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Digestate as a Source of Nutrients: Nitrogen and Its Fractions

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Abstract: Due to fossil-fuel-limitation constraints, new energy sources are being sought. On the other hand, organic fertilizers that can be used in agriculture are increasingly being sought. One of the renewable energy sources is biogas produced from substrates large in organic matter. Apart from biogas, the product of the anaerobic digestion process is digestate. Due to the high content of nutrients, mainly nitrogen, this product can be successfully used as a fertilizer. This study aims to determine the content of total nitrogen (N_{tot}) and its selected fractions in the raw and processed digestate from agricultural biogas plants. The nitrogen fractions included N-NH_4, N-NO_3, and Norganic. The total nitrogen content (N_{tot}) and its fraction in raw digestate were determined. Samples used for the research came from five agricultural biogas plants. Separation into liquid and solid fractions is one of the methods for digestate management. The nitrogen content in selected samples obtained after separation of digestate in a biogas plant and on a laboratory scale was also checked. The obtained results show that digestate from agricultural biogas plants is a nitrogen-rich fertilizer. The content of N_{tot} in the tested samples ranged from 1.63 g·kg^{-1} to 13.22 g·kg^{-1} FM. The N-NH_4 content in the analyzed material ranged from 0.75 to 4.75 g·kg^{-1} FM. The determined physical and chemical properties confirm that the raw and processed digestate is characterized by appropriate fertilization properties, with particular emphasis on the content of N_{tot} and the share of its mineral forms. Based on the chemical composition, digestate from agricultural biogas plants can be considered a multi-component fertilizer.

Keywords: digested pulp; biogas; waste management; sustainable development; circular economy; fertilizer

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1. Introduction

With the development of civilization, both the quantity and the variety of waste produced have increased [1]. On the other hand, in many countries, especially in Europe, environmental protection and sustainable development activities are becoming more and more important [2]. In this context, special attention is paid to organic fertilizers and biodegradable waste, of which Poland is one of the leading producers in the European Union [3]. However, it should be emphasized that they are used primarily for agricultural purposes, and only some of them are used for energy purposes [4].

Agricultural biogas plants are installations where biogas is produced under controlled conditions, the main component of which is methane [5]. From the biochemical point of view, the biological processes taking place in a biogas plant are complex [6], and the production of biogas is based on anaerobic digestion [7]. As a result, organic substrates are decomposed, which results in the production of, i.e., methane and carbon dioxide [8].

The digestate is a residue that is not decomposed in the anaerobic digestion process [9] and requires management similar to the obtained biogas. The digestate consists mainly of non-degradable organic and mineral compounds, the biomass of living organisms, and water. The amount and composition of the product depends on many factors, but the most important is the type of substrates used in the anaerobic digestion process [10,11]. For this reason, the substrates are mainly responsible for the amount and properties of the resulting product. Other factors influencing the properties of the digestate are technological conditions for conducting the anaerobic digestion [12]. For this reason, the content of individual components in digestate from different installations may be different.

Among the main components of the digestate, nitrogen should be mentioned, being an essential component of all types of biomass [13]. Depending on the substrates used for the biogas production, the nitrogen content in the digested pulp may be different [14], which was noted by Czekała et al. [15]. The authors, analyzing the digestate from Polish agricultural biogas plants, found that they contained N_{tot} in the amount from 3.82 to 6.58 $kg \cdot Mg^{-1}$ in the fresh matter. In the same tests, potassium (K_2O) content was from 1.30 to 16.3 $kg \cdot Mg^{-1}$. In the case of potassium, its amounts differed more than tenfold between the samples in two out of three tested biogas plants. The quantitative differentiation of some elements shown in the literature corroborates the necessity to conduct research on not only the total content but also all forms of elements. This applies in particular to nitrogen and its fractions. It is mainly related to the availability of the element for the plant.

A solution that significantly influences the change in the properties of the digestate is the separation process [16], i.e., dividing the substrate, which is the digestate, into at least two fractions. The newly formed fractions of digestate are characterized by different physical and chemical properties. Research on the separation process is also carried out for other agricultural waste and biomass types. This may concern, i.e, sewage sludge [17] and slurry [18]. From a practical point of view, digestate is most often separated into solid and liquid fractions [19] using mechanical separators and centrifuges. In the scientific literature, the total content of elements is most often discussed. For this reason, research about fractions of the most important macroelement for plants is discussed.

This study aims to determine the content of total nitrogen and its selected fractions in the raw and processed digestate from agricultural biogas plants. The nitrogen fractions included $N\text{-}NH_4$, $N\text{-}NO_3$, and Norganic. Determination of individual nitrogen fractional content in various digestate fractions makes it easier to use them for fertilization purposes. The digester pulp used for the research was obtained from five agricultural biogas plants located in Poland and Germany.

2. Materials and Methods

2.1. Subject of Research

The research subject was digestate from various stages of the agricultural biogas plants' technological lines. Additionally, its fractions obtained as a result of separation carried out on a real scale in the biogas plants and in laboratory conditions were also used.

The digestate was collected from five agricultural biogas plants in Poland and Germany (Table 1). The common feature of the installation was the operation in mesophilic conditions and the installed electric power, amounting to over 0.5 MW, which allowed one to classify the power plants as large units of renewable energy sources. All biogas plants from which the research material was collected were characterized by a lack of technological problems in the anaerobic digestion process. This means that the biogas production was sufficiently high and stable. Additionally, there were no disturbing factors during the process, which made it possible to obtain representative material for research.

Table 1. Dominant substrates used for biogas production in individual biogas plants from which the research material was obtained.

Biogas Plant	Dominant Substrates
A	maize silage, fruit pomace, distillers grains, whey, permeate
B	maize silage, slurry
C	maize silage, slurry
D	maize silage, slurry, chicken droppings
E	maize silage, slurry

A total of 17 digestate samples classified into five groups were tested:

- Raw digestate (RD)—5 samples (A, B, C, D, E);
- Digestate liquid fraction (DLF)—3 samples (A, B, D);
- Digestate solid fraction (DSF)—3 samples (A, B, D);
- Centrifuge supernatant (CS)—3 samples (A, D, E);
- Centrifuge sludge (CSL)—3 samples (A, D, E).

The list of analyzed samples is presented in Table 2.

Table 2. List of digestates and their fractions used in the research. The following are defined abbreviations: RD—raw digestate, DLF—digestate liquid fraction, DSF—digestate solid fraction, CS—centrifuge supernatant, CSL—centrifuge sludge.

Biogas Plant	Type of Sample	Sample Code
Biogas Plant A	raw digestate	A-RD
	digestate liquid fraction	A-DLF
	digestate solid fraction	A-DSF
	centrifuge supernatant	A-CS
	centrifuge sludge	A-CSL
Biogas Plant B	raw digestate	B-RD
	digestate liquid fraction	B-DLF
	digestate solid fraction	B-DSF
Biogas Plant C	raw digestate	C-RD
Biogas Plant D	raw digestate	D-RD
	digestate liquid fraction	D-DLF
	digestate solid fraction	D-DSF
	centrifuge supernatant	D-CS
	centrifuge sludge	D-CSL
Biogas Plant E	raw digestate	E-RD
	centrifuge supernatant	E-CS
	centrifuge sludge	E-CSL

All samples after collection were delivered to the laboratory immediately in containers with thermal insulation. After the samples were delivered to the laboratory, they were physico-chemical analyzed, and the remainder was placed in a refrigerator and stored at a temperature of 3 to 5 °C.

2.2. Raw Digestate Separation

Raw digestate samples were separated in the biogas plants and the laboratory. In real scale, industrial separators operating in biogas plants A, B, and D were used. Raw digestate was not separated in the biogas plants C and E.

The ROTANTA 460R laboratory centrifuge by Hettich Zentrifugen was used to separate the liquid fractions formed as a result of separation in the biogas plant from installations A, D, and E. The samples were centrifuged for 10 min at 4000 rpm, which allowed one to separate the liquid fraction after separation into two next fractions: supernatant (a fraction with almost no dry mass) and sludge (Figure 1).

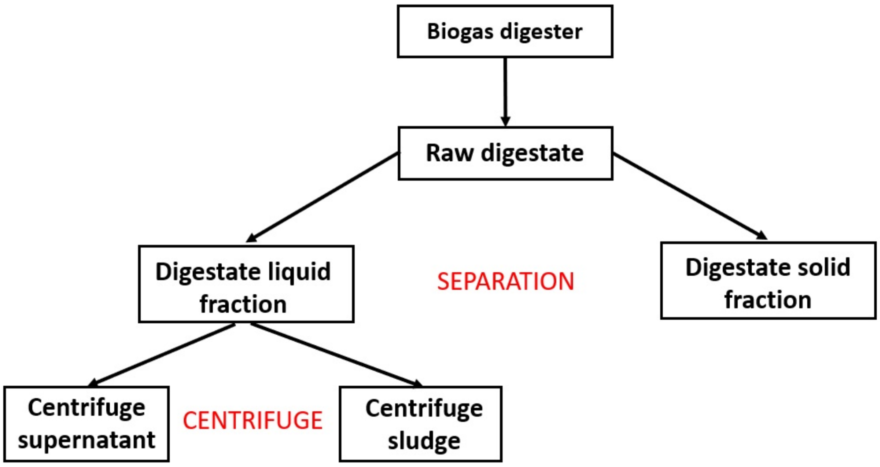

Figure 1. Samples of digestate and its fractions used for research.

2.3. Physical and Chemical Analysis

Analysis of dry matter, organic matter (OM), pH, conductivity, N_{tot}, N-NH_4, and N-NO_3 were performed in the digestate samples and their fractions. The dry matter was determined by the drying method at 105 °C for 24 h. The dried samples were incinerated to determine the organic and mineral matter. This process was carried out by the method of heat loss in a muffle furnace (temperature 550 °C, 3 h). Measurements were made in triplicate.

Measurements of pH and conductivity were performed with the Elmetron CX-401 multifunction device. Before each measurement, the device was checked against standards and calibrated if necessary. In the solutions, measurements were made by direct immersion of the probe. In solid samples (DSF), the measurement was performed in an aqueous extract with a substrate: water ratio of 1:10 (20 g of the fresh substrate and 200 mL of distilled water). Total nitrogen was determined by the Kjeldahl method [20]. N-NH_4 was determined by distillation in an alkaline medium (MgO), the same procedure used for nitrates (N-NO_3) after reduction with Devarda's alloy [21].

3. Results

In fertilizers, the content of individual elements, especially macroelements, is an important element of their fertilizing properties, which are used, i.e., in compiling a fertilization plan. Rational fertilization on the basis of a prepared plan allows one to obtain the desired yield-generating effect with a limited environmental impact. Among the macronutrients, nitrogen is the most yield-generating component [22]. It has a significant impact not only on the quantity of the crop but also on its quality [23–25]. On the other hand, especially if the fertilizer is not used properly, it can have a negative impact on the environment [26]. This applies to, i.e., ammonia emissions [27], the impact on surface waters, and groundwater [28,29]. In addition, pollution of the atmosphere not only with ammonia but also with nitrate nitrogen (V), or more precisely with its denitrification products, should be considered [30]. Therefore, such an important aspect of nitrogen is reason to determine not only its total content but also the share of individual fractions.

3.1. Physical and Chemical Properties

The dry matter content in the analyzed samples varied and ranged from 0.98% to 25.24%. The lowest content was found in the supernatant obtained after centrifugation of digestate liquid fraction from biogas plant A (A-CS), and the highest, 25.24%, solid fraction of digestate was also from the same biogas plant (A-DSF). The dry matter content in the five unprocessed digestates ranged from 3.65% for the D-RD sample to 10.23% for the C-RD sample. On the other hand, the lowest content was found in liquid fractions resulting from separation and supernatants. Regardless of the analyzed digestate samples, it was found that the solid fractions of the digestate were the most abundant in dry matter, regardless of the biogas plant from which the material was collected. These values were at a similar level and amounted to 25.24% for biogas plant A, 24.28% for biogas plant D, and 23.13% for biogas plant B (Table 3).

Table 3. Physical and chemical properties of the analyzed digestates and their fractions.

Biogas Plant	Type of Sample	Sample Code	DM [%]	OM [% of DM]	pH [-]	Conductivity [mS cm^{-1}]
Biogas Plant A	raw digestate	A-RD	5.18	80.85	7.33	14.03
	digestate liquid fraction	A-DLF	2.81	73.15	7.63	15.02
	digestate solid fraction	A-DSF	25.24	94.26	8.75	1.467
	centrifuge supernatant	A-CS	0.98	38.89	7.87	10.98
	centrifuge sludge	A-CSL	8.15	82.74	n.d.	n.d.
Biogas Plant B	raw digestate	B-RD	8.34	83.46	7.50	7.85
	digestate liquid fraction	B-DLF	4.11	75.11	7.45	8.44
	digestate solid fraction	B-DSF	23.13	91.36	9.00	0.865
Biogas Plant C	raw digestate	C-RD	10.23	72.06	8.37	19.41
Biogas Plant D	raw digestate	D-RD	3.65	63.87	7.64	25.10
	digestate liquid fraction	D-DLF	3.5	59.72	7.98	25.80
	digestate solid fraction	D-DSF	24.28	86.17	8.44	2.04
	centrifuge supernatant	D-CS	1.97	54.39	8.05	4.20
	centrifuge sludge	D-CSL	16.54	62.12	n.d.	n.d.
Biogas Plant E	raw digestate	E-RD	7.2	72.98	8.12	19.97
	centrifuge supernatant	E-CS	3.49	69.16	8.17	25.80
	centrifuge sludge	E-CSL	11.95	75.42	8.33	3.22

Note(s): n.d.—not determined.

The organic matter content in the analyzed material was more diverse than the dry matter content and ranged from 38.89% (A-CS) to 94.26% (A-DSF). The content of OM in the raw pulp ranged from 63.87% (biogas plant D) to 83.46% (biogas plant B). It should be emphasized that the extreme values of organic matter were determined in the same samples as in the case of dry matter. This was evidenced, e.g., by an efficiently conducted separation process, both in the biogas plants and in laboratory conditions. The most abundant fractions in OM were solid fractions obtained as a result of separation carried out in the biogas plants. The value of 94.26% (A-DSF) reveals that the produced digestate was rich in organic matter. It is important in the context of the use of organic matter in the fertilization and transformation of soil-humus compounds, as well as for energy purposes, e.g., in the production of solid biofuels. The supernatant obtained from the digestate from biogas plant A was the only one in which the mineral part dominated (61.11%) over the organic part (38.89%).

An important parameter of the digestate and their fractions is the pH value ranging from 7.33 to 9 (Table 3). The lowest value was characteristic of the raw digestate from biogas plant A, and the highest was observed in the digestate solid fraction from biogas plant B. It should be emphasized that the highest pH values occurred in the digestate solid fractions separated in the biogas plant, and the lowest pH value for samples from this group was 8.44.

Conductivity is a parameter that informs, i.a., about the content of elements occurring in ionic forms. It was found that conductivity was a parameter that strongly differentiated the test material samples. The data showed that the values for this parameter ranged from 0.865 mS·cm^{-1} for the sample marked with the B-DSF code to 25.8 mS·cm^{-1} for the digestate liquid fraction D-DLF (Table 3). The lowest values were found in samples of solid fractions and the sludge after centrifugation. On the other hand, the highest average values for individual groups were found in raw digestate pulps and liquid fractions resulting from separation.

In two samples of the centrifuge sludge (A-CSL and D-CSL), the pH and conductivity values were not determined due to the insufficient amount of centrifuged research material. The values of dry matter, organic matter, pH, and conductivity for all analyzed samples are presented in Table 3.

3.2. Content of Nitrogen and Its Fractions

The content of N_{tot} in the tested samples ranged within a wide range from 1.63 g·kg^{-1} to 13.22 g·kg^{-1} FM (Table 4). The lowest nitrogen content was found in the liquid fraction after separation from biogas plant A (A-DLF). The highest was in the digestate solid fraction from biogas plant B (B-DSF). It was shown that the lowest amounts of N_{tot} were found in the digestate liquid fraction and the supernatant after centrifugation. Among the raw digestate, the lowest nitrogen content, 1.64 g·kg^{-1} FM, was observed in a sample from biogas plant A. On the other hand, the highest content was determined for the digestate from biogas plant C (7.76 g·kg^{-1} FM). It was more than twice as high as the N_{tot} content in the remaining raw digestate.

Table 4. Content of nitrogen and its fraction in the digestate.

Biogas Plant	Type of Sample	Sample Code	Content of Nitrogen Forms		
			N_{tot}	N-NH_4	N-NO_3
			g·kg^{-1} FM		
Biogas Plant A	raw digestate	A-RD	1.64	1.30	0.08
	digestate liquid fraction	A-DLF	1.63	1.16	0.20
	digestate solid fraction	A-DSF	4.50	0.75	0.02
	centrifuge supernatant	A-CS	1.71	1.11	0.06
	centrifuge sludge	A-CSL	5.60	1.38	0.10
Biogas Plant B	raw digestate	B-RD	1.80	1.26	0.03
	digestate liquid fraction	B-DLF	1.64	1.18	0.02
	digestate solid fraction	B-DSF	13.22	1.30	0.03
Biogas Plant C	raw digestate	C-RD	7.76	4.75	0.31
Biogas Plant D	raw digestate	D-RD	3.29	2.89	0.06
	digestate liquid fraction	D-DLF	3.52	2.93	0.08
	digestate solid fraction	D-DSF	5.36	2.43	0.05
	centrifuge supernatant	D-CS	3.73	2.76	0.17
	centrifuge sludge	D-CSL	3.41	2.15	0.24
Biogas Plant E	raw digestate	E-RD	3.63	2.94	0.36
	centrifuge supernatant	E-CS	3.24	2.92	0.07
	centrifuge sludge	E-CSL	4.35	3.06	0.07

The ammoniacal nitrogen (N-NH_4) content in the analyzed material ranged from 0.75 to 4.75 g·kg^{-1} FM. The lowest content of N-NH_4 was found for the digestate solid fraction from biogas plant A (A-DSF), and the highest was found similar to N_{tot} in raw digestate from biogas plant C (C-RD). The N-NH_4 form was the dominant form for the unprocessed digestate. Relatively large amounts of the discussed form of N may be the cause of ammonia emission from the digestate, which should be considered an unfavorable phenomenon. Therefore, steps should be taken to limit this process.

The content of N-NO_3 in the analyzed samples was within a narrow range, ranging from 0.02 g·kg^{-1} FM in the A-DSF sample up to 0.36 g·kg^{-1} FM in sample E-RD of raw digestate from biogas plant E (Table 4). The lowest values were observed in some raw digestates (A-RD, B-RD, and D-RD) and liquid fractions (B-DLF and D-DLF). The highest values, apart from the sample mentioned above, were found in the unprocessed digestate from biogas plant C (0.31 g·kg^{-1} FM) and in the centrifuge sludge (0.24 g·kg^{-1} FM) obtained from the digestate from biogas plant D (D-CSL).

The dominant content of ammoniacal nitrogen in the tested material is also evidenced by the share of this form in N_{tot}. In all the tested materials, regardless of their type, it was shown that this share ranged from 9.83% in the digestate solid fraction after separation (B-DSF) to 90.12% in the centrifuged supernatant (E-CS) (Table 5). This share was found to be irrespective of the N_{tot} content. Considering some differences regarding the share of $N\text{-}NH_4$ that appeared between the types of research material, it was shown that N_{tot} had a significant influence on this share only in relation to the raw digestate. This significance was revealed by the value of the correlation coefficient, r = 0.849. Moreover, the coefficient of determination (R2·100) confirms that as much as 72% of the N_{tot} content was determined by the $N\text{-}NH_4$ content in digestate.

Table 5. The share of mineral and organic nitrogen forms in N_{tot} and the quantitative ratio of $N\text{-}NH_4$:$N\text{-}NO_3$.

Biogas Plant	Type of Sample	Share of N_{tot} (%)			$N\text{-}NH_4/N\text{-}NO_3$
		$N\text{-}NH_4$	$N\text{-}NO_3$	Norganic	
Biogas Plant A	raw digestate	79.27	4.88	15.85	16.24
	digestate liquid fraction	71.16	12.27	16.57	5.80
	digestate solid fraction	16.67	0.44	82.89	37.89
	centrifuge supernatant	64.91	3.50	31.59	18.55
	centrifuge sludge	24.64	1.78	73.58	13.84
Biogas Plant B	raw digestate	70.00	1.67	28.33	41.92
	digestate liquid fraction	71.95	1.22	26.83	58.98
	digestate solid fraction	9.83	0.23	89.94	42.74
Biogas Plant C	raw digestate	61.21	4.00	34.79	15.30
Biogas Plant D	raw digestate	87.84	1.82	10.34	48.26
	digestate liquid fraction	83.24	2.27	14.49	36.67
	digestate solid fraction	45.33	0.93	53.74	48.74
	centrifuge supernatant	73.99	4.56	21.45	16.23
	centrifuge sludge	63.05	7.04	29.91	8.96
Biogas Plant E	raw digestate	81.00	9.92	9.08	8.17
	centrifuge supernatant	90.12	2.16	7.72	41.72
	centrifuge sludge	70.34	1.61	28.05	43.69

It should also be mentioned that there is a high proportion of the ammonium nitrogen form in the liquid fraction after separation (A-DLF, B-DLF, and D-DLF), on average 75.45%, compared to the solid fraction, with an average share of 23.94%.

By discussing the ammonium form of nitrogen, the significance of the pH cannot be ignored, although it has been shown that this effect was insignificant for the whole material. On the other hand, the pH in the raw digestate was of much greater importance and the $N\text{-}NH_4$ content in the liquid fraction after separation.

4. Discussion

The main product of the anaerobic digestion process is biogas, and the by-product is digestate. According to Polish law, digestate may be considered as waste, a by-product, or as an organic fertilizer. After production, the digestate should be managed according to legal conditions [31,32], also considering the environmental, economic, and social aspects. It is stated that for large installations above 0.5 MW, the amount of produced digestate is at least tens of thousands of Mg in FM each year. Both the amount and properties of the digestate are variable and depend primarily on the power of the biogas plant and the type of substrates used [33]. Nevertheless, certain properties of the digestate, such as the total nitrogen content and its forms, are within certain ranges.

The most rational method of digestate management is fertilization. Legal regulations regarding the production and use of fertilizers are becoming more and more stringent. They are related, i.e., to the protection of the environment, especially soil [34]. These regulations largely relate to the production and use of mineral fertilizers, the impact of which on the environment at each stage of production, from the acquisition of raw materials, can be very large and often unfavorable [35]. Alternatives to this group of fertilizers are natural and organic fertilizers, the production and application of which should become more common the more that the raw materials from which they are made are widely available globally [36].

The results of many studies show that digestate from agricultural biogas plants is a valuable fertilizer that brings benefits both in agriculture and horticulture. From the results of this study, the raw, unprocessed digestate contained a relatively low dry-matter content, which ranged from 3.65 to 10.23% in the tested materials. This reveals the liquid consistency of the fertilizer. Therefore, the separation of the digestate, both in real and laboratory conditions, significantly changes this parameter. It also allows for a more rational management of digestate. Separation of the digestate on a real scale and in laboratory conditions allowed one to significantly reduce the value of this parameter. This is confirmed by the results obtained.

The digestate is characterized by an alkaline pH, often above 8. It is confirmed in this research, as evidenced by the obtained pH values, ranging from 7.33 to 9. For this reason, the digestate used as fertilizer will be particularly useful on soils with low pH.

Considering the digestate as a source of nutrients, the presence of nitrogen and its forms should be emphasized first of all. Its total content ranged in a wide range from 1.63 $g \cdot kg^{-1}$ to 13.22 $g \cdot kg^{-1}$ FM. Such differentiation is typical, as shown by the research demonstrated in this paper. These differences occurred between the digestates themselves and their fractions.

Similar differences are also found in the research of other authors. For example, Nicholson et al. [37] showed that the nitrogen content in food-based digestate was 8.0 $g \cdot kg^{-1}$. However, in the studies by Riva et al., [38], the nitrogen content in the digestate produced from cattle slurry and energy crops (maize silage and triticale silage) was 3.56 $g \cdot kg^{-1}$. The separated liquid fraction of digestate was characterized by nitrogen content at the level of 3.44 $g \cdot kg^{-1}$, which was similar to the results obtained in this research. However, the content of nitrogen in the elements and its individual fractions is primarily conditioned by the different compositions of the substrates used in the anaerobic digestion process. This is confirmed by the results obtained.

It should also be mentioned that there was not only a high content of the ammonium form of nitrogen ($N\text{-}NH_4$) but also its share in N_{tot}. This share in raw digestate ranged from 61.21% to 90.12%, with significant differentiation in the other types of digestate samples. Relatively less attention is paid to the organic form in digestate. Its dominant share (from 53.83 to 82.89%) was mainly in the solid part of the digestate after separation and, in one case, in the solid part after the centrifuge (73.58%).

Soil resources are limited, and obtaining new acreage is often difficult or even impossible. Therefore, there is a need to increase the yield per unit area. In addition, the growth of the world's population forces agriculture to optimize plant production to meet the population's food needs. In this context, it is challenging to meet food needs without the use of fertilizers because fertilizers, as one of the factors among others, allow increased yields per hectare. In the context of fertilizers, organic fertilizers should also be considered, with which not only macroelements and microelements but also organic matter are introduced into the soil [39].

Nitrogen affects not only crops and their quality but also the environment; hence, the rational nitrogen management in agricultural areas is one of the greatest challenges for agriculture [40]. Based on this element, an on-farm fertilization plan is often created. Therefore, its quantity and availability from individual fractions is a key issue from the agricultural and environmental points of view.

Due to the systematically growing prices of mineral fertilizers in the world in 2021 and 2022, an increased use of alternative fertilizers should be expected. This also applies to digestate from agricultural biogas plants. From an agricultural point of view, the most important parameters characterizing the digestate are dry matter, pH, nitrogen, phosphorus, potassium content, and the absence of chemical and biological contamination. Considering the chemical composition, digestate from agricultural biogas plants can be considered a multi-component fertilizer. However, its agricultural use depends on the fulfillment of all requirements regulated by legal provisions in a country.

Using substrates of agricultural origin for the production of biogas, such as manure, slurry, or by-products of the agri-food industry, e.g., inedible parts of plants, the produced digestate will be safe for the environment if the biogas plant is functioning properly [41,42]. However, for this purpose, the conditions for conducting the anaerobic digestion process should be controlled.

The most rational solution seems to be the transfer of biomass and waste to an agricultural biogas plant and in return collection of high-quality digestate, which would be used for fertilization [43]. This solution will not only shorten the supply chain for the supplier and recipient of products but also fit in with the circular economy trend [44]. In addition to the total content of the analyzed elements, the share of individual fractions should also be considered. Plants take up minerals in different ways. Therefore, it may be useful to determine the availability of the analyzed fraction. However, research needs to be continued, including the use of individual digestate fractions for specifically selected plants.

5. Conclusions and Further Research

Due to the fact that Poland is a country with an agricultural tradition, one should expect a continuous dominance of the share of biofuels in the overall balance of obtaining primary energy from renewable sources. Additionally, it will be favored by the widely developed and decentralized agri-food industry.

Agricultural biogas plants seem to be ideal for processing all kinds of organic waste. However, the need to manage the digestate generated in the anaerobic process should be considered. The digestate can be used for fertilization. However, it should contain minerals and organic ingredients in doses appropriate for the plants. The popularity of organic and natural fertilizers should increase. This is due to, i.a., the increase in gas and mineral fertilizer prices in 2021 and 2022. Therefore, one should expect a large number of studies and an increase in their scope on the topic of utilization of waste and by-products as fertilizer.

In a typical agricultural biogas plant with a capacity of 1 MWe, the annual production of the digestate reaches tens of thousands of Mg. These are huge amounts that can be managed profitably and lawfully. Considering the properties of the discussed residue, it is recommended to use the digestate for fertilization purposes. This solution is also suggested by numerous scientists conducting research around the world.

As part of this study, the content of selected nitrogen fractions in raw digestate and its fractions was determined. It was found that the content of individual forms of nitrogen is different in relation to the biogas plant from which the digestate was obtained and the analyzed digestate fraction. The influence of the raw materials used and the technologies functioning in the biogas plant may also be important for the digestate. Further research on digestates should be carried out for other elements and their fractions. Additionally, environmental, social, and economic aspects should be analyzed.

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Abbreviations

CS	centrifuge supernatant
CSL	centrifuge sludge
DM	dry matter [%]
DLF	digestate liquid fraction
DSF	digestate solid fraction
FM	fresh matter [%]
$N\text{-}NH_4$	ammonium nitrogen
$N\text{-}NO_3$	nitrate nitrogen
N_{tot}	total nitrogen
OM	organic matter
RD	raw digestate

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