

## Article

# Towards a Full Circular Economy in Biogas Plants: Sustainable Management of Digestate for Growing Biomass Feedstocks and Use as Biofertilizer

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**Abstract:** The digestate is a prospective biofertilizer and potential source of income for many biogas plants worldwide. However, its actual impact on the soil properties and biomass yield is still unexploited. The different digestates from eight agricultural biogas plants were researched in terms of their chemical composition and the fertilizing potential. The results obtained from digestate chemical analysis indicate that the digestate biomass had large amount of nitrogen (up to 73 g kg<sup>-1</sup> fresh mass) and potassium (up to 25 g kg<sup>-1</sup> fresh mass). The value of the digestate was estimated in the range of 2.88–7.89 EUR Mg<sup>-1</sup> for liquid digestate and 7.62–13.61 EUR Mg<sup>-1</sup> for solid digestate based on the commercial fertilizer market price of nitrogen, potassium phosphorus, organic carbon, Cu, Zn, Fe and Mg. The digestate produced at the 1 MW biogas plant is worth EUR 941–2095 per day in addition to energy sales income. The application of digestate on low-fertility land in areas close to the biogas plant allows the production of up to three-fold more biomass suitable for biogas production. The digestate's application on semi-natural grass biomass production in the low-fertility soils near the biogas plants could be an alternative strategy for the biogas plant feedstock portfolio diversification.

**Keywords:** digestate; bioproduct; soil improver; fertilizer; circular economy; biogas plant management



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## 1. Introduction

The global increase in energy demand together with ambitious greenhouse gas emission reduction plans creates the opportunity for constant renewable energy capacity growth. The shift from fossil fuel-based energy production to renewable energy generation can partly be achieved by increased biobased energy generation. Biogas-based energy production increases the base load renewable energy production. Furthermore, biogas is an alternative energy source to natural gas. The current natural gas grid infrastructure can be adapted for green and renewable biomethane injection and transmission internationally. The use of biogas to partly replace natural gas has the potential to reduce imports of energy resources in many countries. Local green biomethane production would allow the development of energy independence for many regions and countries worldwide.

Volumes of biogas produced in the 28 EU countries doubled from 93 to 187 TWh between 2008 and 2016 [1,2]. Kampman et al. [3] envisioned another doubling by 2030, with significant biogas capacity growth achieved in some EU member countries. The European Biogas Association estimates growth in demand for green biomethane and a major shift in the utilization of biogas from burning gas for combined heat and power production towards a biomethane production approach. The major drivers for this shift will be the biomethane market demand and price increase and reductions in the price of renewable electricity due to the optimization of photovoltaics and wind energy capital expenses as well as operational expenses [4].

During the anaerobic digestion process, biogas is produced together with a valuable residual stream known as the digestate. Therefore, increasing demand for biogas-based

energy generation will generate a significant increase in the annual volumes of digestate generated. Recycling the digestate back to soil and therefore valuable nutrients such as nitrogen, potassium, phosphorus and organic carbon for plants is the circular economy concept case [5]. Anaerobic digestion is a good example of a closed loop process as the biogas is produced from the volatile matter fraction of various biodegradable feedstock streams such as animal slurry, manure or agricultural waste biomasses and the valuable nutrients available in the digestate are recycled back to the soil. The typical feedstock biomass for biogas production can be applied to soil directly as natural biofertilizer, however, strict environmental requirements encourage the integration of the anaerobic digestion process prior to biomass application on arable lands. First, the odor released during manure application on land can also be prevented when anaerobic digestion is applied [6]. Second, various pathogens present in animal origin feedstocks are removed during the biogas production process [6,7]. Third, according to various publications, the anaerobic digestion process helps to concentrate most of the micro- and macronutrients present in the feedstock biomass [8,9]. However, negative aspects of the misuse of biobased fertilizers, including digestate, are unpleasant odors and uncontrolled flow of leachate to soil and ground waters, as well as ammonia gas or greenhouse gas emissions such as CO<sub>2</sub> and CH<sub>4</sub> released to the atmosphere. Therefore, the European Union (EU) has created legislation resulting in the EU Nitrates Directive [10], limiting the use of biobased fertilizers based on the 170 kg N ha<sup>-1</sup> year<sup>-1</sup> maximum fertilization norm. However, the research of Biernat et al. [11] concludes that both organic and conventional cropping systems are, under current management practices, not sufficient to meet the environmental standards for water protection in the EU. Thus, the better management of nitrogen compounds on small and large farms would lead to better protection of the groundwater quality.

The elements are concentrated in the digestate and, if managed appropriately, the digestate has potential for use as an agricultural fertilizer [12]. Other research studies demonstrate the benefits of digestate compared to mineral fertilizers due to less nitrate leaching potential [11], because the digestate also adds organic carbon substances that can increase the capacity for holding mobile forms, such as ammonium or others, of the particular soil. This aspect is often ignored as most biogas plant operators calculate the value of digestate in terms of NPK concentrations. However, it should be noted as there are more nutrients in the digestate than NPK and, based on that, its actual economic potential increases [13].

Economic and environmental sustainability is challenged by two major factors: first, by the distance and feedstock quantity used for biogas production and, second, the amount of digestate generated during the anaerobic digestion process in each biogas power plant. Thus, if the digestate is not further processed in terms of volume reduction, it is very important to optimize the biogas plants' feedstock portfolio and minimize the digestate's logistics distance. For example, the sustainability aspects can be improved when the digestate volumes are utilized as close to biogas plants (BPs) as possible. Additionally, if the feedstock biomass yields for biogas production were increased in areas where it would not compete with food production, biogas power plants could grow the feedstock biomass in a sustainable manner, while using the digestate in order to increase biomass yields. Increased biomass yields as well as increased biogas potential due to fertilization of the biomass growing area would result in increased energy produced per hectare, resulting in a potential reduction in operational expenses for biogas power plant feedstock portfolios. Currently, there are no serious problems with the spreading of digestate worldwide [14] but biogas plants often struggle to sell digestate. However, the leading strategy for a circular economy-based digestate management approach is still in its immature phase [15]. For example, in Lithuania, major biogas plants distribute the liquid fraction of digestate (LFD) free of charge and the solid fraction of digestate (SFD) is sold through commercial agreements with local farmers. In Europe, the utilization of digestate is complicated when it is classified as waste. This aspect creates barriers for a sustainable digestate utilization

strategy as most biogas plant owners tend to spread the digestate on fields belonging to the biogas plant [16].

Biogas plant operators often underestimate the potential income from digestate sales for their biogas plants. The potential application of digestate to improve feedstock biomass yields could be an attractive strategy towards feedstock portfolio security for remote biogas power plants. For this reason, the potential price of digestate from eight different biogas plants in Lithuania was evaluated in terms of its chemical composition and major elements. The potential price of digestate was determined as the first option for biogas plant operators. As the second option, the digestate fertilization of low-fertility abandoned arable lands overgrown with semi-natural grasslands for the sake of biogas feedstock production was investigated.

The present research was structured towards the better understanding of digestate chemical composition, its potential economic value as a biofertilizer and its impact on biomass yields as well as the biogas potential of digestate-fertilized biomass. The objective of the research was to evaluate the economic potential of the digestates produced in agricultural biogas plants. Therefore, the chemical composition and fertilizing properties of digestate from eight agricultural biogas plants were researched. Based on the chemical composition, the potential sales revenues were evaluated as if the digestate was sold as the biofertilizer. Furthermore, the solid and liquid digestate fertilization field experiment was carried out in order to better understand its impact on soil properties and semi-natural grass biomass yield. Finally, the biomethane potential assessment was carried out on the digestate-fertilized biomass samples. The biomass sampling was carried out in order to better understand the digestate impact on biomass yield, biomass composition and the biogas potential. In addition to that, the soil properties were researched in order to understand the digestate's effect on soil properties. The digestate's impact on soil has been presented in other publications of our research group [17,18]. The research indicates a biomass yield improvement and also a biogas potential increase when digestate is used as biofertilizer on low-fertility soil fields. The promising results demonstrate the possibility to spread the digestate around the areas near the biogas plants, providing the chance to grow potential feedstock for sustainable biogas production. Additionally, the potential digestate economic value for the biogas plants is discussed based on biofertilizers' chemical compositions.

## 2. Materials and Methods

### 2.1. Digestate Sampling and Description of Selected Biogas Plants

Eight different industrial biogas power plants of the same production capacity, located in Lithuania, were selected for the brief feedstock analysis and regular digestate sampling during the experimental year. The digestates were sampled 5 times per year with 2-month intervals. The LFD was sampled from the digestate storage lagoon and the SFD was sampled directly after the solid–liquid separator. The procedure was protocolled and repeated in the same order to minimize any deviation in digestate composition due to uneven sampling methodology. The biogas plant performance was found to be stable and consistent in terms of biogas production, however, the publishing of continuous process analysis data was not tolerated by the managers of the biogas plants.

### 2.2. Digestate Fertilization Field Experimental Area and Field Operations

The semi-natural grassland cultivation and digestate fertilization field experiments were carried out with three field replicates and a plot size of 6 square meters. In the field experiment, three different fertilization rates were applied: control field with no fertilizer, fertilization by separated solid and liquid digestate. The chosen fertilization rate was  $170 \text{ kg ha}^{-1} \text{ N}$  for both solid and liquid fertilization approaches. The amount of fertilization digestate was based on the total Kjeldahl nitrogen (TKN) calculated through the digestate chemical analysis. The location of the experiment was the municipality of Elektrenai, Lithuania,  $54^{\circ}47'01.19'' \text{ N } 24^{\circ}45'01.050'' \text{ E}$ . The experiment was performed

in eroded loamy Retisol soil with a low organic matter content. The soil profile analysis indicated an Ak-AkBC-BC1-BC2-C profile. The pH of the soil was 7.68, organic carbon content was  $1.34 \pm 0.06\%$  TS and nitrogen content was  $0.96 \pm 0.07 \text{ g} \cdot \text{kg}^{-1}$ . Fertilization with digestate was carried out manually in spring (first week of May) during each experimental year in 2018 and 2020. The semi-natural grassland biomass was cut once a year (the first week of July).

### 2.3. Methodology for Estimating Digestate Value

The value of the SFD and LFD from each of the 8 biogas plants tested was evaluated in terms of the market prices of mineral fertilizers typically used in Lithuania. The values of mineral fertilizers were recalculated in order to find out the cost of 1 kg pure component. The  $\text{NH}_4\text{NO}_3$ ,  $(\text{NH}_4)_2\text{H}_2\text{PO}_4$ , KCl,  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ,  $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ ,  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  and  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  fertilizers were used for digestate elements as alternative fertilizers. Additionally, the local price for cow manure was used for the organic carbon (OC) value estimation.

The content and the value of 1 kg of specific elements in the alternative fertilizer were calculated using the following formula:

$$\text{Pr}_{\text{ED}} = (\text{Pr}_{\text{EM}} / \text{C}_{\text{EM}}) \text{C}_{\text{ED}} \quad (1)$$

The price of digestate was calculated as the total sum of ingredients analyzed:

$$\text{V}_{\text{D}} = \text{Pr}_{\text{ED-N}} + \text{Pr}_{\text{ED-P}} + \text{Pr}_{\text{ED-K}} + \text{Pr}_{\text{ED-OC}} + \text{Pr}_{\text{ED-Cu}} + \text{Pr}_{\text{ED-Ca}} + \text{Pr}_{\text{ED-Zn}} + \text{Pr}_{\text{ED-Fe}} + \text{Pr}_{\text{ED-Mg}} \quad (2)$$

The parameters used in Equations (1) and (2) are described in Table 1.

**Table 1.** The description of the parameters and variables followed by units used for digestate value estimation.

Parameter	Description	Unit
$\text{Pr}_{\text{ED}}$	Price of ingredient in digestate	EUR $\text{kg}^{-1}$
$\text{Pr}_{\text{EM}}$	Pure ingredient price in the alternative fertilizer	EUR $\text{kg}^{-1}$
$\text{C}_{\text{EM}}$	Concentration of ingredient in alternative fertilizer	$\text{kg}_{\text{ingredient}} \cdot \text{kg}_{\text{fertilizer}}^{-1}$
$\text{C}_{\text{ED}}$	Concentration of ingredient in the digestate	$\text{kg}_{\text{ingredient}} \cdot \text{kg}_{\text{biofertilizer}}^{-1}$
$\text{V}_{\text{D}}$	Value of digestate with regard to N, P, K, OC, Cu, Zn, Fe, Mg content	EUR $\text{kg}^{-1}$
$\text{Pr}_{\text{ED-N}}$	Value of digestate with regard to N content	EUR $\text{kg}^{-1}$
$\text{Pr}_{\text{ED-P}}$	Value of digestate with regard to P content	EUR $\text{kg}^{-1}$
$\text{Pr}_{\text{ED-K}}$	Value of digestate with regard to K content	EUR $\text{kg}^{-1}$
$\text{Pr}_{\text{ED-Ca}}$	Value of digestate with regard to Ca content	EUR $\text{kg}^{-1}$
$\text{Pr}_{\text{ED-OC}}$	Value of digestate with regard to OC content	EUR $\text{kg}^{-1}$
$\text{Pr}_{\text{ED-Cu}}$	Value of digestate with regard to Cu content	EUR $\text{kg}^{-1}$
$\text{Pr}_{\text{ED-Zn}}$	Value of digestate with regard to Zn content	EUR $\text{kg}^{-1}$
$\text{Pr}_{\text{ED-Fe}}$	Value of digestate with regard to Fe content	EUR $\text{kg}^{-1}$
$\text{Pr}_{\text{ED-Mg}}$	Value of digestate with regard to Mg content	EUR $\text{kg}^{-1}$

The digestate value estimation methodology does not take into account the microbiological activity of digestate biomass as this aspect was not researched during the present study.

### 2.4. Biomethane Potential Assessment

The biogas potential of fresh cut biomass from the field experiment was evaluated. The duration of the tests was 40 days. Biomethane potential was evaluated by an Automatic Methane Potential Test System (AMPTS II, Bioprocess Control, Lund, Sweden). Then, the  $\text{CO}_2$  from biogas was eliminated by passing through 80 mL 3M NaOH solution and  $\text{CH}_4$  yield was measured by the AMPTS II's gas flow meter. The inoculum used was from a mesophilic biogas plant with pig slurry, with beetroot biomass used as the main feedstock for the biogas production. The applied substrate to inoculum ratio was 2:1 on a weight

basis. The experiments were carried out in triplicate, and the temperature was set to  $35 \pm 1$  °C.

### 2.5. Analytical Methods for Digestate Analysis

The SFD and LFD streams were regularly evaluated with regard to TKN, total solids (TS), volatile fraction (VS), total phosphorus (P), total potassium (K), organic C, Cu, Zn, Fe, Ca, Mg and pH. The digestate samples were stored at 5 °C before the analyses. TKN content was measured immediately after the digestate's arrival at the laboratory facilities. TS was measured by the weight loss after drying digestate samples at 105 °C for 24 h. VS was measured after heat treatment at 550 °C for 4 h and then the samples' weight was measured. The P concentrations were quantified by a color reaction with an ammonium molybdate vanadate reagent at a wavelength of 430 nm on a Cary 50 UV-vis spectrophotometer (Varian Inc., Palo Alto, CA, USA), after the wet digestion process with sulfuric acid. For OC, the modified Nikitin–Tyurin method [19] was applied.

Ca, Mg, K, Fe, Cu and Zn content in digestate was determined with atomic absorption spectrometry, measured on an AAnalyst 200 (Perkin Elmer, Waltham, MA, USA) using a wet digestion process with sulfuric acid. For atomic absorption spectrometry, an air-acetylene flame and hollow cathode mono/multi-element lamps were used.

The homogenization was done for the liquid digestate prior to the pH measurement. The pH of solid digestate was measured in deionized water extract (1:5 weight/volume).

### 2.6. Field Experiment and Biomass Sampling

The semi-natural grassland cultivation and digestate-based fertilization randomized field experiment took place in the period 2018–2020. The experiment was repeated for three consecutive years in the same fields with three field replicates under the same fertilization conditions. The comprehensive experimental setup, the methodology and the results are evaluated in [18]. The following treatments were applied: the control, solid digestate and liquid digestate. The fertilization rate of 170 kg ha<sup>-1</sup> N was applied for both solid digestate and liquid digestate fertilization. The 170 kg ha<sup>-1</sup> N fertilization rate was selected as the maximum possible fertilization rate based on the EU Nitrate Directive. Fertilization with digestate was applied manually in spring (first week of May) during each experimental year.

Semi-natural grass biomass was manually cut from each 6 m<sup>2</sup> field replicate. The yield of fresh biomass was weighed immediately after harvesting. The biomass was put into hermetic plastic bags and approximately 1.0 ± 0.1 kg was delivered for further compositional analysis to the laboratory. The size of cut biomass was reduced to 35–40 mm to simulate the size reduction if harvesting machinery was used. The fresh-cut biomass was kept at 5 °C for later experiments for the assessment of biomethane potential.

## 3. Results and Discussion

### 3.1. Characteristics of the Analyzed Biogas Plants

All eight biogas plants are agricultural biogas production facilities. In terms of the feedstock amounts digested, the biogas plants' feedstock mix is dominated by pig slurry, accounting for 48–75% of the total inlet stream (Table 2).

All the plants are similar in terms of the produced electricity capacity and the daily biogas production. All biogas plants are located in Lithuania (Table 3). The operational temperature regime was within the mesophilic range 36–42 °C, with the lowest regimes being BP 7 and BP 8. This aspect can be partly explained due to types of feedstock used, as nitrogen-rich chicken manure and thermally treated waste were used. The organic loading rate (OLR) and the hydraulic retention time (HRT) were similar within all the biogas plants, ranging from 2.05–2.77 kg VS m<sup>-3</sup> d<sup>-1</sup> and 31–44 d, respectively. The digestate after the anaerobic digestion process can be further digested for remaining biomethane potential extraction. According to Demirer et al. (2021), the methane potential can be in the range of 0.055–0.147 L CH<sub>4</sub> g<sup>-1</sup> VS [20]. However, further biomethane extraction

requires additional volumes in the digesters, resulting in increased capital expenses during the facility construction phase. The reduction in hydraulic retention time (HRT) and the increase in organic loading rate (OLR) followed by a biogas yield increase would lead to a significant reduction in capital investment costs [21].

**Table 2.** Feedstock mix in 8 biogas plants tested during the experiment.

Feedstock Used, % of Total Volume	BP 1	BP 2	BP 3	BP 4	BP 5	BP 6	BP 7	BP 8
Pig slurry	75	48	60	54	70	70	52	49
Beetroot pulp	14	26	10	12	0	0	6	0
Grain mill bran	3	5	4	3	0	0	3	2
Starch production waste	8	0	0	21	30	30	14	0
Discarded vegetables	0	13	14	0	0	0	3	3
Whey	0	8	12	10	0	0	0	0
Chicken manure	0	0	0	0	0	0	23	0
Thermally pretreated waste	0	0	0	0	0	0	0	45

**Table 3.** Key parameters of biogas plants from which solid and liquid digestate streams were periodically analyzed. The produced power is the average power per 8200 annual operational hours. The feedstock mix is calculated in terms of each feedstock amount used during the experimental year at each biogas plant.

Parameter		BP 1	BP 2	BP 3	BP 4	BP 5	BP 6	BP 7	BP 8
Produced power capacity	kW	1043	994	1032	1027	977	985	1008	1010
Biogas production	m <sup>3</sup> d <sup>-1</sup>	11,920	11,355	11,795	11,740	11,164	11,260	11,525	11,545
Total solids (TSs) of feedstock mix	%	10.3	15.4	10.4	12.3	9.8	9.8	15.7	11.8
Temperature	°C	39	41	42	42	41	41	38	36
HRT	d	31	32	32	31	35	40	42	44
OLR	kg VS m <sup>-3</sup> d <sup>-1</sup>	2.55	2.76	2.90	2.67	2.45	2.77	2.10	2.05
LFD	m <sup>3</sup>	72,610	31,122	51,058	53,239	79,706	79,706	34,493	38,129
SFD	t	27,840	21,836	19,667	26,028	28,261	28,261	24,957	17,562
Feedstock price	kEUR	363	359	278	393	197	194	350	65

The pig slurry feedstock was dominant in terms of amounts processed at the biogas plants. It is known that pig slurry is a relatively low energetic value feedstock, delivering 15–27 m<sup>3</sup> biogas per Mg biomass used [22–24]. However, it is cheap, constant in terms of seasonality and it is often used for the overall TS dilution in digesters [25]. On the other hand, the pig manure transport cost is very high due to its low energy potential and, therefore, it is often pumped to biogas plants by pipes rather than transported by trucks. This results in targeted biogas plant construction located at a minimum distance from pig farms, as is the case for BP 1–BP 6. The tendency was observed that the more liquid pig slurry is used, the more digestate is produced in the biogas plants. In order to boost the energetic performance of the biogas plants, other biogas feedstocks with more biogas potential were used. The dominant feedstocks were lignocellulosic-based biomasses such as beetroot pulp, discarded vegetables and grain mill waste products. One biogas plant (BP 7) used chicken manure as the major source of biogas due to a commercially favorable agreement with the local chicken farm located next to the biogas plant. A tendency can be observed that the more pig slurry processed, the more liquid digestate was generated in the biogas production plants. BP 8 was the only biogas plant utilizing second and third category waste, which requires strict thermal pretreatment conditions prior to the insertion into anaerobic digestion systems. BP 8's annual expenses for feedstock were

significantly lower compared to the other biogas plants due to the use of thermally treated waste. This type of biogas feedstock has relatively high biogas potential [26]. Furthermore, thermally treated waste biomass is relatively cheap in terms of feedstock price as the waste producers often pay the gate fee for the biogas plant operators in order to properly dispose of their waste.

### 3.2. Characteristics of Analyzed Digestate

The digestate can be spread on fields either directly after anaerobic digestion or after solid–liquid fraction separation. The separation of SFD and LFD allows biogas plant developers to design and construct biogas systems with large liquid digestate storage lagoons rather than more expensive post-fermenters.

There are many factors affecting the composition of digestate, the most important being the feedstock used [27], anaerobic fermentation conditions (HRT, temperature regime, OLR, pH, mixing type and strategy, other) applied and the digestate treatment technology used in the particular biogas plant. The composition of digestate is often determined by its rheological properties, TS content, pH and NPK content. However, there are many more elements available in the digestate mass that are valuable for agricultural production and the soil. The analyzed liquid digestate parameters are presented in Table 4.

**Table 4.** Selected liquid digestate parameters for 8 biogas plants.

Liquid Digestate										
Parameter	Unit	BP 1	BP 2	BP 3	BP 4	BP 5	BP 6	BP 7	BP 8	Average (BP 1–BP 8)
TS	% FM	2.18	3.99	2.46	2.38	2.09	3.49	4.58	4.31	<b>3.18</b>
VS	% FM	1.80	2.92	2.25	2.22	1.75	2.45	3.51	3.46	<b>2.55</b>
pH		7.53	7.97	7.92	7.96	8.18	7.82	7.86	7.63	<b>7.86</b>
TKN	% FM	0.26	0.32	0.25	0.29	0.27	0.38	0.45	0.73	<b>0.37</b>
P	% FM	0.07	0.05	0.05	0.04	0.04	0.08	0.05	0.08	<b>0.06</b>
K	% FM	0.13	0.20	0.25	0.16	0.21	0.33	0.17	0.13	<b>0.20</b>
OC	% FM	0.84	1.17	1.08	0.72	0.72	1.17	1.70	2.63	<b>1.25</b>
Ca	% FM	0.52	0.46	0.30	0.14	0.12	0.12	0.40	0.22	<b>0.28</b>
Mg	% FM	0.04	0.08	0.03	0.03	0.04	0.05	0.04	0.06	<b>0.05</b>
Zn	mg·kg <sup>-1</sup> FM	33.98	44.11	28.34	24.04	53.40	39.31	14.27	27.01	<b>33.06</b>
Fe	mg·kg <sup>-1</sup> FM	82.48	126.64	72.35	88.64	142.11	131.08	77.34	137.51	<b>107.3</b>
Cu	mg·kg <sup>-1</sup> FM	10.60	9.21	5.26	3.94	8.72	6.76	3.77	11.13	<b>7.42</b>

The TS content of liquid digestate was relatively similar in all eight biogas plants, mainly due to the same liquid anaerobic digestion technology being applied. Furthermore, all the biogas plants used screw press digestate separation equipment (Börger BS 75) for the solid–liquid separation process. The pH of all the liquid digestates was in the alkaline range and making the liquid digestates into attractive fertilizers for the land was characterized by an acidic pH value. pH value is an important parameter for soil properties due to its contribution to soils' chemical and physical properties. The alkaline profile of the liquid digestate may have a stronger effect on soils' pH properties in the longer fertilization period compared to the short-term impact [28]. The analyzed solid digestate parameters are presented in Table 5.

**Table 5.** Selected solid digestate parameters for 8 biogas plants.

Parameter	Unit	Solid Digestate								Average
		BP 1	BP 2	BP 3	BP 4	BP 5	BP 6	BP 7	BP 8	
TS	% FM	28.91	29.80	23.92	33.63	27.95	26.73	29.44	25.08	<b>28.18</b>
VS	% FM	24.42	23.12	18.34	27.45	23.15	21.97	25.26	20.30	<b>23.00</b>
pH		8.43	8.66	8.32	8.46	8.67	8.47	8.37	8.39	<b>8.47</b>
TKN	% FM	0.45	0.60	0.42	0.58	0.49	0.52	0.65	0.44	<b>0.52</b>
P	% FM	0.30	0.39	0.42	0.40	0.35	0.26	0.21	0.31	<b>0.33</b>
K	% FM	0.15	0.23	0.26	0.16	0.19	0.33	0.19	0.14	<b>0.21</b>
OC	% FM	14.21	15.14	11.55	15.86	13.71	14.02	14.79	9.81	<b>13.64</b>
Ca	% FM	0.42	1.15	0.60	1.18	0.47	0.48	0.44	0.27	<b>0.63</b>
Mg	% FM	0.14	0.27	0.21	0.19	0.21	0.24	0.12	0.09	<b>0.18</b>
Zn	mg·kg <sup>-1</sup> FM	96.75	79.25	85.18	88.84	151.19	110.57	27.51	27.33	<b>83.33</b>
Fe	mg·kg <sup>-1</sup> FM	411.23	481.28	416.22	523.45	709.83	623.02	280.66	224.51	<b>458.8</b>
Cu	mg·kg <sup>-1</sup> FM	26.51	15.11	15.37	11.66	34.73	20.76	4.65	4.03	<b>16.60</b>

The TKN parameter is used when calculating the amount of digestate applied to a given fertilization area. The TKN contents in analyzed digestates were in the range of 0.26–0.73% FM for liquid digestate and 0.42–0.65% FM for solid digestate. The quality of total and volatile solids, OC, NPK and other parameters defines the digestate as potential biofertilizer. The nitrogen content is often controlled in the daily operation of a biogas plant in order to avoid ammonium/ammonia inhibition phenomena [29,30]. A higher nitrogen content in the digestate was observed in those biogas plants using nitrogen-rich feedstock, namely BP 7 (source of nitrogen: chicken manure) and BP 8 (source of nitrogen: thermally pretreated waste). During the biogas production process, protein molecules are broken down, resulting in a fraction of nitrogen form transformation [31]. It can be stated that after the anaerobic digestion process, nitrogen is in a plant-available form and it is therefore more quickly absorbed by plants when the digestate is spread onto the soil. In terms of phosphorus, solid digestate contained 0.33% FM, on average, of phosphorus and the liquid digestate contained much less, namely 0.06% FM. The highest content of phosphorus was observed in BP 8, using thermally treated food waste as the major feedstock stream for the anaerobic fermentation process.

The potassium concentration in the liquid and solid digestate varied from 0.13–0.25% FM and 0.15–0.26% FM, respectively. Potassium can enhance plants' drought tolerance [32]. Various fertilization strategies can impact the potassium availability in the soil. The application of biobased fertilizers such as manure or digestate to the soils positively impacted the release of potassium and decreased potassium fixation in soils [33]. According to Tariq et al. (2018), the application of phosphorous fertilizer increased root biomass, photosynthesis rate and leaf water content under water stress [34].

A high concentration of OC (9.81–15.86% FM) was found in the SFD. Therefore, supplementation of OC compounds to the soil can be achieved when SFD is used as biofertilizer. On average, the SFD contained 13.64% FM of OC compared to 1.25% FM for the LFD. For example, more than 30% of the Lithuania's soils lack organic carbon and organic matter, therefore, it is beneficial to increase OC content in the soil in Lithuania [17].

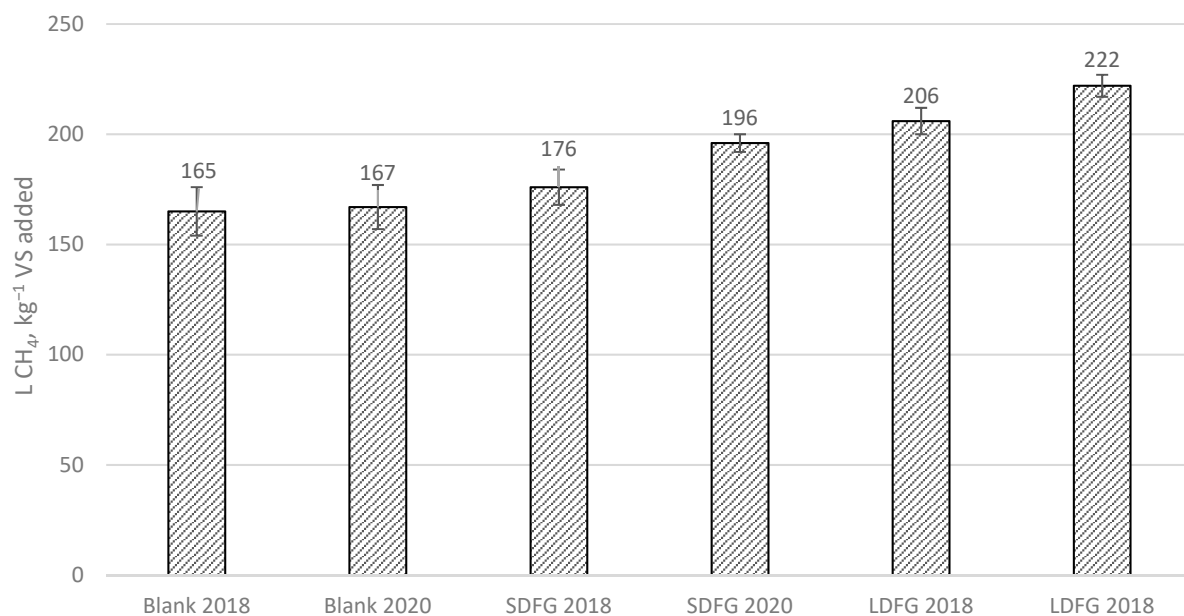
Agricultural soils are usually deficient in nitrogen, and soil fertility depends on added nitrogen. After nitrogen and phosphorus, soils are most deficient in potassium. Therefore, commercial fertilizers usually contain these three main elements (N, P and K). Digestate is an alternative source of these three and other elements. The macronutrients, namely, NPK, Mg, Ca and S, and micronutrients present in the digestate fractions are important elements necessary for plants [17]. The significant impact of fertilization on mobile forms of K and P accumulation in the soil has been measured. Additionally, Mg and Ca serve as a structural component and participate in many enzymatic reactions [35]. The elements



that are required for plants' growth but in very small quantities are called microelements, such as Cu, Zn, Fe and others. Cu, as the one of the eight essential plant micronutrients, is required for enzymatic metabolism in plants and for chlorophyll and seed production [36]. A lack of Cu supply from fertilization agents or from the soil itself can lead to higher susceptibility to plant diseases.

### 3.3. Biogas Potential Results

Digestate can potentially be used as biofertilizer for higher yields of biomass feedstock production near to the biogas power plant. The biomethane potential was measured in order to better understand the potential feedstock value for the biogas power plant if the semi-natural grass biomass was used as the part of the feedstock mix. The biomethane potential test of the ten semi-natural grassland biomass samples demonstrated a specific methane yield within the range of 165–222 L CH<sub>4</sub> kg<sup>-1</sup> VS added (Figure 1). The obtained results indicate that the biomethane potential is affected by the fertilization applied.

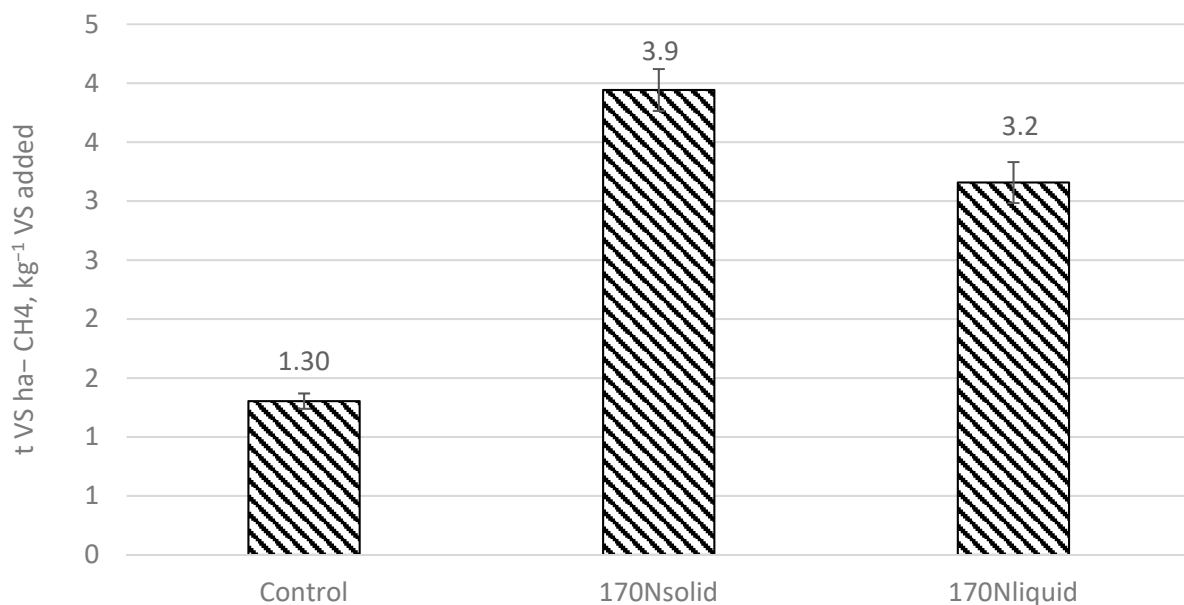


**Figure 1.** Biogas potential results for solid (SDFG) and liquid (LDFG) digestate fertilized grass samples during the years 2018 and 2020. Note: Data represented as mean ± standard deviation.

Other researchers also obtained similar biogas potential results for digestate-fertilized biogas potential analysis. Tilvikiene et al. (2020) [37] demonstrated a methane yield increase of 10% when fertilization with digestate of 180 kg N ha<sup>-1</sup> was used on cocksfoot biomass. The average biomethane yield varied by up to 25% among scenarios where different amounts of digestate were used in a field experiment. Additionally, it was found that 180 kg N ha<sup>-1</sup> digestate application demonstrated the highest biogas yield and further increased the fertilization while decreasing the methane yield by 3% for each additional 90 kg N ha<sup>-1</sup> year<sup>-1</sup> applied [37].

The continuous digestate fertilization effect can be perceived, as semi-natural grass biomass biogas potential results are higher for the year 2020 compared to 2018, however, blank samples' (unfertilized biomass) biogas potential remains relatively stable over the years. The results indicate that continuous fertilization with 170 kg N ha<sup>-1</sup> solid and liquid digestate increased the grassland biomass biogas potential results.

The application of the digestate on low-fertility soil resulted in a semi-natural grass biomass yield increase by a factor of 3 for solid digestate and 2.5 for liquid digestate based on three-year consecutive field experiment data (Figure 2).



**Figure 2.** Semi-natural grassland biomass yield for solid (170 Nsolid) and liquid (170 Nliquid) digestate at a 170 kg N ha<sup>-1</sup> fertilization rate for three-year average experimental results. The yield is expressed in tons of volatile solids per hectare. Note: Data represented as mean  $\pm$  standard deviation.

The application of solid and liquid digestate had a positive effect on grass biomass yield. Additionally, the solid digestate had a higher impact on biomass yield compared to liquid digestate. In the control treatment, yields differed less over the experimental years (2018, 2019, 2020). The digestate fertilization had a cumulative effect in the fertilized soil due to the accumulation of the digestate nutrients which are important for plant growth.

The obtained results indicate that when a 170 kg ha<sup>-1</sup> fertilization rate is applied, biogas plants can generate significant yields of semi-natural grassland feedstock for biogas production. The digestate can be an appropriate source of valuable nutrients for crop production used for bioenergy production purposes [38]. The obtained biogas potential results and volatile solid yields per hectare of digestate-fertilized area indicate that biogas plants can generate 685 m<sup>3</sup> CH<sub>4</sub> ha<sup>-1</sup> for liquid digestate-fertilized areas and 725 m<sup>3</sup> CH<sub>4</sub> ha<sup>-1</sup> for solid digestate-fertilized areas.

### 3.4. Digestate Value

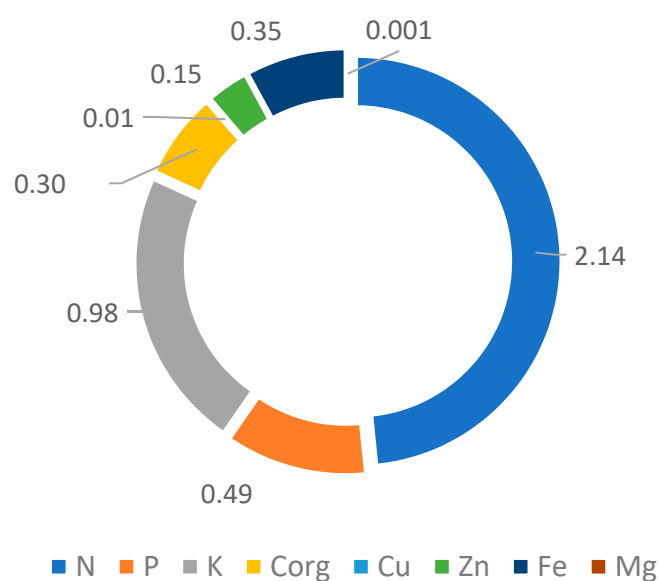
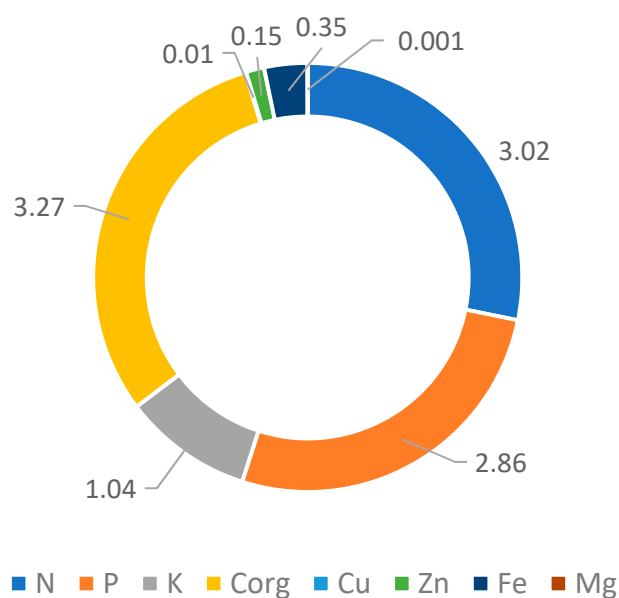
Czekala et al. (2020) emphasized that, in addition to NPK components, digestate contains other valuable elements and organic matter residues [16]. The elements are likely to be in mobile forms, so they are quickly absorbed by growing plants and the fertilization benefits are apparent during the first weeks after fertilization [27], with OC accumulating in the soil and therefore improving soil properties in the long term. The SFD was identified to be a more expensive fertilizer compared to the LFD (Table 6).

For the liquid digestate, the evaluated fertilizer price mostly depends on NPK, representing 82% of calculated average digestate price. The value of solid (Figure 3) and liquid (Figure 4) digestates indicates that NPK and OC are the major components of the fertilizers' prices. The NPK for solid digestate represented 65% of the calculated average digestate price because of the larger amount of OC present in the solid digestate stream. It is important to note that a separate price calculation per element is important, however, the benefit and the value of the digestate should be evaluated as the complex of valuable elements. The symbiosis of NPK, other elements, residual organic matter and OC is greater due to the greater impact on the soil properties and finally the annual biomass yields.

**Table 6.** The value of the digestate fractions from 8 biogas plants.

Element	Price for 1 kg Component *	Liquid Digestate, EUR t <sup>-1</sup>			Solid Digestate, EUR t <sup>-1</sup>		
		Average	Min	Max	Average	Min	Max
N	0.58	2.14	1.46	4.22	3.02	2.45	3.75
P	0.87	0.49	0.30	0.69	2.86	1.81	3.68
K	0.50	0.98	0.64	1.64	1.04	0.70	1.66
OC	0.02	0.30	0.17	0.63	3.27	2.35	3.81
Cu	1.00	0.01	0.004	0.01	0.01	0.004	0.01
Zn	4.40	0.15	0.06	0.23	0.15	0.06	0.23
Fe	3.26	0.35	0.24	0.46	0.35	0.24	0.46
Mg	12.40	0.001	0.001	0.001	0.001	0.001	0.001
<b>Total value</b>		<b>4.42</b>	<b>2.88</b>	<b>7.89</b>	<b>10.70</b>	<b>7.62</b>	<b>13.61</b>

\* Calculated according to the market prices of commercial fertilizers.

**Figure 3.** Average value of liquid digestate according to the different elements, EUR t<sup>-1</sup>.**Figure 4.** Average value of solid digestate according to the different elements, EUR t<sup>-1</sup>.

The calculated values of solid and digestate fertilizers allow the estimation of the additional income that would be obtained for biogas power plant operators by selling the digestate according to the value determined by our research. If digestate was sold as a fertilizer product, the average biogas plant could generate additional income revenues of EUR 941–2095 d<sup>-1</sup> based on the minimum and maximum digestate values determined. It is important to note that digestate spreading and application costs and logistics should be evaluated in order to accurately estimate the earnings from digestate.

#### 4. Conclusions

The present research focused on the better understanding of agricultural biogas plants' digestates' chemical composition, their potential economic value as biofertilizer and their impact on biomass yields as well as the biogas potential once the digestate is used as biofertilizer on low-fertility soils. The anaerobic digestion process is the perfect example of a circular economy and therefore the production of biogas and utilization of digestate as a valuable organic fertilizer are sustainable solutions for organic biowaste utilization approaches. The LFD and SFD differed in their composition and they both contained components that can be used as biofertilizers. Both the LFD and SFD had higher N concentrations when chicken manure and thermally treated biowaste were present in the feedstock mix of the biogas plant.

Digestate is a potential source of income for biogas power plants. The N concentration of LFD and SFD followed by the OC concentration in SFD were the major components in terms of the economic potential of digestate. Based on the market price for commercial fertilizers, digestate can generate EUR 941–2095 of additional income for the average biogas plants analyzed in this research. Therefore, the higher N and OC concentrations in the fractions of digestate should become the priority for biogas plant operators when digestate sales are considered as an additional source of income.

Continuous digestate application on low-fertility soil causes an increase in semi-natural grass yield by up to three times based on the biomass volatile solids harvested. The biogas potential test results indicate that biomass grown on digestate-fertilized soil can generate up to 685 m<sup>3</sup> CH<sub>4</sub> ha<sup>-1</sup> for liquid digestate-fertilized areas and 725 m<sup>3</sup> CH<sub>4</sub> ha<sup>-1</sup> for solid digestate-fertilized areas. The digestate application on semi-natural grass biomass production areas near biogas plants could be an alternative strategy for biogas plant feedstock portfolio diversification. Further research is needed in order to better understand the sustainability aspects for the closed loop digestate utilization concept.

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