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Anaerobic Digestion as a Component of Circular Bioeconomy—Case Study Approach

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Abstract: Current and future trends in the world population lead to the continuous growth of municipal waste volumes. Only in the EU-28 approx. 86 million tons of biowaste is produced yearly. On the other hand, the recent energy crisis calls for a fast transition towards more local and renewable energy sources. Most of this stream could be recycled through anaerobic digestion (AD) to produce energy and high-quality fertilizers. This paper presents a balance of dry anaerobic digestion of municipal biowaste based on three years of system monitoring in an industrial-scale AD plant. The results indicate that the average biogas production rate of 120 Nm^3/ton of fresh waste can be achieved. Biogas utilization in combined heat and power (CHP) units leads to an overall positive energy balance at significantly reduced CO_2 emissions. The overall CO_2 emission reduction of 25.3–26.6% was achieved, considering that biogas utilization is environmentally neutral. Moreover, biowaste conversion allows digestate production to substitute mineral fertilizers in agriculture and other applications. It is beneficial for soil protection and a broader environmental perspective.

Keywords: bioenergy; biogas; fermentation; fertilizer; greenhouse gas; waste management; zero waste

Citation: Seruga, P.; Krzywonos, M.; den Boer, E.; Niedźwiecki, Ł.; Urbanowska, A.; Pawlak-Kruczek, H. Anaerobic Digestion as a Component of Circular Bioeconomy—Case Study Approach. *Energies* **2023**, *16*, 140. https://doi.org/10.3390/en16010140

Academic Editors: Margarida Gonçalves and Cândida Vilarinho

Received: 17 November 2022
Revised: 14 December 2022
Accepted: 21 December 2022
Published: 23 December 2022

1. Introduction

The circular economy (CE) and bioeconomy (BE) concepts are prevalent within the European Union (EU) and other parts of the world as new business models to achieve sustainability [1]. However, there is still a lack of consensus about their universal interpretation. Kirchherr et al. [2] defined CE as "an economic system that is based on business models which replace the "end-of-life" concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes." Ellen MacArthur Foundation considers it "a systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution" [3]. However, it can be concluded that CE is a system governed by the following main principles: design to minimize waste and pollution generation; lifetime expansion of materials and products with reuse, regeneration, and recycling; as well as the usage of renewable resources. It was assessed that CE could halve emissions in the food sector, i.e., by $5.6.10^9$ tons of CO_2 in 2050, followed by economic benefits of 700 billion dollars [4]. In comparison, BE can be defined as a "production model based on biological resources and on innovative biological processes and principles to provide sustainable goods and services in all economic sectors" [1].

Nevertheless, the CE and the BE are seen as primarily resource-oriented and therefore could not be equated with the wider concept of sustainable development [5]. Thus, a new circular bioeconomy (CBE) concept is gaining the attention of researchers [1]. Carus et al. [6] defined CBE as the crisscrossing between BE and CE and emphasized that vast amounts of biowaste can be assimilated into CE through BE. In contrast, the BE will gain from increased circularity. Thus, CBE should keep them at the maximum value, ensuring the preservation of natural capital. With a 34% share, biowaste is the mainstream of municipal solid waste (MSW) in the EU; of which 60% is food waste [7]. The most common treatment processes for biowaste in the EU are composting or anaerobic digestion. When this waste is landfilled, it negatively impacts the environment because of greenhouse gasses released and leachate generation [1].

Furthermore, Europe is currently facing a significant energy crisis caused by global energy consumption growth and the geopolitical situation. This crisis results in a return to energy production based on fossil fuels and an increase in energy commodity prices, contrary to CBE. It also shows the increasing environmental pollution and the growing depletion of fossil fuels [8]. Thus, the implementation and development of renewable energy sources have become essential nowadays. Waste management and renewable energy policies should support the use of bioenergy from properly managed biowaste.

Various methods have been applied to treat biowaste, including biological (anaerobic digestion and composting [9]) as well as thermochemical technologies (gasification [10] and hydrothermal treatment [11]). The treatment method should be matched to the type of waste and its technological properties. Composting and anaerobic digestion are commonly applied among the developed biowaste treatment pathways.

The composting is conducted under aerobic conditions, leading to the mineralization and humification of biomass. The generation of stable humic substances is coupled with the oxidation of a portion of organic matter to carbon dioxide, water, nitrates, phosphates, and sulfates [12,13]. It allows for obtaining valuable biofertilizers. However, the energy cannot be efficiently recovered. Biogas, in contrast, can be easily utilized as a renewable energy source and thus contribute to the de-carbonization of the heating, transport, and gas sectors.

The AD allows for both energy recovery and organic recycling. The most suitable AD technology should be chosen according to the type of feedstock, dry matter content (wet or dry), and other factors, such as required process temperature or available space. According to The European Biogas Association, there have been 18,943 biogas plants and 725 biomethane plants reported in Europe in 2019, which produced 15.8 billion cubic meters of biogas and 2.43 billion cubic meters of bio-methane [14]. AD can be a technological pathway to treat biowaste and sewage sludges and produce bioenergy [15]. Wet AD is widely applicable and well known; dry AD is still challenging for industrial application [16]. Dry fermentation with a high organic load has gained a lot of interest in recent years [17], but its effective use still requires further research, mainly in collaboration with existing installations, which are quite limited in number. Only several studies so far analyzed the techno-economic and environmental parameters of bioenergy and fertilizer production in dry AD technology [17]. Dry AD offers an attractive option for the treatment of waste with low moisture content [18]. This work focuses on a high solid AD exploitation data and thus fits well in this research gap. Furthermore, the presented insight into the operational parameters of AD technology could support decision-making processes toward the broader adoption of this technology and expansion of biowaste-based energy and material cycling [19].

In Europe, the production of biogas and bio-methane is mainly based on animal waste and manure, as well as green waste and food waste [8,20]. Biomass is found as the most significant renewable resource which could substitute the use of fossil fuels [21]. Among biomass, biowaste should be a considerable resource widely used for biogas production.

Among biowaste, those originating from the organic fraction of MSW or household waste have already been studied to a large extent [22], including our previous research [23].

However, still, some gaps exist in this area. For instance, in many developing countries, environmental encumbrance is caused by, e.g., poor collection, lack of pretreatment, or improper disposal [24,25]. Improper biowaste management causes an increase in greenhouse gas (GHG) emissions and soil and groundwater contamination [26].

The existing waste management systems and facilities face the challenge of balancing population growth and sustainable waste treatment to meet regulatory limits. Many countries worldwide, including the European Union, set goals to reduce waste disposal; and increase recycling rates, converting biowaste to value-added bioproducts [26]. The digestate obtained after AD can be used as a biofertilizer for agricultural applications and substitute chemical fertilizers [27,28]. AD can be applied to process biowaste in accordance with the overall zero-discharge biowaste treatment concept [29]. It can also be stated that the resultant bioenergy complies with sustainability principles and the concepts of circular economy, zero waste, and the overall requirements of the European environmental protection policy.

The MSW generation is still growing in most European cities despite efforts to reduce it [30]. The amount of municipal biowaste in 2017 in the EU-28 was estimated at 86.10^6 tons per year [31]. Household and garden biowaste represented 60% and 35% of this volume, respectively [31]. Nowadays, separate waste collection is considered the best management method [32]. Source segregation of biowaste is developing fast in Europe [33]. However, a significant discrepancy in waste treatment facilities among the EU countries exists, which is evidence of a gap in this area.

It Under the current biowaste collection obligation a significant potential of bio fertilisers for agriculture can be expected. If the biowaste is not collected at the source, mechanical–biological treatment (MBT) is applied to recover the organic fraction. Our previous research has proven that the agricultural usage of digestate produced from the mechanically separated organic fraction is limited [23]. Thus, only the AD of source-segregated biowaste meets the CE principle.

In Germany, there are about 10,000 biogas plants, while in Poland only 130 biogas plants are currently operated, although the population of Poland is only about two times smaller than the German one. Furthermore, in Poland so far, only one biogas plant treats separately collected biowaste. Based on the data obtained from this specific biogas plant, the authors would like to support the development of anaerobic digestion in Poland and fill the research gap in this area.

This study aims to present the balance of a full-scale operated biogas plant, including the quantity of treated waste, quantity, and quality of obtained biogas, amount of generated energy and heat, quantity and quality of generated digestate, as well as carbon dioxide reduction rate due to energy production in combined heat and power units in compliance with the novel circular bioeconomy concept.

2. Materials and Methods

2.1. The Research Conditions Uner Full-Scale Operation

The waste treatment plant, located in Lower Silesia Region in Poland, was selected for the presented research. It processes waste from 16 communes, coveringabout 260,000 inhabitants. The anaerobic biological treatment stage consists of two Kompogas® chambers of 1500 m^3, each, operated under thermophilic conditions (54 °C). The agitation speed has been set at 0.4 rpm during 300 s operation period, and 100 s break intervals, with alternating directions. One of the chambers has been fed by the mechanically sorted organic fraction of MSW derived from the sorting area.

The other chamber, the first of this type in Poland, has been dedicated to processing separately collected biowaste. The operational scheme of the plant is presented in Figure 1. The extraction pump operation time determines the digester's filling level (at about 1100 m^3). The digestate has been dewatered with screw presses (TSP350, Thöni, Austria) and stored for further soil application. The presented process parameters have been derived from the central control system, operated on a daily basis. The biogas has been used in two combined heat and power (CHP) units (Caterpillar CG132-12) with a capacity of 600 kWh, each. The plant processes around 16,000 tons of separately collected biowaste (such as food waste, kitchen waste, and green waste) per year. Data from the biogas plant processing biowaste has been collected and analyzed.

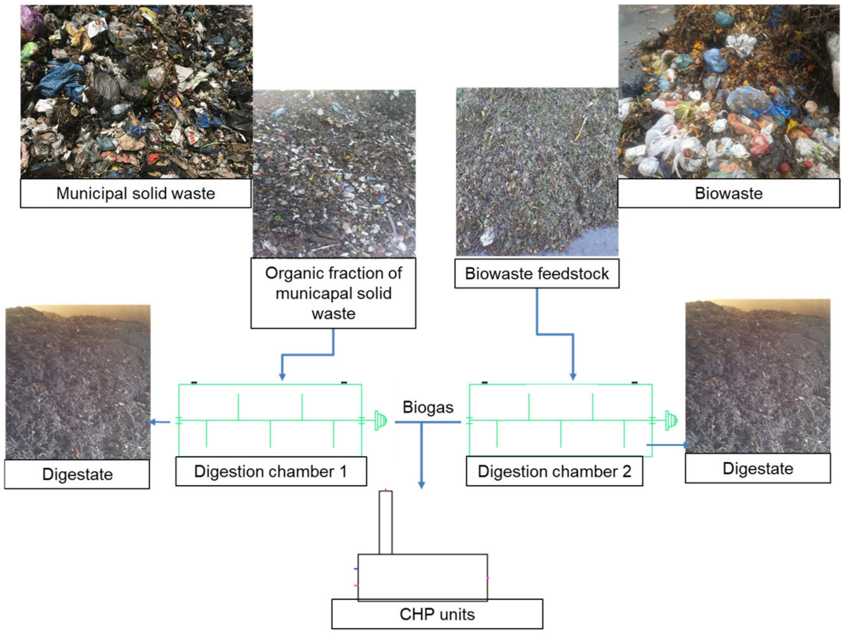

Figure 1. Simplified scheme of the anaerobic digestion facility.

2.2. Analytical Methods

The feedstock samples consisting of biowaste have been collected over a month. First, the daily sample has been prepared by collecting 10–15 kg samples at about 60 min. intervals. Then, the daily samples collected over a week have been mixed and averaged to get one weekly sample of approx. 100 kg each. The composition, including 11 main material fractions: organics, wood, paper, plastics, glass, metals, textiles, composites, inerts, hazardous, and other waste of a fine fraction, has been determined. Finally, the average values based on the weekly samples were reported. The operation data from the analyzed biogas plant have been collected from 2019 to 2021.

The chemical analyses have been conducted on dried samples (dried at 105 °C for 12 h). The samples were analyzed in three replicates. Average values were reported.

The digestate obtained after AD was characterized with respect of its application as a soil amendment. The heavy metals: chrome (Cr), phosphorus (P), cadmium (Cd), nickel (Ni), lead (Pb), potassium (K), and mercury (Hg) were determined using the PN-EN 16319 + A1:2016-02 and PN-EN 15960:2011 standards. An atomic emission spectrometer with inductively coupled plasma (ICP-AES), Shimadzu ICPE-9820 (Shimadzu, Kyoto, Japan), has been used for their content determination. Samples were digested in nitric acid (HNO_3) and hydrochloric acid (HCl) in the ratio of 3:1(v/v), The total organic carbon (TOC) was determined following the standard PN-EN 13137:2004, using Vario TOC Cube (Elementar Analysensysteme GmbH, Langenselbold Germany). The suspended solids (SS), dry organic mass, and pH were determined using standard methods [34].

The content of fatty acids was determined by gas chromatography (Varian GC 450) with an FID detector (H2: 30 mL/min, air: 300 mL/min, He: 30 mL/min). Helium (constant flow through the 1 mL/min column) was used as the carrier gas, 1:30 split.

The acidity and alkalinity were determined by pH-metric titration according to standard methods [34].

The biogas analyzer (DP-28, Nanosens, Tarnowo Podgorne, Poland) was used to determine methane content, carbon dioxide, hydrogen sulfide, oxygen, and ammonia. Average values have been reported.

2.3. Carbon Dioxide Emission Reduction—Calculation Method

For verification of the carbon dioxide (CO_2) emission reduction, authors compared CO_2 emissions (a) from the usage of (renewable) biowaste for power generation in CHP units (final emission) and (b) from electricity purchased from the grid (basic emission) in the analyzed biogas plant.

For the reduction calculation, the authors adopted the Clean Development Mechanism (CDM) Small Methodology [35] and proposed the following Equation (1):

$$\text{Rey} = ((\text{Eby} - \text{EPy})/\text{EBy}) \times 100\% \quad (1)$$

where:

REy—yearly emission reduction,
EBy—yearly basic emission, calculated according to Equation (2)
EPy—yearly final emission, calculated according to Equation (3).

$$\text{Eby} = \text{WE}_{\text{CO2}} \times \text{EE} \quad (2)$$

where:

EBy—yearly basic emission,
WE_{CO2}—emission factor of purchased electricity from the grid (kg_{CO2}/MWh),
EE—the total quantity of purchased electricity (MWh).

$$\text{EPy} = [(\text{WE1}_{\text{CO2}} \times \text{EE1}) + (\text{WE2}_{\text{CO2}} \times \text{EE2})] \quad (3)$$

where:

EPy—yearly final emission,
$WE1_{CO2}$—emission factor of electricity produced in CHP unit (kg_{CO2}/MWh),
EE1—the total quantity of electricity produced in CHP unit (MWh),
$WE2_{CO2}$—emission factor of purchased electricity from the grid (kg_{CO2}/MWh),
EE2—the total quantity of purchased electricity (MWh).
$WE2_{CO2}$ and EE2 were applied because the CHP unit did not cover all electricity demand.

3. Results and Discussion

3.1. Waste Treatment

The biogas plant under study has been designed to treat non-segregated municipal solid waste, which once constituted more than 85% of the total waste stream. Subsequently, a separate collection system has been implemented in the analyzed area, according to the Minister of the Environment Regulation of 7 October 2019. Five fractions are required to be collected separately, including: metals and plastics, paper, glass, biowaste, and residual/mixed waste [36]. The biowaste fraction includes both food waste and green waste. The separate collection implementation has recently been enlarged [37]. Since 2019, the biogas plant under study has processed about 110,000 tons of waste yearly. The decrease in non-segregated waste share (from about 60% in 2019 to about 52% in 2021) and an increment in biowaste (to over 25,000 tons in 2021) were noticed. The biowaste treatment via anaerobic digestion has been started considering the changes in the collected waste stream.

The characteristic of AD feedstock obtained from biowaste is presented in Table 1. The fraction contents were similar to the results obtained in our previous study [38]; however, some improvement in the quality of the separately collected biowaste can be observed. It was noticed that the organic and wood contents were slightly higher (69.3% and 8.7%, respectively); however content of plastics increased (5.4%) due to the bag collection system in the analyzed area. The presence of paper, plastics, glass, inert, and other fractions may indicate insufficient segregation by the inhabitants. Thus, still, the separate collection system should be improved.

Table 1. The composition of the separately collected biowaste.

Fraction	Mass Share
Organic (incl. green waste) (%)	69.3 ± 4.9
Wood (%)	8.7 ± 1.1
Paper (%)	1.3 ± 0.2
Plastics (%)	5.4 ± 0.7
Glass (%)	0.9 ± 0.4
Inert waste (%)	1.1 ± 0.7
Textiles (%)	0.1 ± 0.1
Metals (%)	0.1 ± 0.1
Hazardous (%)	0.1 ± 0.1
Tetra Pak (%)	0.1 ± 0.1
Others (%)	0.3 ± 0.1
Fine fraction 0–15 mm (%)	11.7 ± 2.5

The exploitation data from the AD plant is presented in Table 2 and Figure 2. Based on the exploitation data of the biogas plant, the AD of biowaste was found to be a stable process. For instance, the volatile fatty acid concentrations reached around 1.2 g/kg, indicating a stable biogas production [39]. The pH value remained stable in the analyzed period and amounted to 8.3–8.4 at the initial part of the reactor, with a slight increase to 8.6 at the end of it. Dry matter content and ammonium ion concentration remained stable at 33–35% (Figure 2c) and 4.0–4.8 $g_{NH4\text{-}N}$ g/kg (Figure 2d), respectively. Moreover, acidity and alkanility remained stable (Figure 2e,f), and their ratio did not exceed 0.2. These values correspond with stability limits for parameters characterizing the biogas process [40]. The hydraulic retention time was around 36 days.

Table 2. The exploitation data from the analyzed biogas plant in 2019–2021.

Parameter	Year			Changes in Parameters	
	2019	2020	2021	2020–2019	2021–2020
AD feedstock volume (tons)	20,347	23,294	23,473	14.5%	0.8%
Generated biogas (m^3)	2,598,983	2,724,955	2,724,717	4.8%	0.0%
Electricity generated in CHP-units (MWh)	5101	5558	5545	9.0%	−0.2%
Purchased electricity from the grid (MWh)	703	678	716	−3.7%	5.6%
Consumed electricity (MWh)	4443	5184	4881	16.7%	−5.8%
The heat generated in CHP units (GJ)	6194	6418	6802	3.6%	6.0%
Consumed heat (GJ)	3595	4267	3272	18.7%	−23.3%
Digestate volume (m^3)	19,534	21,506	21,364	−4.6%	−0.7%

Figure 2. The monthly exploitation data from analyzed biogas plant in 2019–2021: (**a**) AD feedstock mass; (**b**) digestate volume; (**c**) dry matter content; (**d**) ammonium nitrogen ions concentration; (**e**) acidity; (**f**) alkalinity.

Compared to 2019, about a 14.5% increment in treated waste was noticed (Figure 2a, Table 2). Reason for that was the implementation of a biowaste separate collection system. The "door-to-door" in the case of rural and single-family housing and collective waste bins regarding multi-family housing. Due to different collection systems, some disproportions in the quality of collected waste were noticed. Waste from the shared containers was much more contaminated, i.e., the biowaste from multi-family housing contained over 30% plastics and glass. Furthermore, in the summertime, the available feedstock mass increment was noticed due to the combined collection of food waste and green waste.

3.2. Electricity Balance—Biogas Utilization

Since 2020, the company has processed about 23,000 tons of biowaste yearly, obtaining over 2.7 million cubic meters of biogas (Figure 3a); this resulted in an increment of annual electricity production in the CHP units at the level of about 5500 MWh (Figure 3b). The main biogas utilization systems are the production of heat, electricity production, and CHP [41]. According to [42], heat generation dominates in low-income countries, while CHP plants dominate in high-income countries.

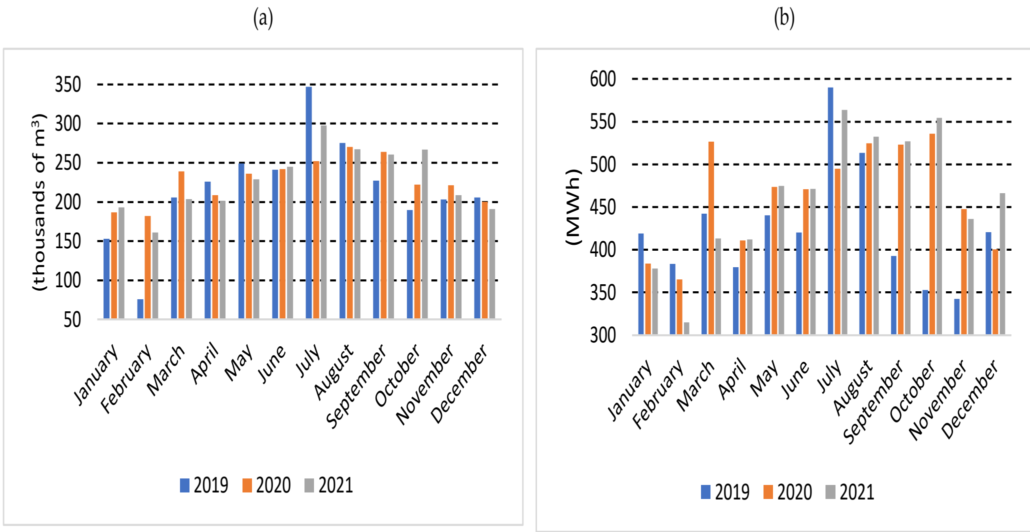

Figure 3. The monthly exploitation data from the analyzed biogas plant in 2019–2021: (**a**) generated biogas; (**b**) electricity generated in CHP units.

In this study, the generated electricity was sufficient to cover plant needs; however, some electricity was purchased due to CHP-units maintenance breaks. Surplus energy was sold, and the system could reduce fossil fuel electricity. The biogas plant heat and electrical requirement is about 22% of the energy produced for dry AD [43]; however, many factors influence energy production, e.g., feedstock supply and quality, local conditions, and plant operation.

The average biogas yield was about 116 m^3/ton, which is slightly higher than the results reported by other researchers [44]. The composition of biogas is presented in Table 3 and was similar as similar to that in the literature [41]. The methane content in biogas was about 58%, directly affecting the production of electricity in CHP units. The methane concentration in biogas is usually between 50% and 65% [41]. Due to chemical adsorption, the hydrogen sulfide content was kept at about 125 ppm (Table 3). Although present only in traces, the biogas contaminants, mainly H_2S and siloxanes, can damage the engines, heat exchangers, and other fittings. Thus, the biogas should be purified to avoid corrosion problems [45]. During the combustion process, corrosive acids such as H_2SO_4, HCl, and HF the H_2S can be formed [41]. The O_2 content did not exceed 0.2% (Table 3), which confirms there were no leaks in the facility.

Table 3. The biogas characterization.

Parameter	Content
Methane (CH_4) ($\%_{vol}$)	58.0 ± 3.0
Carbon dioxide (CO_2) ($\%_{vol}$)	39.0 ± 3.0
Ammonia (NH_3) (ppm)	190.0 ± 15.0
Hydrogen sulfide (H_2S) (ppm)	124.0 ± 20.0
Oxygen (O_2) ($\%_{vol}$)	<0.2

3.3. Digestate and CO_2 Emission

The digestate obtained after AD should be useful as a soil amendment to fulfill the organic recycling goal and to comply with the CBE principles and should aim to replace mineral fertilizers [46]. Long-term usage of inorganic fertilizers causes water pollution and soil structure degradation [47]. In contrast, organic fertilizers might improve these soil parameters [48]. The digestate valuableness was determined by law regulations at the European [49] and country levels [50,51]. The biofertilizer must firstly be safe from the sanitary standpoint and plant-toxicity perspective and, secondly, enrich the crops. The organic matter (OM) of digestate reached 34.7%, which meets the minimum requirements (30%) [50] (Table 4). Moreover, the contents of nitrogen, carbon, and phosphorus and their balance are essential [52]. The analyzed digestate also fulfilled these requirements (Table 4). Moreover, heavy metal contamination is crucial to ensure the safe fertilization of crops [53]. The examined digestate fulfilled the requirements (Table 4).

Table 4. The digestate derived from biowaste characterization.

Parameter	Digestate	Polish Required Levels [21]	EU Required Levels [19]
Metal Contents			
Cadmium (Cd) (mg/kg $_{\text{dry matter}}$)	0.42 ± 0.08	Max. 5	Max. 1.5
Chrome (Cr) (mg/kg $_{\text{dry matter}}$)	31.2 ± 6.0	Max. 100	Max. 100 *
Lead (Pb) (mg/kg $_{\text{dry matter}}$)	31.2 ± 6.0	Max. 140	Max. 120
Mercury (Hg) (mg/kg $_{\text{dry matter}}$)	<0.1	Max. 2	Max. 1
Nickel (Ni) (mg/kg $_{\text{dry matter}}$)	22.3 ± 4.0	Max. 60	Max. 50
Nonmetal Contents			
Organic matter ($\%_{\text{dry matter}}$)	34.7 ± 2.8	Min. 30	-
Phosphorus (P_2O_5) ($\%_{\text{dry matter}}$)	0.59 ± 0.04	Min. 0.2	Min. 1
Total organic carbon (TOC) ($\%_{\text{dry matter}}$)	17.2 ± 2.4	-	Min. 5
Total nitrogen ($\%_{\text{dry matter}}$)	1.3 ± 0.2	Min. 0.3	Min. 1
Dry matter (%)	43.3 ± 2.9	-	-

* Hexavalent chromium (Cr VI) must not exceed 2 mg/kg $_{\text{dry matter}}$.

It should be mentioned that some researchers pointed out the hazard of digestates [54] and sewage sludges [55] application. The digestate usage may caouse potential environmental problems by, e.g., nutrient volatilization (i.e., nitrogen) [56]; moreover, odors may arise over storage, transport, and land spreading. The dry matter content affects the stickiness and viscosity, impacting crop application [52]. Thus, safetyits usage requires careful control. Moreover, sanitary safety is crucial. The biofertilizer cannot contain pathogens or toxins. Based on Regulation (EU) 142/2011, the absence of Salmonella in 25 g of a sample and the number of colony-forming units (CFU) less than 1000 of *Enterobacteriaceae* or *Enterococci* is necessary.

Considering biowaste AD performance, biogas yield, and digestate characterization, it can be assumed that AD allows for treating biowaste and recovery of by-products without causing environmental pollution, thus it complies with the concepts of circular economy and zero waste. Furthermore, with renewable energy generation and GHG reduction it addresses the goals of climate neutrality [57].

In this research, simplified CO_2 emission reduction (RE) was calculated and presented in Table 5. The yearly RE reached 26.6%, 25.7%, and 25.3% in 2019, 2020, and 2021 respectively. The obtained net CO_2 reduction can be related to a study [57], in which emission reduction by small-scale anaerobic digestion on Irish dairy farms has been investigated and described with the use of a non-linear model. All analyzed scenarios with dairy herd sizes exceeding 100 cows showed a net yearly CO_2 reduction between 2059 and 173,237 kg $_{CO2}$.

Table 5. The carbon dioxide emission reduction.

Parameter	Year			Changes in Parameters	
	2019	2020	2021	2020–2019	2021–2020
EB_y (kg CO_2)	3194.3	3618.4	3406.1	13.3%	−5.8%
EP_y (kg CO_2)	2343.3	2687.2	2546.3	14.7%	−5.2%
RE_y (%)	26.6	25.7	25.3	−3.4%	−1.8%

It should be mentioned that the current research was performed under Polish conditions, where the share of coal in electricity production in 2021 was at the level of about 72%, and the respective CO_2 emission factors for electricity production reached 719 kg per MWh in 2019, and 698 kk per MWh in 2020 [58]. Thus, every renewable energy source offers a great potential to reduce the gran house gas emissions. Furthermore, reduction in this study was calculated with consideration of purchased electricity. The surplus electricity, which was sold, was not considered; although, it reduced CO_2 generation by the other end users.

With respect to the above-presented outcome, the authors emphasize that potential leakage was not considered to simplify the calculations. E.g., the indirect GHG emission can occur in the form of transport emissions from the collection of biowaste to the treatment plant. However, the authors assumed that if AD was not used the waste had to be collected and treated by composting, which would result in adequate emissions from waste collection and storage because the MSW management system impacts the number of emissions. Baldasano and Soriano investigated different MSW systems and calculated emissions factors [59]. Their study has shown that GHG emission reduction commonly occurs in an integrated MSW management system combining various treatments as compared to one single process. Single landfilling resulted in 1.97 t eq. CO_2 generation of each MSW ton, while for a combination of processes like sorting, dry anaerobic digestion, and landfilling, the emission factor reached 1.42 t eq. CO_2/t MSW [59]. Kim et al. [60] analyzed operation data of CHP plants and boilers in Korea to estimate GHG reduction. The size of GHG reduction was, as in this study, calculated as an alternative effect of replacing fossil fuels. The decrease was higher in CHP plants than in boilers and 1.86 times higher than in CHP plants when calculating the GHG reduction per GJ of biogas fuel.

4. Conclusions

Stopping climate change is one of the most pressing challenges facing modern society. Dependence on importing raw fossil materials in the face of current geopolitical problems has made many European companies and municipalities face considerable increases in operating costs. In this context, it is obvious that the drive to maximize renewable energy in Europe's energy mix is an urgent need. Renewable energy sources are distributed sources as opposed to highly centralized conventional energy. The presented data clearly shows that using the methane AD process of municipal biowaste to obtain electricity is associated with a reduction in CO_2 emissions, compared to a basic scenario with conventional electricity generation by 25.3–26.6%. This is because CO_2 emissions from a renewable source, including biogas combustion, are not included in the sum of emissions, in line with the rules set out in the emission allowance trading scheme. The method of calculating CO_2 reduction assumes that some methane emissions take place at feedstocks and digestate storage. However, the national average emission factors used for this calculation are relatively high when compared to the reduction factors provided by the Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources. It is important to stress that biowaste, as opposed to energy crops, is considered sustainable biogas feedstock per the legislation mentioned above and the current energy policy.

Author Contributions: M.K. and P.S. conceived and designed the experiments; P.S. and E.d.B. performed the experiments; P.S., M.K. and A.U. analyzed the data; M.K. and H.P.-K. contributed reagents/materials/analysis tools; P.S., M.K., E.d.B. and Ł.N. wrote and revised the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: Zaklad Gospodarki Odpadami GAC in Poland supported this research.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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