculated that the avoided emission of pollutants from the use of chemical fertilizers exceeds 858, 837 and 1848 kg of CO_2 equivalent from biogas plants A, B and C, respectively.

It is necessary to prevent contamination of soils and waters with fertilizers, including natural ones, including digestate. Therefore, preventive studies and assessments in this area are being carried out (Gajewska et al. 2017). The amount of natural and organic fertilizers used in the EU depends on their nitrogen content. The limit value is 170 kg N/ha/year (Council…, 1991). Taking this indicator into account, the maximum dose of digestate from the examined biogas plants that can be distributed on an area of 1 hectare and the area of agricultural land necessary for this purpose was calculated. In order for the use of digestate to comply with the legal provisions regulating the outflow of nitrogen from soils, 25.8 Mg/ha of digestate from biogas plant A, 42.5 Mg/ha from biogas plant B and 44.5 Mg/ha from biogas plant C should be used. Koszel et al. (2020) mentioned the use of digestate in doses of 25–50 m^3/ha. Crolla et al. (2013) emphasized that a fertilization plan should be developed in order to rationally use digestate for fertilization and obtain satisfactory crop yields without causing damage to the environment.

CONCLUSIONS

The digestate from the biogas plant is an excellent agricultural fertilizer that provides both basic nutrients (N, P, K) as well as organic matter that gradually decomposes in the soil. Owing to such properties, fertilization with digestate can replace, in whole or at least in part, the use of artificial fertilizers and avoid the emission of pollutants associated with their production. The conducted research shows that digestates can vary greatly in composition, depending on the co-substrates used. This then influences the amount of digestate used per field unit to make its use legal. In order not to exceed the allowed nitrogen fertilization, the tested digestates can be used in the amount of 25.6–44.5 Mg/ha. This means that in order to utilize the annual production of digestate, it is necessary to spread it over an area of almost 2,000 ha in the case of a biogas plant with a capacity of 1.8 MW.

The use of digestate as a fertilizer allows reducing or completely resigning from mineral fertilization. Thus, it is possible to reduce the greenhouse gas emissions associated with the production of artificial fertilizers. The calculated reduction of GHG emissions was 27.9–61.6 kg CO_2 eq/Mg of digestate, which means that fertilization with an annual amount of digestate from the biogas plants under study reduces emissions by approx. 570 Mg CO_2 eq for the smallest biogas plant to over 3000 Mg CO_2 eq for the largest biogas plant. Therefore, the use of digestate as a fertilizer does not only provide nutrients to the soil, but also protects the atmosphere and reduces the greenhouse effect.

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