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Economic and Energy Efficiency Analysis of the Biogas Plant Digestate Management Methods

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Abstract: The aim of this study was to conduct a comprehensive economic and energy efficiency analysis of selected digestate management methods, considering their implications on operational costs and resource management. To achieve this aim, the study focuses on a comparative assessment of different digestate management methods, including land application, mechanical separation, the composting process and pellet production. The economic analysis involves the evaluation of the initial investment, operational expenses, and potential revenue streams associated with each method. The most economical and popular solution of digestate management is direct use as fertilizer, with total costs of 1.98 EUR·Mg^{-1}. All of the other methods involve higher digestate management costs, respectively; for separation it is 2.42 EUR·Mg^{-1}, for composting it is 2.81 EUR·Mg^{-1}. The process that is the most energy-intensive, but profitable, is the production of pellets from digestate, resulting in profits of 334,926 EUR·year^{-1}. It should be noted that the other analyzed methods of digestate management also bring many environmental benefits, affecting sustainability and reducing emissions. The results of this research will contribute unique data on the feasibility of managing the digestate and its fractions. The calculations of economic and energy values for different strategies will allow for the optimization of the overall performance of the biogas plant, thus promoting a circular economy.

Keywords: energy efficiency; sustainable energy; waste management; waste as resources; digestate; fertilizer; energy recovery

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1. Introduction

Biogas, defined as a renewable gaseous energy source, is constantly strengthening its position in the structure of energy acquisition in the European Union countries and the world. The development of technology allows for the versatile use of this type of fuel. Currently, the largest percentage of installations operate in cogeneration, generating electricity and heat, while a new trend is the production of high-calorific gaseous fuel biomethane, which is then liquefied into a liquid fuel like bioLNG [1,2]. Fuels in liquefied or compressed form, particularly, are promoted as the best alternative for land and sea transportation, replacing fossil fuels. In addition, the greatest advantage of biogas plants is the controlled and constant operation time compared to, for example, wind power. The answer to the intermittent operation of other renewable energy sources is the implementation of biogas peaking plants, responding to the changing demand of the energy grid [3,4].

Based on archival data, it has been estimated that the amount of energy produced from biogas doubled across the EU between 2008 and 2016, and it is predicted that an-other such increase is possible as early as 2030 [5]. The fulfillment of these predictions is only possible if the efforts of many entities are properly combined, starting from scientists through to investors and legislators, and ending with public attitudes [6]. An established law for the biomass and biogas sector can help achieve up to half of the goals set in directives, such as RED II and RED III. The fuel produced by anaerobic digestion, when properly refined, can replace the fossil fuels used in all the energy sectors that actually have the

strongest environmental impact, such as transportation [7,8]. The digestate generated after the process is also part of the EU's biogas energy policy models. The significant growth of biogas installations is the same as the increasing amount of digestate, which is the last element of the closed cycle. So far, regulations in most countries are still not clearly formed with regard to the possibility of digestate valorization, which is a major threat to the development of biogas installations [9]. Therefore, it should be noted that European directives and recommendations should not only focus on the possibilities of using and processing the main product, which is biogas, but also address the issue of managing the valuable digestate product [10,11].

The growth of biogas plants is inevitable, and currently dominates among the technologies that facilitate organic waste management. Despite its many advantages, this technology is very often criticized with regard to the issue of safe digestate management, as well as an only partial recovery of energy and materials from the initial input mass, since a significant amount of matter is left in the digestate [12,13]. The main aim of anaerobic digestion is to produce gaseous fuel, and its by-product is the digestate [14]. The digestate, which enters a storage tank or lagoon, usually contains more than 90% water, while the remaining components are nutrient-rich biomass [15].

In Europe, currently, about 19,000 biogas plants that produce biogas or biomethane, and also the digestate, are in operation [16]. The leader in promoting this technology is Germany, where the number of operating facilities is close to 10,000. After many years of growth, the industry has slowed down and is currently in a state of transition. This fact is mainly due to changes in regulations supporting investments in this type of renewable energy source, as well as those limiting the use of classical substrates, such as corn silage. A significant number of installations are also currently being upgraded for biomethane production [17,18]. The situation is different in other EU countries, such as Poland, where the biogas installation market is at a stage of dynamic growth and development [19]. It is this continuous development of the biogas sector that is associated with the generation of significant amounts of digestate pulp, requiring management. It is estimated that more than 180 million tons of the valuable product is currently produced in the EU, which is usually unprocessed and managed in the form of farm fields [20].

When the digestate produced goes into the storage tank, it is usually in liquid form, the composition and organic matter content of which depends mainly on the substrates used for biogas production [11]. It contains, among other things, water and microorganisms, as well as mineral substances and undecomposed organic compounds. Depending on the literature sources, it is assumed that the amount of digestate produced by biogas plants ranges from 90% to 97% of the mass of feedstock substrates [21], although there are cases where this amount falls below 90% of the initial mass of the substrates used for biogas production. In addition, digestate is characterized by higher NH_4 and higher pH levels, a reduced organic matter content, and a lower C:N ratio compared to animal manure, among others. Studies conducted by Gobern et al. also show the beneficial characteristics of digestate, such as high odor reduction, an improved nutrient availability, especially for plants, and a more uniform fertilizer mix compared to other natural fertilizers [22].

However, for anaerobic digestion technology to be both environmentally and economically viable, it is necessary to take into account the possibility of managing digestate for energy recovery, as well as value added products. The current direction of digestate management recommended by scientists involves moving away from traditional applications, such as direct fertilizer use, in favor of valorization using available techniques. To manage digestate fractions, directions such as composting, biofuel and biocarbon production are being promoted to maximize energy and material recovery [23]. Great interest exists in the thermal processes, such as gasification and pyrolysis. The bio-oil produced using these techniques, along with pyrolysis gas, can provide additional fuel for cogeneration units, and the resulting biocarbon is an excellent product for improving soil properties. The high concentration of ash in the digestate eliminates the possibility of direct combustion due to the possibility of problems with sludging in boilers. Due to its high level of sophistica-

tion, this technology is not often implemented on an industrial scale [13]. Another of the alternative uses of the digestate's solid fraction is to use it as bedding to replace straw in animal husbandry. Properly dried and prepared material is characterized by hygroscopic properties similar to those of straw. The significant advantage of this type of mulch is due to its better grindability, thanks to which the manure created in this way is more easily mineralized in the soil. The use of modern methods of pulp management is in line with the concepts of a circular economy. It is important that individual technological solutions are able to cope with the changing composition and structure of the digestate. However, the technological and, more importantly, economic aspects of the proposed methods depend on the specific case of the biogas plant, as well as its capacity and location. The expansion of the selected processing methods depends mainly on financial factors [10,24].

The constant increase in the number of biogas installations in some countries around the world leads to problems related to the management of significant amounts of digestate. In most EU countries, the obligation to store digestate results from the seasonality of collection, which is not possible in the winter. This fact makes it necessary to build tanks to store the digestate, which is very expensive, and the use of cheaper open lagoons causes emissions and losses of fertilizer compounds [25].

If no methods of digestate valorization have been introduced, the only way to use it is to fertilize agricultural fields. An unfavorable aspect of using digestate as a fertilizer is its high hydration. The high water content of the fertilizer makes it expensive to transport in relation to its fertilizer value. Therefore, it is reasonable to develop only a small area in the immediate vicinity of the plant. The disadvantages of using digestate as a fertilizer relate to controlling the content of heavy metals and microbiological contaminants within legally permissible limits [26]. In the context of biogas plants, digestate pulp can be a potential source of valuable organic components that, if properly processed, can find application in various industrial sectors.

The aim of the study was to make an economic and energy efficiency analysis of the digestate management involving selected processing methods. In addition, the environmental issues related to the technologies discussed were analysis. Based on the literature data and our own data from a real scale biogas plant, an analysis was made considering four selected methods of digestate management. The analysis presents the most favorable aspect of digestate management in terms of energy, economics and environment. Regardless of the method chosen, each contributes to a more sustainable biogas plant.

2. Materials and Methods

2.1. Research Object and Characteristics of the Research Materials

For the calculations and analysis, actual data from a selected biogas plant operating in Poland were used. The analyzed plant uses feedstock from agricultural sources for energy production and is classified as an agricultural biogas plant according to the Act on Renewable Energy Sources of 20 February 2015 [27]. A site visit was made at the installation, which allowed for data to be collected on the fermentation technology used, the amount of feedstock processed and the total mass of digestate pulp produced. It was established that the produced digestate is used in its entirety, directly to fertilize agricultural fields. Data on the amount of generated digestate is for the full reference year 2023.

The biogas plant operates using wet fermentation technology with a nominal capacity of about 2 MW of electricity and a capacity of one digestate tank of 5000 m^3. The installation has three such tanks. A total of about 79,500 Mg of agricultural biomass was processed during the year of the installation's operation. The main substrates used at the installation are manure and corn silage, which account for more than 95% of the annual mix. Other substrates accepted depending on availability may include manure. After the methane digestion process, the residual fraction is treated as a digestate, generated at a rate of 71,500 Mg per year. The reduction in the mass of the resulting digestate compared to the mass of the input is due to the partial decomposition of organic matter during the fermentation process and biogas production [28].

During the last few years of the plant's operation, the process has been controlled while keeping the optimal parameters of anaerobic digestion. However, it should be mentioned that the composition of the digestate is affected not only by the type of feedstock, but is also dependent on the degree of size reduction or the temperature of the anaerobic digestion process. The digestate for the study was taken from storage tanks (digestate tank). The tank was also homogenized before taking a representative sample, which was made possible by an internal mixing system. This was carried out to minimize possible discrepancies in the results obtained and to create optimal conditions for the experiment, as also confirmed by other researchers [29,30]. The installation is equipped with a screw press, which is used to separate the digestate into fractions. The separation of the digestate fraction provides an opportunity to turn back some of the liquid fraction to the dilution of the feedstock substrates. The screw press used at the plant had a capacity of 75 $m^3 \cdot h^{-1}$. The samples taken were free of biological and chemical contamination.

2.2. Physicochemical Parameters of the Digestate

In order to carry out economic and energy calculations, the necessary physicochemical properties of the digestate product were determined and performed, meeting certified laboratory standards. An analysis and testing of the dry mass and the organic dry mass parameters of the test material were performed in accordance with the standard for dry mass PN-75 C-04616/01 and organic dry mass PN-Z-15011e3:200. The determination of dry mass content was performed for the collected samples of raw digestate, liquid fraction and solid fraction. The dry matter parameter was tested using a dryer for the samples, at a temperature of 105 °C for a period of 24 h. For each measurement, the collected samples were homogenized. The determination of organic dry matter content was performed as normal, and the substrates, after the drying process, were placed in a muffle furnace for 3 h at 550 °C [31].

The pH value was measured in accordance with PN-90 C-04540/01 using Elmetron's CX-401 multifunctional device (Elemtron, Zabrze, Poland). Twenty grams of each of the analyzed samples of the digestate were weighed and then poured into 180 mL of distilled water to obtain an aqueous suspension, which made the analysis possible.

The last measurement that determined the size of the area for the method of the agricultural management of the digestate (fertilizer) was the content of total nitrogen in the analyzed pulp. Using this analysis, organic nitrogen is converted to ammonium nitrogen by evaporating samples of the digestate in the presence of sulfuric acid and a catalyst. The nitrogen concentration was determined by the Kiejdahl method according to ICP-OES [32].

2.3. Digestate Management Methods

For the selected biogas plant, an economic and energy analysis was carried out using four options for the processing and management of the digestate. The calculations estimated the current investment and operating costs for each of the selected technologies for the processing and management of the digestate. In addition, energy expenditures, such as energy consumption, as well as the need to adapt equipment and employ additional people to operate machinery, were also considered.

Together with the development of the biogas sector, the amount of generated digestate is increasing [33]. The characteristic and unique properties of the digestate allow it to be managed in many ways, while fitting into the idea of a circular economy. The article analyzes such technologies and management methods as direct fertilization with the digestate, separation of the digestate with a fertilizer-based utilization of its fractions, the composting of the digestate, as well as the production of bio-solid fuels such as pellets [34]. Analyzing the results of our own research and the other studies available in the scientific literature, a methodology was developed for the presented technologies of digestate processing [33,35].

2.3.1. Direct Application of Raw Digestate

The largest percentage of biogas plants operating in Poland manage the generated digestate as an unprocessed product interchangeably with other organic fertilizers, such as slurry. The analyzed method of digestate management for the selected biogas plant is recovery according to the R10 method, i.e., using the digestate as organic fertilizer [36]. To realize the recovery of digestate by the R10 method, it is necessary to meet a number of the requirements contained in the Regulation of the Minister of Environment on R10 recovery. In order to be considered a soil conditioner, the digestate must be tested for physicochemical, chemical and microbiological properties. According to Polish law, such a digestate, after obtaining the appropriate certifications, is treated as a soil improver (agricultural fertilizer) [25].

For the method of management of the raw fraction of the digestate, it was based on the available literature sources [37,38], referring, however, to actual prices. The calculations took into account the actual capacity of the plant, which translates into the amount of raw digestate produced equal to 71,500 Mg per year. The digestate was also analyzed for its physicochemical content. These values were used to calculate the nitrogen content in Mg of raw digestate, which directly translates into calculations of the maximum fertilizer application rate. According to Polish law, the limit for the amount of nitrogen applied is 170 kg N·ha^{-1} [39]. The total area of fields for the application of digestate was calculated using Equation (1).

$$Total\ area\ [ha] = \frac{nitrogen\ content\ in\ the\ digestate[\frac{N}{Mg_{FM}}]}{llimit\ fot\ the\ amount\ of\ nitrogen\ [\frac{N}{Mg} * ha]}, \quad (1)$$

However, it is important to note the fact that under real conditions, roads never directly extend in a straight line. Such assumptions were formulated for the most favorable transport option (pulp is bottled on 100% of the field area near to the biogas plant). Under real conditions, pulp cannot be spilled on some areas (forests, lakes, swamps and urbanized areas). The calculations have been carried out for the most common method of distributing digestate, for which this will be undertaken with a set consisting of a slurry tanker coupled to an agricultural tractor. On the basis of the available literature data and the authors own calculations of the study, the operating times of the bottling unit, the capacity, and the annual capacity of their use have been adopted, respectively. All the operating costs of the machine set were also taken into account based on the methodology developed by IBMER [37,38,40]. The following general assumptions were made for the calculations related to the analysis of direct fertilization technology with digestate:

- operating time of one set is 1400 h per year;
- the capacity of spreading digestate is 26 Mg·h^{-1};
- capacity of the slurry tanker is 20,000 m^3.

2.3.2. Separation of the Digestate and Fertilizer Use of Its Fractions

Biogas plants, which are characterized by a significant amount of processed substrates, also struggle with a higher amount of generated digestate pulp. This problem is especially true for plants that use low-energy and hydrated substrates, such as slurry, in their feedstock composition [41]. The resulting amounts of digestate product for such a case can then cause problems with its direct management without the appropriate processing [42].

The digestate is processed into liquid and solid fractions. Both the raw digestate and the fractions obtained after separation can be used for fertilization applications, which increases the number of instructions for its management. The liquid fraction is applied agriculturally using slurry tankers equipped with splash plates (pre-sowing application), spill hoses (post-sowing application) or by soil application using special applicators. Soil application with an immediate soil cover of the introduced digestate is the most advantageous technique, as it minimizes the loss of a valuable product for plants—nitrogen. In

the case of the solid fraction of the digestate, pre-sowing solutions should be used, and the product should be spread on the field with an agricultural fertilizer spreader [43,44]. The method for the management of the liquid fraction and the solid fraction of the digestate is based on a methodology consistent with that presented in Section 2.3.1.

The process of separation and then direct fertilization with fractions of the digestate is characterized by additional cost due to, among other things, the purchase of specialized equipment, energy expenditures or the need for storage space for two different end products. For calculation purposes, for the method of separation of the raw fraction of the digestate, this was based on the literature data [45–47].

Separation efficiency indicates the rate at which raw material can be separated into individual fractions. Small screw presses separate at an average efficiency of 18 $m^3 \cdot h^{-1}$, and range from 6 to 25 $m^3 \cdot h^{-1}$ [48]. The real flow rate will depend on the input dry matter content of the digestate. A product with a high dry matter content will have a lower flow rate than one characterized by higher hydration. The total volume of feedstock and the number of operating hours will determine the required capacity of the separator, and thus the choice of technology and the number of separators required for the biogas plant [49].

Capital costs (CAPEX) and operating costs (OPEX) determine the combined cost of the separation process. Screw presses appropriate for separating slurry and digested sludge will have a total capital and installation cost of about 17,500–77,000 EUR [35]. Capital costs will depend mainly on the maximum amount of raw material to be processed, as well as the need to install additional feed pumps and control automation. In addition to the capital costs associated with the purchase of the equipment and the technological adjustment of the plant, it should be noted that the press requires electricity to operate. The amount of energy required per unit volume of separated raw material is closely related to the efficiency of separation. Higher energy consumption per unit volume means increased separation costs and a higher investment cost. For cost-effectiveness, it is important to strike a balance between investment costs and maintenance, as well as operation costs. The energy requirement for separating raw material with screw presses is usually in the range of 0.4–1.5 $kWh \cdot Mg^{-1}$ [35,50]. For calculations and analysis, a press from a well-known producer was selected based on data from the selected biogas plant. The calculated electricity demand was 0.5 $kWh \cdot Mg^{-1}$ for the analyzed case. The energy economic analysis for this type of technology took into account the value and parameters of the biogas plant digestate given in Section 3.1.

2.3.3. Composting Process

The solid fraction of the digestate is an ideal material for the production of a high-quality fertilizer, such as compost. The composting process is an aerobic management method, during which the biological decomposition of organic matter takes place in the presence of oxygen in a wet and warm environment. The product of composting is compost, and the by-products are carbon dioxide, water and heat [31,51]. However, the condition is the use of appropriate technology that guarantees the maintenance of the process parameters, such as proper temperature, giving microorganisms optimal conditions for the process. Depending on the needs of a given plant, there are various waste composting technologies on the market. The most common are prism composting with the use of re-dumpers, membrane composting and chamber composting. The smell of the digestate is not unpleasant, and after composting it is even odorless, so it can be stored near house-holds [14]. For a facility such as composting, the lifetime of operation and project planning is usually 20 years, and this is the value used for calculations. The individual costs of composting technology also consist of [52]:

- land requirements per unit capacity (depending on re-tenure and maturation times);
- purchase of additional machines;
- the level of utilization of the installation;
- selected technology;
- the character and length of the contracts and materials received;

- product sales income, related to raw material quality and final maturity.

Additionally, in order to accurately perform the analysis, assumptions were made regarding: the raw material acquisition and transportation costs, the costs associated with the operation of selected equipment and machinery (depreciation, electricity consumption, repair and maintenance), personnel costs and other costs. The selling price of the final product, which is compost, based on source data, is 14 EUR·Mg^{-1} [53].

The digestate from the anaerobic digestion process becomes the raw material for composting. The typical period of this process ranges from 8–12 weeks required for composting feedstock, but it is possible to reduce this period to as little as 2–3 weeks for the digestate because the material has been partially decomposed during the fermentation process, making it easier for composting organisms to break it down into stable compost. This is a significant reduction in time, resulting in a simultaneous reduction in both the capital and operating costs associated with processing the same amount of material [54].

The energy mix is more important for a biogas plant than for composting. In the case of anerobic digestion, net energy production is key, since energy from biogas is usually the main benefit (i.e., source of revenue). The analysis is more straightforward for a composting operation, where all the energy comes from the feedstock, but it is still very important because the energy input is the main determinant of the operation and maintenance costs [55].

2.3.4. Solid Biofuel Production from the Solid Fraction of the Digestate

After the separation process on a biogas plant, the digestate can also be used to produce solid fuels, such as pellets. The use of dried digestate as solid fuel also appears to be a promising alternative [50]. The digestate product, converted into solid biofuel, creates new opportunities for its fertilizer or energy use. Characterizing the methodology for this process, similarly to the screw press, individual equipment such as a pellet press was selected for the pelletizing process. For the selected biogas plant, a pellet machine with a minimum capacity of 1 Mg·h^{-1} is required. The analysis uses a modular pellet press with a total capacity of up to 2 Mg·h^{-1}. The press is characterized by a low electricity consumption of 60 kWh·h^{-1}. The price of such a production line is about 120,000 EUR. This type of press is characteristic of the technology that allows for the use of digested pulp as feedstock. An additional full-time employee is required to operate such equipment. As in previous considerations, all necessary criteria related to the operation of the selected equipment (depreciation, electricity consumption, repair and maintenance), personnel costs, as well as the cost of 1 Mg big bag-type bags for the packaging of finished solid biofuel were included in the analysis [56].

In order to produce pellets from digestate, it is necessary to carry out a series of stages, starting with separation on a screw press. The next stages are drying, grinding and the actual granulation process. The costs of solid biofuel production were estimated based on the methodology presented by Czekała et al. [34]. An economic analysis based on the assumptions of Czekała et al. [31] determined the cost of pellet production, as well as the price of the finished product.

3. Result and Discussion

In the analysis conducted, four possible options for the management of the digestate were selected. In the analyzed biogas plant, the first option is mainly used, which is due to the widespread use of recovery by the R10 method (fertilization). Occasionally, option two is also used. Option three and option four are alternatives that set current trends. In order to illustrate the digestate management options selected in the calculations, a flow chart was created, as shown in Figure 1.

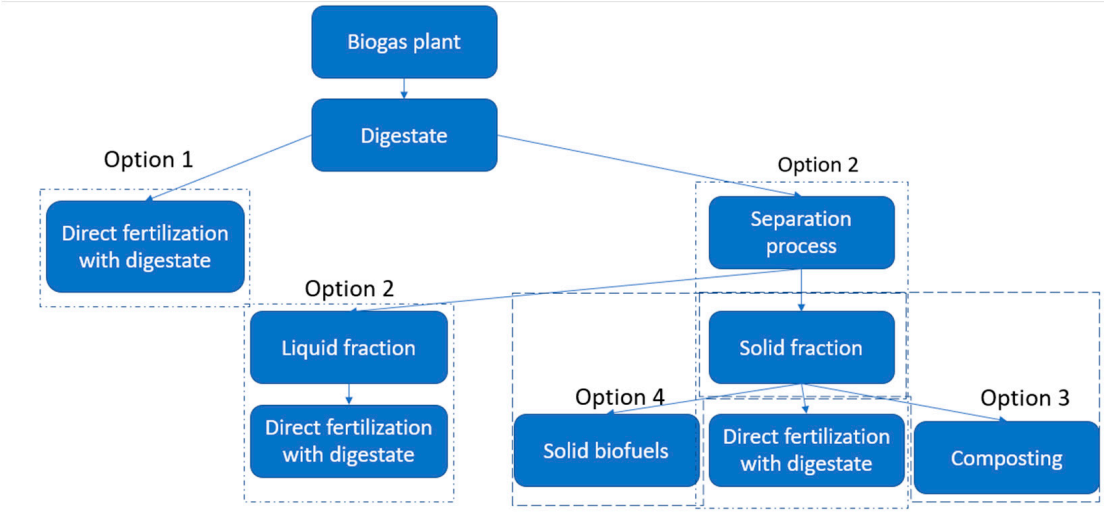


Figure 1. Flow chart of the digestate management options (own study).

In all calculations and analyses performed, values were used, taken according to Table 1.

Table 1. Assumptions used in the calculations (own study).

Name	Value
Currency converter	1 Euro = 4.2572 PLN (21 May 2024)
Operating time	20 year
Price of electricity in Poland	0.27 EUR·kWh^{-1} (2024)
Employee's daily working time	10 h
Employee's hourly salary	9.40 EUR·h^{-1}

3.1. Amount and Properties of the Analyzed Digestate

The total mass of the generated digestate at the selected biogas plant is equal to 71,500 Mg. Converting this value into daily production, an average of 195.9 Mg of raw digestate was obtained. Taking into account the separation process, the solid fraction accounts for 30%, while the liquid fraction accounts for 70% of the total amount of raw digest, which, respectively, implies the need to manage 21,450 Mg of the solid fraction and 50,050 Mg of the liquid fraction. The raw and unprocessed digestate from the analyzed biogas plant is in the form of a slurry, with a dry matter content of 6.1% and an organic dry matter content of 71.2% D.M. The analyzed fraction of the digestate was characterized by a total nitrogen content of 5.8 kg N·Mg$_{FM}$$^{-1}$. With a content of 5.8 kg N·Mg$_{FM}$$^{-1}$, the result was about 414.7 Mg of nitrogen content present in the total mass of digestate pulp. Such a value translates into the total amount of hectares needed to manage the untreated digestate, which was calculated according to Equation (2):

$$Total\ area\ [ha] = \frac{414.7\left[\frac{N}{Mg_{FM}}\right]}{0.170\left[\frac{N}{Mg} * ha\right]} = 2439.4\ ha, \quad (2)$$

The calculated value of the area was taken as a circle with a radius of 27.9 km, so in simplified terms it can be assumed that the average transport distance will be half of this size, at 13.95 km. After converting by the realization factor, this value is 36.3 km and 18.1 km, respectively. On this basis, the calculated digestate rate according to the regulations is 29.3 Mg$_{FM}$ ·ha^{-1}, which gives a value of 1.79 Mg on a dry matter. The density of the raw digestate used in the calculations is 1 Mg·m^{-3}, while that of the solid fraction is

equal to 0.6 Mg·m^{-3}. Using the above calculations and test results, the properties of the raw digestate and its fractions are shown in Table 2.

Table 2. Parameters of the digestate and its fractions (own study).

Name	Unit	Raw Digestate	Solid Fraction	Liquid Fraction
Dry mass	[%]	6.1	29.67	3.9
Organic dry matter	[% D.M.]	71.2	91.50	64.4
pH	[-]	7.69	8.49	7.96
Total nitrogen	[N kg·Mg$_{FM}$$^{-1}$]	5.8	4.9	3.7
Mass	[Mg$_{FM}$·year^{-1}]	71,500	21,450	50,050

3.2. Direct Agriculture Application of Raw Digestate

The high water content and low nutrient concentration of the digestate result in high costs during storage, transportation and utilization. The processing of the digestate can effectively remove water and affect the partitioning of nutrients between the digestate fractions and the final products. From the economic point of view, in addition to the total nitrogen content, which was the determinant of the experiments conducted, the digestate contains in its composition many valuable fertilizer compounds, such as the micro and macro elements, magnesium, phosphorus and potassium, among others. In the calculations, the value of the digestate was the information obtained from the owner of the biogas plant as the price at which it is currently (May 2024) possible to sell this product. The price of 1 Mg of fresh digestate was 25 PLN, which is equal to 5.87 EUR. The economic value of this product should be considered as a revenue component in the total mix of the individual revenues of the biogas plant. The analysis of this scenario is aimed at determining the energy inputs in the case of fertilization by the biogas plant owner of agricultural fields. The specified maximum nitrogen application rate per hectare/year, as well as the required storage time of the digestate for selected EU countries, is presented in Table 3.

Table 3. Examples of nitrogen application rates and application dates (own study based on [57]).

Country	Maximum Nitrogen Rate	Storage Time	Possible Date of Application of Nitrogen Fertilizers
Poland	170 kg N·ha^{-1}·year^{-1}	3 months	1 March–30 October
German	170 kg N·ha^{-1}·year^{-1}	6 months	1 February–until harvest
Sweden	170 kg N·ha^{-1}·year^{-1}	6–10 months	1 February–1 December
Austria	170 kg N·ha^{-1}·year^{-1}	6 months	28 February–5 September

The basic indicator needed to determine the economic analysis of digestate management was to establish the costs associated with the purchase of a farm tractor together with a slurry tanker. Based on the study by Pilarski et al. and current prices of agricultural machinery, the purchase price of the New Holland T7.260 Classic type agricultural tractor was assumed for the calculation to be at the level of 152,000 EUR net, and the price of the Joskin Quadra type slurry tanker at the level of 162,000 EUR, making a total of 314,000 EUR [38,58,59]. The straight-line depreciation method was used to calculate the depreciation value of the set, assuming a 20-year service life and 1400 h of operation per year [60]. The calculated annual depreciation cost of one set is 15,665 EUR·year^{-1}, while the hourly cost is equal to 11.20 EUR·h^{-1}. The operating costs were assumed at 50% of the depreciation cost. The calculated fuel costs, at an average consumption of 17 L, are 25.84 EUR·h^{-1}.

Based on the input data, the market value of raw digestate calculated according to Equation (3) is:

$$V_D = M \cdot C_D = 71{,}500\ Mg \cdot 5.87\ \ EUR \cdot Mg^{-1} = 418{,}705\ EUR, \quad (3)$$

where

V_D—total value of digestate;
M—total mass of digestate;
C_D—market price.

The value mentioned above was related to the costs associated with the management of the digestate by the owner of the biogas plant in relation to the income obtained from the sale of the digestate. Table 4 summarizes the unit costs of operating the fertilizer set-up.

Table 4. The unit cost of managing agricultural raw digestate for one set (own study).

Name	Value
Depreciation of the digestate spreading set	0.43 EUR·Mg^{-1}
Costs of operating the set (maintenance, repairs, insurance)	0.21 EUR·Mg^{-1}
Salary for one employee	0.36 EUR·Mg^{-1}
Fuel consumption	0.98 EUR·Mg-^{1}
Total costs	1.98 EUR·Mg^{-1}

The land area of 2439.4 hectares, calculated in Chapter 3.1, translates into an average length of the route taken by a tractor with a slurry tanker of 18.1 km.

Based on the data in Table 4, the total cost of utilizing the digestate for fertilizer applications was calculated according to Equation (4).

$$V_d = M \cdot C_d = 71{,}500\ Mg \cdot 1.98\ \ EUR \cdot Mg^{-1} = 141{,}670\ EUR, \quad (4)$$

where

V_d—total cost of digestate applications;
M—total mass;
C_d—unit management cost.

An employee, during 10 h of working time, is able to achieve a capacity of 13 courses of 20 Mg each, which gives a total capacity of 260 Mg of digestate per day, giving a capacity of 26 Mg·h^{-1} of digestate bottling by one employee. In order to be able to manage the entire amount of digestate pulp, two such sets and two employees need to work.

Based on this, the calculated digestion rate according to Polish regulations is 29.3 Mg_{FM}·ha^{-1}, which, on a dry matter ratio, gives a value of 1.79 Mg_{FM}.

From an energy perspective, in the case of fertilizing with raw digestate, it is necessary to take into account the energy consumption of the tractor per unit of fuel used, amounting to a total of 23,800 L. Assuming the weight of one liter according to the literature at 0.84 kg·L^{-1}, we obtain 20.23 Mg of fuel. The calorific value of diesel fuel is 10.7 kWh·L^{-1}, which gives a value of 254,660 kWh of energy required for bottling the digestate in the fields.

3.3. Digestate Separation and Agriculture Application of Its Fraction

The separation of the digestate into solid and liquid fractions is a basic element necessary for further processing. The most popular technology used today is the screw press [48,61]. The yield-forming elements, including nitrogen, are separated into solid and liquid fractions. In the analyses and calculations, a screw press was used for the separation of raw digestate, for which data based on a literature review and technical documents obtained from the manufacturer were used, and are presented in Table 5. The electricity consumption of the screw press was calculated based on the separation of the total digestate.

It should be noted that the separation of digestate into solid and liquid fractions does not change the total area of land needed for digestate application.

Table 5. Technological data for the selected screw press (own study).

Name	Value
Electrical power	11 kW
Average level of dry matter of the produced solid fraction	29.7%
Separation efficiency for the selected digestate	45 $m^3 \cdot h^{-1}$
Energy consumption	0.5 $kWh \cdot m^{-3}$
Working time	1589 $h \cdot year^{-1}$

In accordance with the specified methodology, and using assumptions from the direct management of the digestate, tables were created to summarize the costs associated with the operation and depreciation of the screw press for the selected biogas plant. No additional technical personnel are required to operate the press, so the personnel costs are related only to the process of the agricultural management of the digestate. However, it is important to note the fact that the solid digestate must be distributed with another agricultural device, i.e., a manure spreader. In order to simplify the calculations, it was assumed that the productivity of both machines and costs are at the same level.

In the method of the separation of digestate, it is necessary to include in the total depreciation costs the need to prepare the site for the screw press, along with its necessary infrastructure. The value of this type of investment, without including the cost of purchasing the screw press, was estimated at 100,000 EUR. On the other hand, the cost of purchasing the equipment, which is a screw press, is 72,820 EUR. The cost of maintenance and repairing the screw press was assumed at 30% of the depreciation cost. All the cost of digestate separation is summarized in Table 6.

Table 6. Costs of digestate separation (own study).

Name	Value
Depreciation of installation costs	0.23 $EUR \cdot Mg^{-1}$
Depreciation of the aerator	0.05 $EUR \cdot Mg^{-1}$
Maintenance and repair costs of the aerator machine	0.02 $EUR \cdot Mg^{-1}$
Energy consumption	0.14 $EUR \cdot Mg^{-1}$
Total value	0.44 $EUR \cdot Mg^{-1}$

The economic value of the digestate separated into two fractions, calculated in accordance with formula (5), should be similarly considered, as in the case of raw digestate, as the cost of distribution on the fields and the benefit of using it as a fertilizer in comparison with the previous methods of its management. The cost of distributing the digestate was assumed at the same level as in the case of raw digestate management, taking into account only the additional costs resulting from the use of a screw press.

$$V_s = M \cdot C_s + V_d = 71{,}500\ Mg \cdot 0.44\ \ EUR \cdot Mg^{-1} + 141{,}670\ EUR = 173{,}130\ EUR, \quad (5)$$

where

V_s—total costs of digestate management including separation;
M—total digestate mass;
C_s—unit cost of digestate separation.

Using the above calculations and the results of testing the properties of the raw digestate and its fractions, the market value of the liquid fraction and the solid fraction of the digestate was calculated according to Equation (6).

$$V_s = M_{solid} \cdot C_{solid} + M_{liquid} \cdot C_{liquid} = 21{,}450\ Mg \cdot 9.3\ \ EUR \cdot Mg^{-1} + 50{,}050\ Mg \cdot 4.65\ EUR \cdot Mg^{-1} = 432{,}218\ EUR, \quad (6)$$

where

V_s—total income;
M_{liquid}—total mass of the liquid fraction of the digestate;
M_{solid}—total mass of the solid fraction of the digestate;
C_{liquid}—market price of the liquid fraction of the digestate;
C_{solid}—market price of the solid fraction of the digestate.

Figure 2 shows an example of a screw press used at one of the biogas plants in Poland. In the calculations and analysis, an analogous device with a suitable capacity, in line with the daily amount of raw digestate pulp generated, was included.

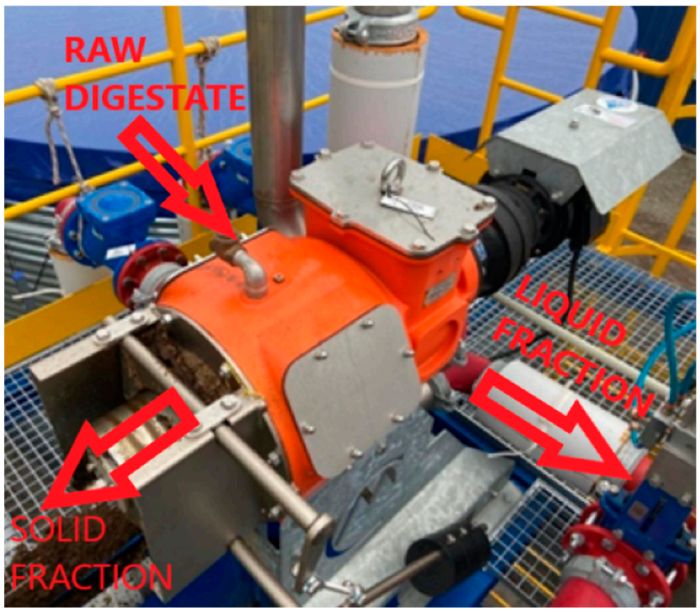


Figure 2. Screw press in biogas plant (own photo).

It is impossible to include all the benefits of the separation process in a thorough analysis. However, it should be noted that in some biogas plants the liquid fraction of the digestate is returned to the fermentation tanks, which allows for the hydration of solid substrates characterized by high dry matter content, such as manure. In addition, the use of a screw press makes it possible to reduce the size of storage tanks, which has a positive impact on reducing investment costs during the construction of a biogas plant [15,46].

3.4. Composting of the Solid Fraction of the Digestate

A process that allows us to improve the quality and stability of the produced fertilizer from the digestate is its composting. Any parameter variations during the operation of an agricultural biogas plant can result in the formation of a digestate containing incompletely processed organic matter. Through composting with micro- and macro-organisms in the presence of oxygen, the material is stabilized and pathogens are eliminated, mainly in the thermophilic phase of the process [14].

For the calculation assumptions, a simplified composting system was assumed: the composting system in the heaps, where aeration is carried out using a tractor aerator. This is a classic solution used for various types of biomass, including the solid fraction of the digestate. The process takes place on an open-air concrete yard. The investment costs of

this method include the complete preparation of the yard for the compost piles and the purchase of a device for aerating the compost, which at the same time serves to mix it. The site should ensure proper impermeability and have a tank for the resulting leachate. The site needed for this type of technology is an area of about 3 hectares, with a maximum capacity of up to 25,000 Mg. The estimated investment expenditure for the construction of this type of composting plant is the sum of the costs of all components, and amounts to about 365,000 EUR. The purchase of the shredding and aeration equipment was determined on the basis of the manufacturer's price, and for this size of plant it is equal to 35,235 EUR. It was assumed that the mass loss for the solid fraction in the composting process is about 15%. The remaining liquid fraction of the digestate will be managed according to the R10 recovery method presented in Section 3.1. The process data for the selected composting method are summarized in Table 7.

Table 7. Process data for the selected composting method (own study).

Name	Value
Technology	Composting in heaps
Installation efficiency	to 25,000 Mg
The size of the site for the installation	3 ha
Total investment costs	400,235 EUR
Price of finished compost	14 EUR·Mg^{-1}
Working time during the year	8600 h

In accordance with the defined methodology and the assumptions presented on the basis of the available literature, the unit costs associated with the operation and amortization of the composting plant at the selected biogas plant were compiled. One additional employee is required to operate the equipment and manage the composting process. The cost of converting and repairing the aerator was assumed to be 30% of the amortization cost of the aerator. All the unit cost of digestate composting is summarized in Table 8.

Table 8. Unit cost of composting per Mg of solid fraction of digestate (own study).

Name	Value
Depreciation of installation costs	0.90 EUR·Mg^{-1}
Depreciation of the aerator	0.08 EUR·Mg^{-1}
Maintenance and repair costs of the aerator machine	0.03 EUR·Mg^{-1}
Energy consumption	0.29 EUR·Mg^{-1}
Total costs	1.29 EUR·Mg^{-1}

The cost of preparing the digestate was assumed at the same level as for the development of raw digestate, taking into account the additional costs resulting from the use of composting technology to manage the solid fraction of the digestate.

$$V_k = M \cdot C_k + V_{sd} = 21{,}450\ Mg \cdot 1.29\ \ EUR \cdot Mg^{-1} + 173{,}130\ EUR = 200{,}801\ EUR, \quad (7)$$

where

V_k—total cost of digestate management including composting process;
V_{sd}—the cost of separation and management of the digestate;
M—total mass;
C_s—unit cost of composting the solid fraction of the digestate.

Using the above, the value of revenue from the sale of compost and the liquid fraction of digestate was calculated according to Equation (8):

$$V_{sk} = M_k \cdot C_k + M_{liquid} \cdot C_{liquid} = 20{,}000\ Mg \cdot 14\ \ EUR \cdot Mg^{-1} + 50{,}050\ \text{Mg} \cdot 4.65\ EUR \cdot Mg^{-1} = 512{,}733\ EUR, \quad (8)$$

where

V_{sk}—total value of digestate;
M_{liquid}—total mass of the liquid fraction of the digestate;
M_k—total mass of compost;
C_{liquid}—market price of the liquid fraction of the digestate;
C_k—market price of compost.

In carrying out a thorough analysis, it is not possible to include all the benefits of composting technology. The most important advantage of such a solution is the production of a stable fertilizer product, the use of which is possible in many branches of the agrofood industry [14].

3.5. Production of Solid Biofuel from Digestate Fractions

The digestate is a substrate that can be used for management in various ways, including for energy purposes [62]. The digestate can be a substitute, or the only material that is suitable for solid biofuel production, with a similar calorific value to sawdust pellets [34]. There are many technological solutions in pellet production that use materials such as the solid fraction of digestate, whose moisture content is around 30% [34]. The calculations were based on current investment values in a solid biofuel production line with a certain capacity. Due to the current energy and political situation, the demand for alternative fuels has increased, which has affected the price of energy substrates such as pellets [63]. The average calorific value of the finished product is about 10 MJ·kg^{-1}, which translates into its sales value of 69.8 EUR·Mg^{-1}. The economic analysis was also carried out considering the cost of separation of the digestate. The analysis did not take into account the possible heat needed for any additional drying of the digestate, because in the case of a biogas plant with a cogeneration system, this energy is treated as incidental (free). In Poland, the vast majority of the heat generated is not used due to the lack of infrastructure adaptation. For the purpose of the analysis, all costs associated with the palletization line that will be implemented on the biogas plant are summarized in Table 9. Production will take place in an additional building made of lightweight construction, the cost of which for an area of about 350 m^2 is 165,000 EUR. A process line with a total capacity of 2 Mg·h^{-1} of pellets will cost about 115,000 EUR. It was assumed that the mass loss for the solid fraction of the digestate after the palletization process is about 65%, which makes it possible to obtain 7500 Mg of pellets.

Table 9. Process data for solid biofuel production from digestate (own study).

Name	Value
Price of pellet bags	10.5 EUR·pc^{-1}
The size of the site for the installation	350 m^2
Total investment costs	280,000 EUR
Price of finished pellets	69.8 EUR·Mg^{-1}
Working time during the year	8600 h
Energy consumption	60 kWh·Mg^{-1}

According to the methodology defined and the assumptions presented on the basis of the available literature, tables were created, in which the unit costs associated with the operation and depreciation of the composting plant at the selected biogas plant were summarized. One additional employee is required to operate the equipment and manage

the process line. The cost of converting and repairing the aerator was assumed at 30% of the depreciation cost of the pelletizing line. All the unit cost of digestate palletization is summarized in Table 10.

Table 10. Unit cost of palletization per Mg of solid fraction of digestate (own study).

Name	Value
Depreciation of installation costs	0.39 EUR·Mg^{-1}
Depreciation of the pelletizer machine	0.27 EUR·Mg^{-1}
Maintenance and repair costs of the pelletizer machine	0.07 EUR·Mg^{-1}
Energy consumption	5.62 EUR·Mg^{-1}
Worker	1.56 EUR·Mg^{-1}
Bags	3.66 EUR·Mg^{-1}
Total cost	11.57 EUR·Mg^{-1}

The value of economic expenditure on pellet preparation was converted into the mass of the solid digestate fraction, which was necessary to be able to compare other technologies together. The costs of digestate preparation were assumed to be at the same level as in the case of raw digestate management, taking into account the additional costs resulting from the use of palletization technology to manage the solid fraction of the digestate.

$$V_p = M \cdot C_p + V_{sd} = 21{,}450\ Mg \cdot 11.57\ \ EUR \cdot Mg^{-1} + 173{,}130\ EUR = 421{,}307\ EUR, \quad (9)$$

where

V_p—costs of digestate management, including palletization;
V_{sd}—cost of management the liquid fraction of digestate;
M—total mass of solid digestate;
C_p—unit cost of solid digestate palletization.

The value of revenues from the sale of pellets and the liquid fraction was calculated using Equation (10):

$$V_p = M_p \cdot C_p + M_{liquid} \cdot C_{liquid} = 7500\ Mg \cdot 69.8\ \ EUR \cdot Mg^{-1} + 50{,}050\ \text{Mg} \cdot 4.65\ EUR \cdot Mg^{-1} = 421{,}307\ EUR \quad (10)$$

where:

V_p—total
M_{liquid}—total mass liquid fraction;
M_p—total mass pellets;
C_{liquid}—market value of liquid fraction;
C_p—pellets market value.

The analyses presented in the article show that investing in a solid biofuel pellet production line is a cost-effective alternative to utilizing the solid fraction of the digestate. The most important part of the solid biofuel production cycle is the pelletizing equipment. The profit can be as high as close to 170 EUR·Mg^{-1} of pellet product sold. This value of the profits is similar to the calculations of other researchers [31,34].

3.6. The Economic Balance

Based on the calculations carried out, a Table 11 was prepared, in which the costs and profits of the selected technology of digestate management are summarized. The calculations and economic analysis carried out indicate that the most cost-effective method of managing biogas plant digestate is to use it for pellet production, which at the same time increases its value compared to raw digestate.. Direct fertilization is advantageous due to its simplicity and low cost, so it is the method most often preferred by biogas plant operators. The use of a separation process, although the least cost-effective, is chosen due to

the specifics of the operation of a given biogas plant. The choice of an appropriate method should always take into account both economic and energy aspects and, most importantly, the specifics of the local market [64].

Table 11. Summary of calculations for selected methods of digestate management (own study).

Name	Direct Application of Raw Digestate	Separation of the Digestate and Application of its Fraction	Composting the Solid Fraction of Digestate	Production of Solid Biofuels (Pellets)
Cost per unit	1.98 EUR·Mg^{-1}	0.44 EUR·Mg^{-1}	1.29 EUR·Mg^{-1}	11.57 EUR·Mg^{-1}
Total cost	141,670 EUR	173,130 EUR	200,801 EUR	421,307 EUR
Income	418,705 EUR	432,218 EUR	512,733 EUR	756,233 EUR
Profits	277,035 EUR	259,088 EUR	311,932 EUR	334,926 EUR

4. Conclusions

Currently, optimization of the anaerobic digestion process focuses solely on increasing biogas efficiency, sometimes not including the quality of the digestate produced. A paradigm shift in the approach from "biogas optimization" to "integrated biogas and digestate optimization" is needed. To date, digestate has been used mainly on farms for soil improvement. However, its increasing production poses problems related to transportation costs, greenhouse gas emissions during storage, and high nitrogen content, which limits its use exclusively for soil purposes. Therefore, research into alternative valorization routes to reduce environmental impact and improve the economic viability of biogas facilities should attract more and more interest in the future. The sustainable management and utilization of digestate resources plays a key role in achieving a closed resource cycle and implementing a circular economy.

Research to date has mainly focused on improving the operational efficiency and stability of anaerobic digestion, with a limited exploration of the sustainable management and utilization of digestate resources. In the management and utilization of digestate, many factors, such as technology, environment, economy and society, must be comprehensively considered. The calculations presented in the article show exactly which technology is the most cost-effective. The cheapest and most popular solution is the direct fertilizer management of digestate, the total cost of which is 1.98 EUR·Mg^{-1}. All of the other methods involve higher digestate management costs, respectively; for separation it is 2.42 EUR·Mg^{-1}, for composting it is 2.81 EUR·Mg^{-1}. The process that is the most energy-intensive, yet profitable, is the production of pellets from digestate, translating into profits of 334,926 EUR·year^{-1} for the biogas plant analyzed. Each of the mentioned costs should be analysed idividually, since, depending on the location, the chosen method of management of the digestate affects the final use of the product in question as a fertilizer or energy feedstock, allowing it to be recycled.

The challenges of digestate management remain an important issue that requires further research and solutions. This calculation aims to promote the standardization of digestate management, provide a direction for further in-depth research on digestate, and contribute to the further development of anaerobic digestion product resource cycles.

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