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Importance of Feedstock in a Small-Scale Agricultural Biogas Plant

Robert Czubaszek *, Agnieszka Wysocka-Czubaszek and Piotr Banaszuk

Faculty of Civil Engineering and Environmental Sciences, Bialystok University of Technology, Wiejska 45A Str., 15-351 Bialystok, Poland
* Correspondence: r.czubaszek@pb.edu.pl

Abstract: Although no legal sustainability criteria have been formulated for electricity and heat production from biogas, the sustainability and profitability of large-scale biogas plants which use mainly energy crops is now questioned. Small (farm-size) biogas plants characterized by CHP electrical output in the range between 15 kW_{el} and 99 kW_{el}, operating on agricultural wastes and by-products, seem more suitable; however, the variety of feedstock may be crucial in the proper design and operation of such family biogas plants. This paper aims to present the problems that occurred in small agricultural biogas plants fed with sheep manure (SM), horse manure (HM), and grass-clover silage (GCS). This paper also focuses on analyzing the energy balance and carbon dioxide (CO_2) emissions related to four technological solutions (Scenarios 1–4) based on various feedstocks, grinding and feeding systems, and wet/dry fermentation. The biogas plant was originally based on dry fermentation with an organic loading rate ~10.4 $kg_{VS} \cdot m^{-3} \cdot d^{-1}$, a hydraulic retention time of 16 days, and temperature of 45 °C in the fermentation chamber. The material was shredded and mixed in a mixing device, then the mixture of manures and silage was introduced to the horizontal fermentation chamber through a system of screw feeders. The biogas and the digestate were collected in a reinforced concrete tank. The biogas was sent to the CHP unit of an installed electrical power of 37 kW_{el}, used to produce electricity and recover the heat generated in this process. Scenario 1 is based on the design assumptions used for the biogas plant construction and start-up phase. Scenario 2 includes a new feeding and grinding system, in Scenario 3 the feedstock is limited to SM and HM and wet fermentation is introduced. In Scenario 4, a dry fermentation of SM, HM, and maize silage (MS) is assumed. Avoided CO_2 emissions through electricity and heat production from biogas were the highest in the case of Scenarios 1 and 4 (262,764 kg $CO_2 \cdot y^{-1}$ and 240,992 kg $CO_2 \cdot y^{-1}$) due to high biogas production, and were the lowest in Scenario 3 (7,481,977 kg $CO_2 \cdot y^{-1}$) because of the low specific methane yield (SMY) of SM and HM. Nevertheless, in all scenarios, except Scenario 3, CO_2 emissions from feedstock preparation and biogas plant operation are much lower than that which can be avoided by replacing the fossil fuel energy for the electricity and heat produced from biogas. Our observations show that a small agricultural biogas plant can be an effective energy source, and can contribute to reducing CO_2 emissions only if the appropriate technological assumptions are adopted, and the entire installation is designed correctly.

Keywords: small-scale biogas plant; feedstock; manure; CO_2 emissions; energy balance

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1. Introduction

The growing population, and an increasing demand for energy, together with the depletion of natural resources including fossil fuels, biodiversity loss, and climate change, entail the need for a profound transition from a traditional linear economy to a circular economy in which the value of products, materials, and resources, is maintained in the economy for as long as possible, and the generation of waste minimized [1]. In a circular economy, sustainable growth should be based on the energy generated from renewable sources. In addition, the political situation in Europe forces the acceleration of actions that phase out the dependency on external fossil fuels. The European Union REPowerEU

Plan [2] responds to this situation through energy savings, the diversification of energy supplies, and an accelerated roll-out of renewable energy to replace fossil fuels in homes, industry, and in power generation. The bioeconomy provides alternatives to fossil-based energy and can contribute to the circular economy and increase bio-based renewable energy generation. On the other hand, using biological resources requires attention to their lifecycle environmental impacts and sustainable sourcing. The multiple possibilities for their use can also generate competition for them and create pressure on land use [1].

In the bioeconomy, bioenergy plays a vital role in sustainable development and decreasing greenhouse gases (GHG) emissions. One of the well-established and effective biofuel production technologies that can play a crucial role in achieving climate-related targets, such as at least a 55% net reduction in GHG emissions by 2030 [3], is anaerobic digestion (AD). AD is a microbiological process in which organic materials are converted in the absence of oxygen into methane-rich biogas and nutrient-rich digestion residue, i.e., digestate [4]. Biogas production effectively reduces GHG emissions and is a sustainable way to utilize wastes and manage agricultural residues and food-processing by-products [5–7]. Biogas is mainly used as a fuel in combined heat and power (CHP) generation but can be injected into the gas grid after cleaning from impurities, or treated or upgraded to biomethane used as a transport fuel or in industrial applications [8]. In addition, the energy obtained from biogas is non-intermediate, and biogas can be relatively easily stored, which seems to be a significant advantage compared to solar or wind power, which needs a more flexible energy system [9].

As was shown in the literature, AD performance depends on feedstock type, operational parameters, biogas utilization pathways, digestate treatment method [10], plant scale [11], and fermentation technology [12]. Biogas plants use various organic materials as feedstock, including energy crops, agricultural residues such as manure and crop residues, residues from the food and beverage industry, biowaste, municipal organic waste, and sewage sludge [13]. The energy crops used as feedstock for biogas production are controversial since their cultivation requires agricultural land and, therefore, can compete with food production. In particular, the sustainability of biogas production from maize silage (MS) is questioned [14,15]. On the other hand, crop residues and food processing residues are now considered raw materials for various product formations. Even though crop residues used as feedstock for biofuels production is a promising option for reduction of GHG emissions, the removal of crop residues from the fields may contribute to increased erosion and adversely affect soil fertility [16–18].

Generally, AD of waste is more sustainable than waste disposal. The AD of poultry litter is a suitable disposal route which may lead to reduced environmental impacts [19]. Biogas produced from grasses grown naturally show beneficial effects on ecosystem quality; however, the GHG emissions related to grass collection and transport are pretty high since more grass is needed to produce the same amount of energy as it is generated from MS [20]. The GHG emissions reduction depends on the biomethane potential of feedstock; therefore, Zhang et al. [21] reported better co-digestion of pig manure with grasses compared to mono-digestion of pig manure, in terms of global warming potential and fossil fuel depletion potential. The comparison of biogas production from maize and biennial and perennial wild plant mixtures cultivated under maize showed that both systems had lower marine eutrophication and global warming potentials than maize; however, the maize system was more favorable from an economic perspective and performed best in terms of freshwater eutrophication, terrestrial acidification, fine particulate matter, and ozone formation [22].

Depending on CHP electrical output, biogas plants can be divided into four categories. Micro-scale biogas plants are those where CHP electrical output is less than 15 kW_{el}, and small-scale biogas plants are characterized by CHP electrical output in the range between 15 kW_{el} and 99 kW_{el}, medium-sized biogas systems produce 100–299 kW_{el} and large-scale systems electrical output is more than 300 kW_{el} [23]. Micro-scale biogas plants are widespread in tropical climates [24] and play an essential role in rural areas in developing countries [25]. Today, almost 50 million micro-scale digesters are operating around the globe, mainly in China, India, Asia, Africa, and South America. Biogas generated in these micro-scale digesters is most often used for cooking [25].

In Europe, large-scale biogas plants prevail. In Sweden only, the 10 largest biogas plants have an average capacity of 61 GWh per plant and 15 new large-scale plants are planned to fulfil the governmental biogas production target of 7 TWh per year by 2030 [26]. The German biogas industry, leading in Europe, has historically been driven by large energy crop-based digesters [25]. However, the literature provides numerous examples of negative impacts on the environment, the local agricultural economy, and society, caused by large-scale and high-density biogas plants [27]. In response to these problems, small-scale (farm-scale) biogas plants, whose size is primarily determined by local heat demand and which use the waste from agricultural production and agri-food processing, are becoming increasingly popular since they can work economically in small to medium-sized farms with small available biomass quantities [23,27]. Small-scale biogas systems may also solve the problem of excess slurry in areas of high animal production [27].

In Europe, several countries already have special support schemes for small- or micro-scale biogas plants [27], and others are now opening their doors to small manure-based digesters [25]. The average capacity of an agricultural biogas plant in Poland is still around 1 MW_{el}, and biogas plants smaller than 500 kW_{el} represent only ~14%. In Bavaria, which, compared to Germany, is characterized by a high fragmentation of farms, the average capacity of a biogas plant is 370 kW_{el} (out of 2385 facilities; as of 31 December 2015), biogas plants smaller than 500 kW_{el} account for 73% and smaller than 200 kW_{el} for 37%. In 2021, 59 new installations were registered in Bavaria, among them 36 biogas plants with a capacity of less than 150 kW_{el} [28]. The average size of an agricultural biogas plant in Switzerland (affiliated to Ökostrom Schweiz) is equal to ~150 kW_{el} [29], which classifies the facilities into medium- and small-size systems. These values show an apparent skewing of the size structure of Polish agricultural biogas plants towards large-scale facilities. Such large-scale biogas plants are owned by investors and based on purchased feedstock, owned by large industrial producers of swine, poultry, cattle, etc., or constructed on large-area farms.

In contrast, family farms hardly participate in the biogas market, except as biomass suppliers, the processing of which benefits someone else. Assuming that 1 kW_{el} installed in a biogas plant requires an annual yield of maize from 0.5 ha or biomass from 0.8–1.2 ha of grassland [30], it is easy to calculate that an average Polish 1 MW_{el} biogas plant requires ~500 ha of maize or ~1000 ha of grasslands. In Poland, farms with an agricultural area of more than 500 ha are 1063, and in 2020 they used 7.1% of the total area of farms [31].

Small-scale biogas plants are still relatively rare, and therefore the ability and skills of developers to design and build such installations are often meagre. This can lead to poorly constructed and maintained plants, which can even be abandoned due to breakdowns, design errors, and equipment failures [32,33]. Small-scale biogas systems suffer from low-quality construction, the leakage of pipelines, and low biogas production [34]. A variety of difficulties with connecting to the grid, the unreliability of CHP running with significant capital costs of CHP unit, extra costs for its maintenance, and the additional costs of engineering the digester in terms of gas scrubbing, monitoring, and achieving a steady state of biogas production, were reported in the United Kingdom [33]. Technical problems often occur in the start-up phase due to incorrect design and the estimation of plant operating conditions, process parameters, and feedstock demand and supply. Feedstock variability in farm-scale biogas plants is often challenging in technological aspects; therefore, such biogas plant projects are at risk of failure. In China, less than 60% of existing household biogas plants operate effectively. In comparison, in Bangladesh, only 3% of small-scale biogas systems function without defects, while 76% function with defects and 21% do not function at all [34]. Biogas plants were usually built within the framework of support policy and therefore commonly received subsidies to cover costs of investments or operation. Nowadays, in many countries, the supporting system is changed or finished and therefore possible shutdowns of biogas plants are considered [35]. In Germany, especially small-scale biogas plants require new supporting solutions to maintain the profitability [36]. The contribution of small-scale biogas plants into biomethane production through upgrading the biogas also seems to be rather difficult, since feasibility studies revealed that such biogas plants need a subsidy to reach profitability [37,38]. In this context, biogas production sustainability and the profitability of small agricultural biogas plants may be questioned.

Most literature considering problems occurring in biogas plants is based on questionaries and describes overall issues [32–34]. The problems of single small-size biogas plant are described to a lesser extent.

This paper aims to describe the problems that occurred in a small agricultural biogas plant fed with sheep manure (SM), horse manure (HM), and grass-clover silage (GCS). This paper also describes the potential solutions and discusses the energy balance and carbon dioxide (CO_2) emissions related to four technological scenarios. We analyzed Scenario 1, which was based on the design assumptions used for the biogas plant construction and start-up phase. Scenario 2 was a result of change of the feeding and grinding system, which was caused by problems related to feeding biogas plant with feedstock in the start-up phase. The third analyzed scenario was a result of further technical problems with feeding and the limitation of the feedstock to SM and HM, as well as changing dry technology to wet fermentation (Scenario 3). We also analyzed Scenario 4, where dry technology was used and maize silage (MS) was used as a feedstock instead of GCS for co-digestion with manures. Scenario 1, 2, and 3, were those which had been conducted in the operational conditions of studied biogas plant, while Scenario 4 was only theoretical case and was not implemented in the biogas plant.

2. Technological Solutions (Scenarios) in the Analyzed Biogas Plant

The analyzed agricultural biogas plant is located on a farm in Hryniewicze Duże village (52°48′59″ N, 23°13′45″ E), Podlaskie Voivodeship, in the eastern part of Poland. The farm is focused on breeding sheep and horses and crop production. The significant amount of manure produced requires proper and sustainable management, and AD seems to be a favorable solution. Since, for biogas production, the available amount of manure on the farm does not meet the plant's demand, the co-digestion of manure with another feedstock is needed. The grass-clover mixture is the only available additional feedstock on the farm. It therefore is introduced in the form of silage as a feedstock for co-digestion.

According to the operational assumptions, the described biogas plant should work in the technology of dry fermentation (Scenario 1). The basic substrates used in a biogas plant should be SM, HM, and GCS (Table 1). These feedstocks are mixed and ground in a Bio-Mix 750 stationary device and then fed to the fermentation chamber via screw conveyors. The chamber is a horizontal steel tank with a volume of 80 m^3, thermally insulated and heated by heating coils with circulating hot water. Inside the tank, an agitator is installed. The agitator prevents the formation of a floating layer and sediments on the bottom, facilitates the release of biogas, and moves the feedstock with DM of 22–25% in a "piston" manner. In order to obtain the required DM content, the liquid fraction of the digestate obtained through its separation is also introduced into the chamber. This fraction is collected in an underground concrete tank from which it is pumped into the fermentation chamber. The organic loading rate (OLR) is assumed to be ~10.4 $kg_{VS} \cdot m^{-3} \cdot d^{-1}$, while the hydraulic retention time (HRT) will be 16 days. Implementing these assumptions will be possible only with a temperature of 45 °C in the fermentation chamber. The temperature in the fermentation chamber will be maintained via the external heating system. The planned demand for the substrates used is 300 $t \cdot y^{-1}$ for manure, and 850 $t \cdot y^{-1}$ for silages. Considering the demand for GCS in a biogas plant and the average yield of a grass-clover mixture equal to 25 $t \cdot ha^{-1}$, ~34 ha of arable land is needed to produce at sufficient amount of this feedstock. The 365 t of the liquid phase of digestate per year was required to ensure the dilution necessary to obtain an appropriate DM content in the fermentation chamber. The biogas plant is working in a semi-continuous mode with feeding and emptying sequences. The digestate obtained as a result of fermentation is pumped into a concrete tank with a circular cross-section (internal diameter 12.60 m, internal wall height 4.1 m). The tank is covered with a flexible membrane that allows the collection of biogas sent from the fermentation chamber, as well as biogas from the complete digestion of the digestate. After cleaning, the biogas is sent to a cogeneration system with an installed electrical capacity of 37 kW, used to generate electricity and recover the heat generated in this process. The expected yield of biogas with the content of 52–53% is 158,045 $m^3 \cdot y^{-1}$, which will enable the production of 284 MWh of electricity and 1300 GJ of heat energy per year. According to the assumptions, 7.1% of produced electricity (20.2 MWh) and 36% of produced heat energy (471 GJ) will be used for the own needs of the biogas plant. The electricity generated in the biogas plant is sent to the grid, while the heat is used to heat the fermentation chamber and the post-fermentation tank, to dry the grain, and to heat the farmer′s house.

Table 1. Four operational scenarios of small-scale agricultural biogas plant.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Feedstock	SM, HM, GCS	SM, HM, GCS	SM, HM	SM, HM, MS
Fermentation technology	dry, thermophilic	dry, thermophilic	wet, mesophilic	dry, mesophilic
Electric power installed, kW_{el}	37	37	37	37

SM—sheep manure, HM—horse manure, GCS—grass-clover silage, MS—maize silage.

The problems related to feeding a large amount of feedstock formed by long stems with high DM content occurred in the start-up phase. This problem was partially solved by changing the grinder for a new grinding system consisting of a new type of grinder and a new additional device for its feeding (Scenario 2). The other technological assumptions (thermophilic dry fermentation) described in Scenario 1 were unchanged.

The new grinding and feeding system was much more efficient, but not optimal for shredding GCS with long stems, which still blocked the grinding device. Due to this problem, after installing the new feeding system, the biogas plant operated only on a mixture of SM and HM (Scenario 3) diluted with cattle slurry (CS). The AD process was changed to wet mesophilic technology with 10% DM content and a temperature of 38 °C.

The operation of the biogas plant in these conditions was stable. However, the low methane potential of all used manures and their limited amount resulted in the inability to use the full potential of the installed CHP unit. Due to the low efficiency of the biogas plant operating only on SM and HM, the energy potential of the existing biogas plant was estimated with the assumption that MS would be added to the feedstock (Scenario 4). GCS replacement with MS, which is chipped to 1 cm pieces, will significantly improve the feedstock feeding to the fermentation chamber. Such a system requires dry fermentation technology, but opposite to Scenarios 1 and 2, the biogas plant will operate at 38 °C.

In Scenarios 1, 2, and 3, the calculations of energy balance and CO_2 emissions used operational procedures (technology, feedstock, temperature of process) proceeded in the real conditions of the start-up phase in the biogas plant located on the farm in Hryniewicze Duże. Since biogas plant changes the operational modes several times in short periods, the biogas production and energy demand and production were theoretically calculated and were based on the results of laboratory experiments on methane production from HM and SM, real operational procedures, and assumption taken from literature. The results of laboratory experiments were used to calculate the amount of methane possible to produce in the biogas plant. Scenario 4 is based only on theoretical assumptions about technology, feedstock, and biogas production rate.

3. Materials and Methods

3.1. Chemical Composition and Specific Methane Yield of Feedstock

The inoculum for biomethane potential (BMP) test was collected from the mesophilic agricultural biogas plant that processed maize silage with 10–20% of food and agricultural wastes. The sample of CS was taken from the pre-tank, and the SM, HM, and GCS samples were taken from the heaps. The chemical composition was analyzed in all four feedstocks, while specific methane yield (SMY) was measured only for SM and HM.

The following parameters were analyzed in CS, HM, SM, and GCS: total solids (TS), volatile solids (VS), total Kjeldahl nitrogen (TKN) content, total phosphorus (TP) content, potassium (K) content, and total organic carbon (TOC) content. The TS content was obtained by drying the material to a constant weight at 105 °C. VS content was determined after incineration of dried material at 550 °C for 6 h in a muffle furnace according to standard method [39]. TKN was determined by the Kjeldahl method in Vapodest 50 s analyzer (Gerhardt, Königswinter, Germany). The oven-dried samples were ground and used for further analyses. After nitric acid/hydrogen peroxide microwave digestion in ETHOS One (Milestone s.r.l., Milan, Italy), the content of TP was determined with the ammonium metavanadate method using UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan) and content of K was analyzed using flame photometry (BWB Technology, Newbury, UK). TOC content was determined in the TOC-L analyzer with SSM-5000A Solid Sample Combustion Unit (Shimadzu, Kyoto, Japan). The analyses were performed in triplicate, and the results were given on a dry weight basis.

The BMP tests of HM and SM used in the biogas plant were performed in eudiometers. The reactors, with a total volume of 1 L and a working volume of ~500 mL, were incubated at 38 ± 1 °C in a water bath (Figure 1). The amount of SM and HM and the amount of inoculum were added to the reactors to set the inoculum to substrate ratio as 2:1 based on VS content. Distilled water was added to obtain the reactors' TS content of 10%. The reactors were flushed with nitrogen for 2 min and sealed to ensure anaerobic conditions. The blank experiment was performed with inoculum and water only. The biogas composition was measured with a portable biogas analyzer DP-28BIO (Nanosens, Tarnowo Podgórne, Poland).

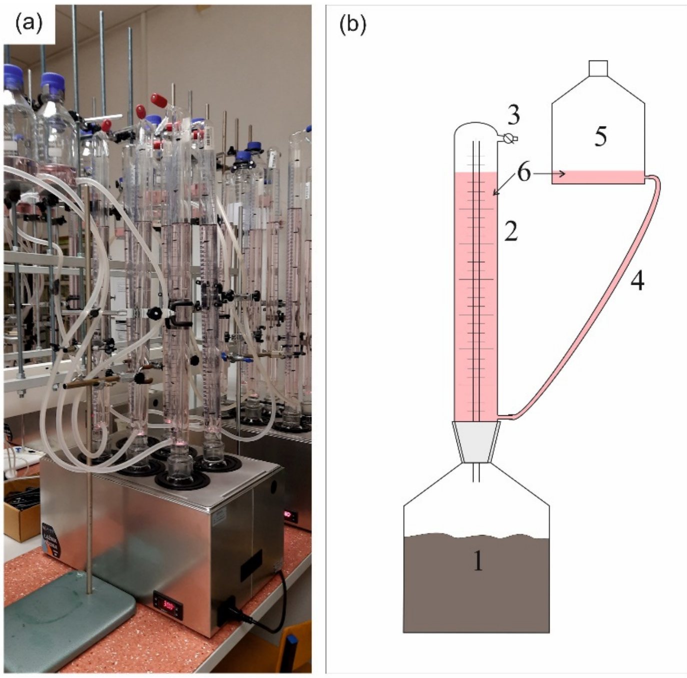

Figure 1. The BMP experiment: (**a**) eudiometer sets in water bath; (**b**) the eudiometer set: 1—glass bottle (reactor) with mixture of inoculum and substrate, 2—the eudiometer with internal glass tube for gas transport, 3—valve for gas sampling, 4—connecting tube, 5—pressure compensation reservoir, 6—confining liquid.

The SMY was calculated as the difference between the amount of methane produced from the feedstock and amount of methane produced from the inoculum. The SMY is given in NL $CH_4 \cdot kg_{VS}^{-1}$. The calculations were performed according to the ideal gas law and the molar volume of ideal gases at standard temperature and pressure conditions (NL = normal litre, i.e., gas volume corrected to 0 °C and 1013 bar). The kinetics of methane production was determined using the modified Gompertz model, which is commonly used to determine the relationship between cumulative gas production and fermentation time [36]:

$$G(t) = G_0 \times exp\{-exp\left[\frac{R_{max} \times e}{G_0}(\lambda - t) + 1\right]\} \quad (1)$$

where

$G(t)$—cumulative methane production at a specific time t (mL)
G_0—methane production potential (mL)
R_{max}—maximum methane production rate (mL·day^{-1})
λ—duration of lag phase (minimum time to produce methane) (days)
t—cumulative time for methane production (days)
e—mathematical constant (2.71828)

The modified Gompertz equation estimates the methane production potential, the maximum methane potential rate, and the lag phase, which is essential for evaluating the AD process [40].

Based on the plotted curves, the time (days) when 50% (T50) and 95% (T95) of the possible methane production had been reached was determined.

3.2. Statistical Analyses

The statistical differences in the chemical composition of feedstocks were tested with a simple one-way analysis of variance (ANOVA). Before ANOVA, the normality was checked, and the homogeneity of variance was checked using the Levene test. When significant differences were detected, means were compared using Tukey's test ($p < 0.05$). All the statistical analyses of data were performed using the STATISTICA 12 software (StatSoft Polska, Kraków, Poland).

3.3. Energy Balance and CO_2 Emissions Calculations

The energy demand for feedstock preparation included only the transportation of manures (SM and HM) from the stable and sheepfold to the heap and from the heap to the grinding and feeding system. In the case of silages (GCS and MS), the energy demand for cultivation, harvest, transportation, ensilaging, and transportation of material from silos to the grinding and feeding system were considered. All the calculations were based on the direct energy input from fuel. The calorific value of diesel oil was assumed to be 36 MJ·L^{-1} [41], while the data on diesel oil consumption for every feedstock preparation stage was obtained from a farmer operating the biogas plant. The direct energy input from fuel for maize cultivation was taken from Pawlak [42].

The methods of determining the energy produced in biogas plants differed depending on the adopted scenarios. Scenarios 1 and 2 adopted the data from the technological assumptions prepared for the planned biogas plant. In Scenarios 3 and 4, the actual quantities of feedstock needed to ensure the operation of the biogas plant and measured SMY was used in calculations. The average value for SMY of MS was taken from Herrmann and Rath [43]. The energy efficiency of the scenarios was estimated based on biogas plant energy demand for biogas production. The biogas plant electricity demand was calculated based on the electric power of devices installed in the biogas plant and their operating time. The thermal energy demand was calculated as the heat needed for heating the fermentation chamber and digestate tank.

In the calculations concerning the reduction of CO_2 resulting from the biogas plant operation, it was assumed that electricity and heat generated from conventional fuels would be replaced with energy produced in the biogas plant. As in the case of energy, the CO_2 emissions calculations only included the direct emissions from diesel oil and electricity used in a biogas plant. The emission factor for electricity (698 kg CO_2·MWh^{-1})

and for diesel oil (74.1 kg $CO_2 \cdot GJ^{-1}$) were adopted from The National Centre for Emissions Management [41,44]. The calculations did not consider the indirect emissions related to the production of materials for the cultivation of maize, grasses, and clover, as well as the indirect emissions related to the production of agricultural equipment.

4. Results

4.1. Chemical Composition of Feedstock

All feedstocks used in the biogas plant differed from each other significantly ($p < 0.05$) in terms of both physical and chemical properties (Table 2). The lowest TS (1.72 ± 0.06%) was observed in the case of CS; both manures and GCS were characterized by significantly ($p < 0.05$) higher TS, however, the highest value (64.08 ± 1.15%) was found for GCS. VS value in CS was also the lowest (56.87 ± 4.14% TS) compared to the values in both manures and GCS, which were very similar and ranged from 84.40 ± 2.61% TS to 89.85 ± 1.72% TS. The highest TKN (24.23 ± 0.64 $g \cdot kg_{DM}{}^{-1}$) was found in the case of CS and it was significantly ($p < 0.05$) different only from the lowest value (15.60 ± 2.39 $g \cdot kg_{DM}{}^{-1}$) found for HM. The TP concentration was similar in all studied feedstocks and ranged from 2.16 ± 0.23 $g \cdot kg_{DM}{}^{-1}$ to 3.92 $g \cdot kg_{DM}{}^{-1}$. The TOC content was also similar in all studied materials and ranged between 369.29 ± 47.70 $g \cdot kg_{DM}{}^{-1}$ and 433.74 ± 16.47 $g \cdot kg_{DM}{}^{-1}$. The highest K content equal to 122.43 ± 5.15 $g \cdot kg_{DM}{}^{-1}$ was found in CS and was significantly ($p < 0.05$) different from the values observed in both manures and GCS. The K concentration also differed significantly ($p < 0.05$) between both manures and was the lowest for HM (11.77 ± 0.09 $g \cdot kg_{DM}{}^{-1}$).

Table 2. Chemical composition of feedstocks used in the analyzed biogas plant.

Parameters	Cattle Slurry (CS)	Sheep Manure (SM)	Horse Manure (HM)	Grass-Clover Silage (GCS)
Total solids (TS), %	1.72 ± 0.06 ^{a}	37.41 ± 2.44 ^{b}	26.36 ± 0.20 ^{c}	64.08 ±1.15 ^{d}
Volatile solids (VS), % TS	56.87 ± 4.14 ^{a}	84.40 ± 2.61 ^{b}	89.85 ± 1.72 ^{b}	89.12 ± 0.54 ^{b}
Total Kjeldahl Nitrogen (TKN), $g \cdot kg_{DM}{}^{-1}$	24.23 ± 0.64 ^{a}	23.36 ± 3.68 ^{a}	15.60 ± 2.39 ^{b}	19.71 ± 1.88 ^{ab}
Total phosphorus (TP), $g \cdot kg_{DM}{}^{-1}$	3.47 ± 0.64 ^{a}	3.92 ± 1.00 ^{a}	3.13 ± 0.21 ^{a}	2.16 ± 0.23 ^{a}
Total potassium (K), $g \cdot kg_{DM}{}^{-1}$	122.43 ± 5.15 ^{a}	26.47 ± 0.71 ^{b}	11.77 ± 0.09 ^{c}	17.03 ± 1.57 ^{c}
Total organic carbon (TOC), $g \cdot kg_{DM}{}^{-1}$	369.29 ± 47.70 ^{a}	399.29 ± 20.25 ^{a}	392.50 ± 14.95 ^{a}	433.74 ± 16.47 ^{a}
C:N	15:1	17:1	25:1	21:1
N:P	7:1	6:1	5:1	8:1

Lowercase letters—statistical differences at $p < 0.05$ among the feedstocks.

The C:N ratio plays an essential role in the AD process. The highest C:N ratio equal to 25:1 was found for HM. Much lower values were obtained for CS and SM, 15:1 and 17:1, respectively. The C:N ratio for GCS was closer to this for HM and was equal to 21:1. The relations between the contents of N and P were more even and ranged from 5:1 to 8:1, with the lowest value for HM and the highest value for GCS (Table 2).

4.2. Specific Methane Yield

Both studied feedstocks obtained similar SMY equal to 247.0 $NL \cdot kg_{VS}{}^{-1}$ and 248.5 $NL \cdot kg_{VS}{}^{-1}$ for HM and SM, respectively. The kinetics of biogas production in both manures were similar (Figure 2). The time (days) when 50% (T50) and 95% (T95) of the possible methane production was reached, based on the plotted curves, was 14 (T50) and 28 (T95) days.

Maximum daily methane production, equal to 11.9 $NL \cdot kg_{VS}{}^{-1}$ d^{-1} and 12.4 $NL \cdot kg_{VS}{}^{-1}$ d^{-1} for SM and HM, respectively, was obtained in case of SM on day 12 and in case of HM on day 13 of the BMP test (Figure 3). The lag time of AD of both manures took 3 or 4 days.

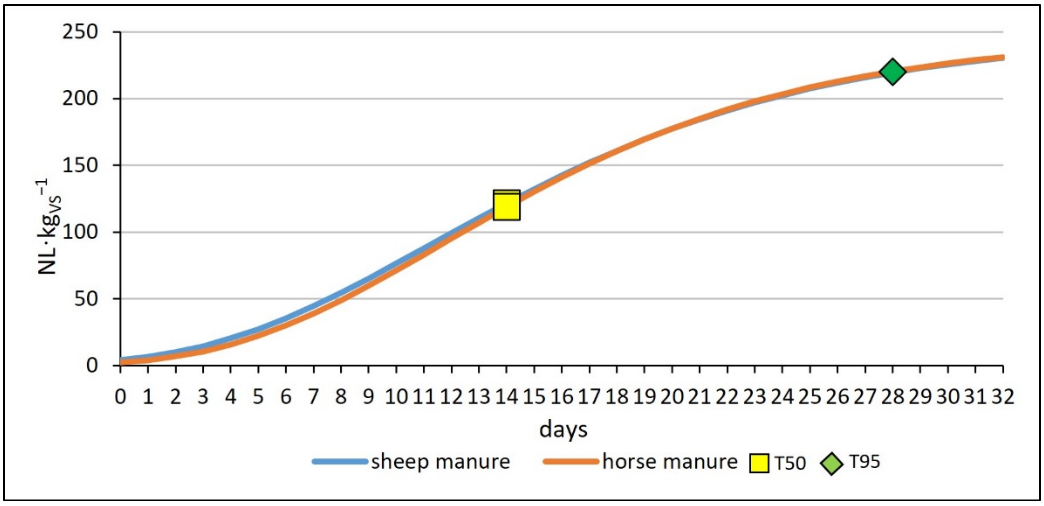

Figure 2. Cumulative methane production of sheep manure and horse manure.

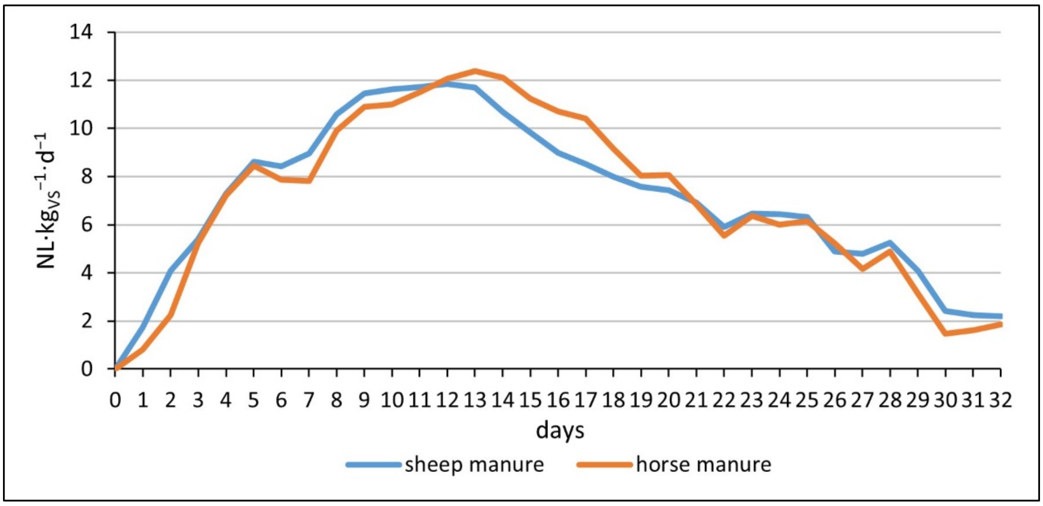

Figure 3. Daily methane production of sheep manure and horse manure.

Methane concentration in biogas increased rapidly in the first ten days of the BMP test of SM. The increase in CH_4 concentration in the case of HM was slightly longer and lasted 13 days (Figure 4). The maximum concentration of CH_4 was ~55% and was obtained on day 14 of the BMP test in the case of both manures. The CH_4 concentration was stable from day 14 until the end of the BMP test and equaled 52–53%.

The hydrogen sulphide (H_2S) concentration in biogas ranged from 313 ppm to 1755 ppm and from 265 ppm to 1534 ppm for SM and HM, respectively (Figure 5). At the start of the BMP test, the H_2S concentration in biogas produced from HM was much lower than the H_2S concentration in biogas produced from SM. The highest difference was observed on day 3 when the H_2S concentration in biogas produced from HM was equal to 433 ppm while the H_2S concentration in biogas produced from SM was equal to 1201 ppm. The highest H_2S concentration was observed on day 5 for SM (1755 ppm) and day 6 for HM (1534 ppm). After the first week of the BMP test, the H_2S concentration in biogas produced from both manures was slightly different, but the differences were much lower than that observed in the first 5 or 6 days.

4.3. Energy Balance and CO_2 Emissions

Since the same feedstock in Scenarios 1 and 2 is assumed, the methane production and resulting electricity and thermal energy production are the same (Table 3). Similar energy production in Scenarios 1, 2, and 4, results from the assumption that GCS used as feedstock in Scenarios 1 and 2 is replaced by MS in Scenario 4, and the assumed amount of MS (485 $t \cdot y^{-1}$) in Scenario 4 was sufficient to produce methane on the same level as in Scenarios 1 and 2. The main difference in Scenarios 1, 2, and 4, is the biogas plant's internal electricity consumption, which results from different grinding and feeding systems in Scenarios 2 and 4 compared to Scenario 1. The lower internal electricity consumption in Scenario 4 than in Scenario 2 results from the shorter time required to feed the fermentation chamber with MS instead of GCS to produce the same amount of methane. In addition, the amount of maize necessary for the operation of the biogas plant under the Scenario 4 requires ~12 ha of arable land, which is much lower than the area needed for grass-clover mixture cultivation in Scenarios 1 and 2. Scenario 3 differs significantly from other studied systems because the biogas plant is fed only with SM and HM diluted with CS, which results in low energy production. The availability on the farm of SM and HM, which low SMY characterizes, could ensure the operation of the CHP with a power of 10 kW_{el}.

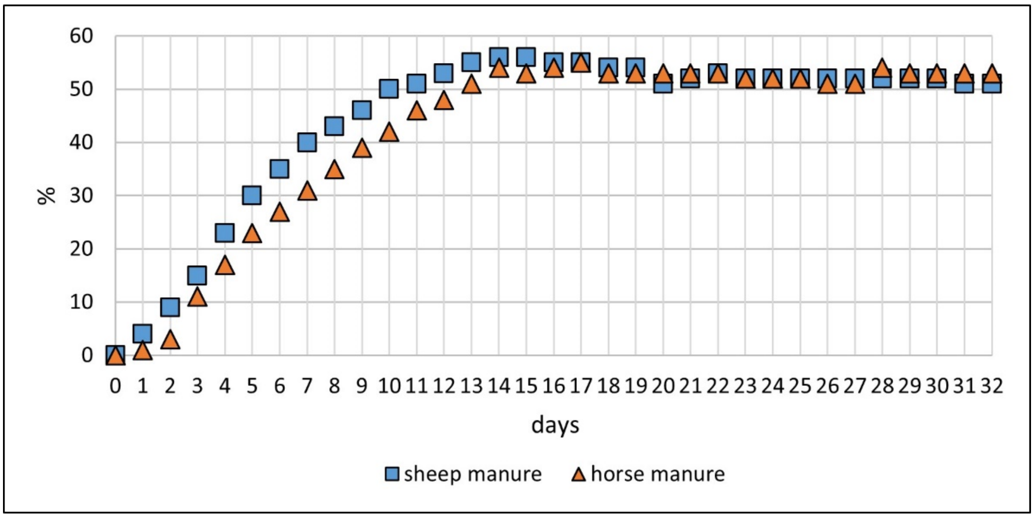

Figure 4. Methane (CH_4) concentration in biogas produced from sheep manure and horse manure.

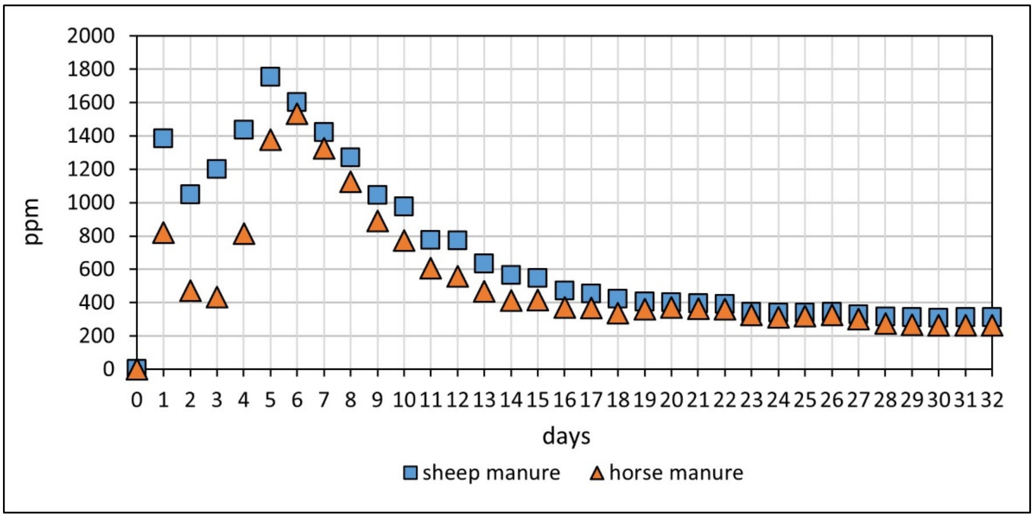

Figure 5. Hydrogen sulphide (H_2S) concentration in biogas produced from sheep manure and horse manure.

The analyzed scenarios of biogas plant operating systems, apart from Scenario 3, did not differ significantly in terms of energy consumption resulting from the feedstock preparation. In Scenarios 1, 2, and 4, the energy for feedstock preparation constituted 6–9% of the net energy produced in the biogas plant. In Scenario 3, the energy used for feedstock preparation was much lower than in other scenarios (Table 4); however, it accounted for 24% of the net energy produced by the biogas plant.

Table 3. Energy balance of small-scale agricultural biogas plant.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	SM, HM, GCS	SM, HM, GCS	SM, HM	SM, HM, MS
Methane production, $m^3 \cdot y^{-1}$	83,764	83,764	19,945	82,515
Electric power installed, kW_{el}	37	37	37	37
Gross electricity produced, $MWh \cdot y^{-1}$	284.2	284.2	67.7	279.9
The internal electricity consumption in the biogas plant, $MWh \cdot y^{-1}$	20.2	51.4	37.6	44.6
Net electricity produced, $MWh \cdot y^{-1}$	264.0	232.8	30.1	235.3
Gross thermal energy produced, $GJ \cdot y^{-1}$	1300	1300	316	1308
The internal thermal energy consumption in the biogas plant, $GJ \cdot y^{-1}$	471	471	237	271
Net thermal energy, $GJ \cdot y^{-1}$	829	829	79	1037

SM—sheep manure, HM—horse manure, GCS—grass-clover silage, MS—maize silage.

Table 4. Annual energy production and demand in a small-scale agricultural biogas plant.

Energy	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Net energy produced in the biogas plant, GJ	1779	1667	187	1884
Energy for feedstock preparation, GJ	151	151	45	112
Energy consumption for feedstock preparation, %	8.5	9.1	24.3	5.9

The estimated CO_2 emissions differed among the analyzed scenarios (Table 5). The low CO_2 value calculated for Scenario 1 resulted from an incorrect working time of individual engines in the biogas plant given in the design assumptions. In all other scenarios with the new feeding and grinding system, CO_2 emissions were much higher. Lower CO_2 emissions were calculated for Scenario 4 due to lower demand for electricity for feeding since MS is fed faster to the fermentation chamber than GCS. Lower demand for diesel oil for MS transportation to biogas plant also decreased CO_2 emissions.

Table 5. Annual CO_2 emissions in a small-scale agricultural biogas plant.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
CO_2 emissions, kg CO_2	33,593	54,355	30,517	46,845
CO_2 emissions, kg $CO_2 \cdot GJ^{-1}$	19	33	163	25
CO_2 emissions, g $CO_2 \cdot kWh^{-1}$	127	233	1015	199
Avoided CO_2 emissions through electricity production from biogas, kg CO_2	184,289	162,517	20,977	164,306
Avoided CO_2 emissions through thermal energy production from biogas, kg CO_2	78,475	78,475	7461	98,222

5. Discussion

The concept of AD of agricultural waste and by-products in small-scale biogas plants has unquestionable advantages. Many small- and medium-size farms in Europe cannot adopt large centralized AD biogas plant configurations due to high demand for feedstock, high investment costs and uneconomical biomass transport costs [23]. Small-scale agricultural biogas plants, adapted to the size structure of European agriculture, can be an exciting energy solution to support the economic development of rural areas and contribute to energy security. However, small-scale plants cannot be based on feedstock from a single average rural farm of ~16 ha in Europe. Cost-effective solutions require feedstock from much larger farms, e.g., 75 kW_{el} biogas plant, depending on the proportion of manure and/or other solid feedstock to the slurry, requires from 80 to 215 livestock units [45].

Most of the studies revealed that small-scale biogas plants suffer from leakages from reactors leading to undesired CH_4 emissions, solid digestate incrustation floating in the main tank resulting in low biogas production [46], low-quality construction, and low biogas production [34]. In our study, the biogas plant suffered mostly from low-quality construction of grinding and feeding system, which also after the replacement did not function properly. Design errors and equipment failures were also revealed as problem often occurring in small-scale biogas plants in literature [32,33]. In our case study, the design error in energy demand did not allow to implement better grinding and feeding systems. Therefore, unlike similar biogas plants, the main possible change was the feedstock and AD technology.

Our study described the agricultural biogas plant operating on the feedstock with varied parameters. The TS content and TKN content in studied CS was lower than that given in the literature [47,48], while the TP content was similar to the values reported by Grześkowiak [42] and higher than the concentration given by Grabowski [48]. The K content of the studied CS was in the range of values reported in the literature [47,48].

The TS content of the studied HM was similar to the value given by Zhang et al. [49] and Chastain [50], but much lower than the results obtained by Grabowski [48]. The TKN content in HM obtained in this study was similar to the value given by Chastain [50], while much lower than Grabowski's [48] results. The TP content of the studied HM was lower than the values given in the literature [48,50], while the K content was lower than the results given by Grabowski [48] but within the range shown by Chastain [50]. The TOC content was similar to that given in the literature [49,50].

The chemical composition of SM in our study, except for TP, differed from the values given by Pérez-Luna et al. [51] based on a literature review. The SM chemical composition was in the range Ansah et al. [52] gave; only the TOC content was much higher in the studied SM. It must be emphasized that TS and nutrient composition variability within every type of studied organic materials is very high [53] and depends on the fodder type and rate, housing type, animal age, and waste management, in the case of both solid and liquid manure [54].

The TS content of the studied GCS was much higher than the values given in the literature. Typically, the TS content of GCS ranges between 24 and 41% [55–57]. However, the VS content of the studied GCS was similar to the values reported by Naadland et al. [56]. The TP content in studied GCS was lower than results reported by Vanhatalo et al. [55], who found the TP concentration in GCS equal to 3.0 $g \cdot kg_{DM}^{-1}$.

Both C:N and N:P ratios represent the feedstock's amount of carbon, nitrogen, and phosphorus. In general, the microbes in the digester use C as a structural unit and source of energy and utilize it 25–30 times faster than N, which facilitates the synthesis of amino acids, proteins, and nucleic acids [58]. Therefore, efficient biogas production requires the C:N ratio in feedstock equal to 20–30 [59,60]. The C:N ratios of CS and SM are too low, meaning that these feedstocks are rich in nitrogen, which is typical for manures. This may lead to ammonia accumulation in the digester, increasing the risk of ammonia inhibition of biogas production since ammonia is toxic to methanogens [61]. Only the C:N ratios of HM and GCS are in the range required for proper AD. The N:P ratio in the studied feedstock is higher than the optimal ratio in anaerobic digestion (3:1) [62].

Manure characteristics depend on feed amount and type, amount and type of bedding material in indoor housing, outdoor residence time, outdoor regime collection, manure storage type, and time [63]. Those several factors may significantly influence the SMY from HM. The manure obtained for this study was taken from the stable. The horses are fed for meat production and kept in a stable, partially grazed outdoor. Methane yield from HM, obtained in this study, was slightly higher compared to results reported by Böske et al. [64], who obtained the SMY from HM with wheat straw as bedding material equal to 235.4 NL $CH_4 \cdot kg_{VS}^{-1}$ in case of horses fed with hay, and 222.6 NL $CH_4 \cdot kg_{VS}^{-1}$ in the case of horses fed with silage. Lower results (164–208 NL $CH_4 \cdot kg_{VS}^{-1}$) were also reported by Mönch-Tegeder et al. [65] for fresh HM in a bedding system with straw. Other materials used for horse bedding, except straw pellets and straw with flax, decreased the SMY of HM to 104–150 NL $CH_4 \cdot kg_{VS}^{-1}$. The stored manure had even lower SMY ranging from 128 NL $CH_4 \cdot kg_{VS}^{-1}$ to 196 NL $CH_4 \cdot kg_{VS}^{-1}$ for straw bedding systems [65]. In the solid phase digestion system, the SMY of HM is much lower, as reported by Kusch et al. [66], and is equalled to 170 NL $CH_4 \cdot kg_{VS}^{-1}$.

The SMY of SM obtained in this study was lower compared with cumulative methane production given by González et al. [67], who observed SMY equal to ~300 NL $CH_4 \cdot kg_{VS}^{-1}$. However, Kozłowski et al. [68] reported SMY equal to 223.44 NL $CH_4 \cdot kg_{VS}^{-1}$, slightly lower than this study's result. The differences in SMY may be the result of BMP assumptions as well as the characteristics of manure.

Biogas production may be ceased through the inhibitors introduced to the biogas plant with feedstock or released during digestion. The H_2S is one of the gaseous inhibitors released during the AD process, and this gas is of particular concern as it is abundantly found in agricultural biogas [69]. The H_2S concentration ranges from 50 ppm to 10,000 ppm depending on the feedstock and AD technology [70]. The decomposition of sulphur-containing compounds such as amino acids, sulphoxides, and sulphonic acids, is the source of high H_2S concentration in biogas. This gas is also produced during the biological reduction of sulphates in the feedstock. H_2S can diffuse through cell membranes and causes denaturation of proteins, thus disturbing the metabolism of microorganisms and decreasing methane production [71]. High H_2S concentration not only decreases CH_4 production but also negatively affecting the installation and engine in a biogas plant. H_2S is acidic gas that, together with water in biogas, creates the condensate, causing the installation's corrosion and negatively affects the engine's working condition [72,73]. The H_2S content in biogas should be low, but the threshold values depend on the different applications. The lowest (<4 ppm–10 ppm) H_2S content in biogas is required when gas is used as natural gas, while the highest threshold value (<70,000 ppm) is acceptable if biogas is used in microturbines [74]. Commonly used in biogas plants, CHP engines can operate only when the H_2S content in biogas is below 500 ppm [75,76]. Therefore, this gas is removed in all biogas installations through several technologies such as adsorption into liquid or on a solid and by biological conversion by sulphide oxidizing microorganisms with the addition of air or oxygen [70].

In our study, the lowest values of daily H_2S concentration in biogas were 265 ppm and 313 ppm for HM and SM, respectively. They were similar to the results reported from cow manure [77]. The maximum H_2S concentration reached the value of 1534 ppm for HM and 1755 ppm for SM and was higher than that reported for cow manure [77]. Much lower values, up to 338.65 ppm, were reported for semi-continuous anaerobic digestion of cow manure and corn stover [78]. However, Lund et al. [79] reported a much higher H_2S concentration in a range of 1750–2100 ppm in semi-continuous anaerobic digestion of mixture including pig and cow manure with household waste. The study of biogas production from chicken manure in a continuously stirred anaerobic digester revealed the H_2S concentration in the range of 600 ppm to 8500 ppm [80], which is a much higher value than that obtained in our study. Contradictory to the finding of Sürmeli et al. [80], the H_2S content in biogas produced from poultry litter reused for seven consecutive cycles of broiler rearing was low and ranged from 65 ppm to 82 ppm [81].

The environmental impact of biogas production may be analyzed concerning GHG emissions, atmospheric pollution emissions, acidification, or eutrophication. In our study, only the direct CO_2 emissions were analyzed. The calculations included CO_2 emitted from diesel oil and electricity used for feedstock production, preparation, and operation in a biogas plant. The system boundaries included the maize and grass-clover silage production, including cultivation, harvest, transportation, and ensilaging the material. These assumptions, however, limited the CO_2 emissions only to fuel and electricity used for feedstock preparation and biogas plant operations and, at the same time, decreased the calculated CO_2 emissions. In the case of SM and HM, only fuel consumption for manure transportation and loading to the grinding and feeding system was considered. If the indirect energy demand (machines production, material production, human labor) was included in the calculations, the overall energy demand for feedstock production and preparation and the resulting CO_2 emission would be much higher. The most significant increase in CO_2 emissions would concern Scenario 4, which assumes MS as feedstock since indirect energy demand and related GHG emissions from maize cultivation almost double the direct energy demand and GHG emissions from fuel used for maize production [82]. In our study, the CH_4 emissions were not taken into account; however, in studied biogas plant the leakages which may enhance the total GHG emission were not noted. In poorly managed biogas digesters with unproper distribution system for biogas CH_4 can be released through. Such leakages may be as high as 40% and therefore small-scale biogas plants could contribute significantly to global emissions of CH_4 [83].

Some Life Cycle Analysis (LCA) studies have assessed the environmental impact of biogas plant operations; however, comparing the results is difficult due to variability in LCA approaches, assumptions, and boundaries. The variability in feedstock, biogas plant size, operating parameters, and technology, also hinder comparing the results. The allocation of environmental impacts is another critical issue differentiating the results [6]. Our study's results agree with Agostini et al. [10], who reported the lowest GHG emissions in biogas plant operated on manure, while in the crop-based system, the sorghum-operated biogas plants were more sustainable than the maize-based system since maize cultivation was more intensive. The GHG savings from biogas electricity production may be as low as 3% for maize silage, while in the case of manure as feedstock, the GHG saving can be up to 100% [10]. In our study, most CO_2 emissions in Scenario 4 come from fossil fuels used for maize cultivation, collection, and transportation. Higher CO_2 emissions in Scenario 2 are related to a higher amount of grass harvested and transported to the biogas plant to produce the same amount of energy as from MS. Bedoić et al. [20] reported a similar situation comparing the GHG emissions from biogas plants operated on MS and the co-digestion of naturally grown grasses with MS. High GHG emissions from grass collection resulted from the high input of fossil fuels for grass harvest and baling and the transportation of higher amounts of grass compared to maize to produce the same energy since SMY of grass silage was lower than that of MS [20].

Our results show that the CO_2 emissions from feedstock preparation and biogas plant operation are much lower than that which can be avoided by replacing the fossil fuel energy for the electricity and heat produced from biogas. A similar finding was given by Yao et al. [84], who calculated a high reduction of GHG emissions from usual manure management through AD. Zhang et al. [21] also concluded that the AD of pig manure decreased direct GHG emissions compared with the direct land application.

An essential step in the analysis of biogas production sustainability is digestate utilization. However, the results of various studies are contradictory. According to Gómez-Camacho et al. [85], the availability of sufficient land to spread digestate on the field is essential to ensure the sustainability of AD technology. Timonen et al. [4] reported that the digestate storage, transportation, and application on the arable field generated higher emissions than mineral fertilizer utilization. However, the combined emissions of AD allocated for digestate and emissions of the digestate application on the arable field were lower than mineral fertilizer production and use on the field.

Nevertheless, the most significant GHG emissions of digestate were from digestate application on the field as fertilizer. The contradictory results were reported by

Duan et al. [86], who demonstrated that digestate utilization on the field was the most environmentally favorable option. In our study, digestate was assumed to be stored in a tightly covered tank and separated into liquid and solid phases. Liquid digestate was assumed to be used for the dilution of manure and silages. The storage and application of solid digestate were not included in the present study. This assumption also influenced the results since high emissions from digestate storage and application were omitted.

6. Conclusions

In this study, the problems occurring in small-scale agricultural biogas plant with a CHP unit of an installed electrical power of 37 kW_{el} were described. Four scenarios based on various feedstock and AD technology were analyzed and used for the calculations of energy balance and CO_2 emissions from biogas production in real conditions (Scenario 1, 2, and 3), and with theoretical assumptions for studied installation in Scenario 4. The results revealed that lignocellulosic feedstock in the form of GCS or MS is necessary to achieve the proper energy balance; however, the replacement GCS with MS would not only solve the problem with feeding but also would improve energy balance. Despite, the analyzed scenarios, the CO_2 emissions were low and much below the level of emissions avoided by replacement of energy from fossil fuels by energy from biogas. In the case of studied biogas plant, Scenario 4 seems to be the best option adjusted to the operational conditions and farm's energy demand. Compared to a biogas plant operating based on design assumptions, the biogas plant operating on manure and maize silage adopted as Scenario 4 characterizes with better energy efficiency, a higher reduction of CO_2 emissions, and less demand for the land area for energy crop cultivation, which means that more area can be used for food production.

Small-scale agricultural biogas plants should be more prevalent in Europe, adjusted to the small amounts of feedstock and farm-scale demand for energy. The installed electrical power in such small-scale biogas plants should meet the demand of one farm in terms of electricity and heat. At the same time, they supply the farm with energy and digestate, which is a valuable fertilizer, and when applied on farm arable land introduces the circular economy to agriculture on the farm scale.

The results of this study draw attention to careful calculations and sound recognition of the nature and parameters of feedstock in small-scale biogas plants. Such an approach would also reduce the costs associated with adapting the described biogas plant to the feedstock, which should be used according to the technical assumptions. Our studies revealed that the feeding system may be the most troublesome in small-size agricultural biogas plant. Agricultural family biogas plants must be flexible in terms of technology and equipment since physical parameters of feedstock used by operators can be very different. Further studies on economically justified pretreatment technology, which allows better performance of small-size biogas plants, are needed.

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