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Impact of Digestate Fertilization on Crop Production – A Comprehensive Review

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ABSTRACT

This article examined the utilization of digestate as an organic fertilizer to enhance crop yields. In contemporary agriculture, applying digestate as a fertilizer is gaining traction as a viable method for boosting crop productivity. The paper delved into recent studies on the impact of digestate fertilization on crop quality and yield, explaining the production process of digestate, its application techniques, and its effects on plant health. The rise in environmental pollution has underscored the importance of sustainable agricultural practices, increasing the adoption of natural fertilizers. Digestate, a by-product of the methane fermentation process in biogas production, is rich in essential nutrients vital for plant growth and development. This article explored various aspects of digestate fertilization, including its chemical composition and effects on soil and plants. Additionally, it presented scientific findings on the use of digestate as an alternative fertilizer for field crops. The review aimed to provide a thorough understanding of digestate fertilization as well as highlight its potential advantages and challenges in agricultural applications.

Keywords: digestate, fertilizer application methods, sustainable farming, environmental sustainability.

INTRODUCTION

Economic development brings with it an increased demand for raw materials and energy. Unfortunately, fossil energy resources are not only limited, but their exploitation leads to emissions of pollutants, including greenhouse gases, which contribute to global warming. In the face of these challenges, the search for and of alternative energy sources implementation thereof is becoming crucial [1, 2]. Agricultural workers, as they progress, are increasingly aware of the environmental impact of their activities. Both crop cultivation and animal husbandry require the use of a variety of materials and electrical and thermal energy, which can have varying impacts on the surrounding environment [3]. Agriculture is heavily dependent on the use of fertilizers to maintain adequate food and feed production. It is estimated that the global demand for fertilizers is about 110 million tons of nitrogen (N), 470 million tons of phosphorus (P_2O_5) and 375 million tons of potassium (K_2O) per year [4]. The problem of adequate supply of nutrients to the soil, including nitrogen, is crucial for sustainable agriculture, since nitrogen is closely linked to animal husbandry, which is the main source of traditional organic fertilizers [5]. However, it should be noted that nitrogen is also one of the main components of mineral fertilizers, making them an attractive alternative for the farms without access to sufficient amounts of organic fertilizers [6]. Livestock farming comes with challenges of waste management and disposal, as well as the need to protect ecosystems and the environment, especially in the context of global warming [5]. In Poland, it is common to see greater use of mineral fertilizers accompanied by inappropriate use of natural fertilizers. To prevent this, the processing of some waste generated on farms into biogas and digestate is being considered [7]. Biogas plants make it possible to manage the waste from livestock and poultry farming, reducing the landfill area for this waste and ensuring environmental safety [8]. Methane fermentation of organic waste is a process that mainly focuses on the extraction of biogas, which can be used for energy purposes. In addition, when agricultural residues are not suitable for direct use, this technology makes it possible to partially solve the problem of their storage [9]. Biogas can be used to produce biomethane, which is a fuel capable of powering land vehicles, agricultural machinery, as well as combined heat and power plants to generate electricity and heat [10]. Anaerobic digestion produces a by-product called anaerobic digestate, which can be used in agriculture as an organic additive, but mainly as an alternative fertilizer source due to its high concentration of nitrogen, mainly in mineral form [11]. It is worth noting that the chemical composition of digestate can vary depending on the type of feedstock and the process carried out at the biogas plant. The use of digestate as fertilizer contributes to the reuse of organic matter and minerals, which can improve the profitability of crop production by reducing the costs associated with the purchase of fertilizers [12]. In order to optimize the extraction of methane potential and the flow of material and nutrients, the digestate can be physically separated into solid and liquid fractions, which have different properties. The solid fraction with high methane potential can be used for energy production, for example, through reuse in the fermentation process. The liquid fraction, which has a low methane potential, can be diverted to other processes. The solid fraction, which is rich in nutrients, can be destined for fertilizer purposes after separation [13]. The liquid fraction can be bottled in fields, provided the requirements of the Ministry of the Environment's Regulation on Recovery of R-10 are met, or reused as a process liquid for various industrial purposes.

The purpose of this article was to show the possibility of using digestate as a fertilizer and discuss techniques for its application.

Utilization of digestate

Digestate is a by-product produced in an agricultural biogas plant during biogas production [14]. The composition of the biogas and thus the digestate will largely depend on the substrates used to create them [15]. The percentage composition of the substrates can vary depending on the type of substrate, the proportion of mixed feedstock, and the fermentation conditions. In general, the organic substrate mix consists of: water – usually makes up the majority of the volume of the mix, in most cases about 80–95%, organic matter – organic components make up a significant portion of the substrates, usually 5–20%. Minerals mineral content is usually small, but important for the fermentation process, accounting for about 1–5%. The main components include: food scraps, residues from food production (starch, cellulose), sludge from food processing (dairies, breweries), vegetable residues, residues from oilseed crops [16, 17].

Any type of biomass that following biodegradation has carbohydrates, fats, and proteins in its composition, can be used to produce digestion liquor. Taking into account the financial criterion regarding the use of the chosen substrate, the amount of organic matter contained in it must be above 30% d.m. [16]. An additional advantage is also the fact that biogas production involves substrates that cannot be used in any other way. Using them for biogas production results in a solution to the problem associated with the disposal of agricultural waste, the storage of which can pose a threat to the environment. This creates the possibility of obtaining significant amounts of organic, high-quality and organic fertilizers [18].

Methane fermentation process

The increased interest in biogas production is, among other things, due to the presence of sludge as a by-product of the fermentation process. Increasing attention is being paid to the methodology of managing this sludge, especially its potential use in agriculture. In many countries, anaerobic digestion is an essential component of comprehensive waste management systems that integrate various processes to efficiently utilize organic raw materials [19]. Anaerobic microorganisms cause the decomposition of organic compounds during methane fermentation under appropriate conditions, such as constant and optimal temperature, anaerobic conditions, a humid environment, and sufficient available matter, thus producing biogas (Figure 1) [20].

After the completion of the methane fermentation process, various types of separators are used to separate the liquid phase from the solid phase of the digested mass [22]. This process helps save a significant amount of water, reduces transportation costs, and enriches the freshly delivered substrate

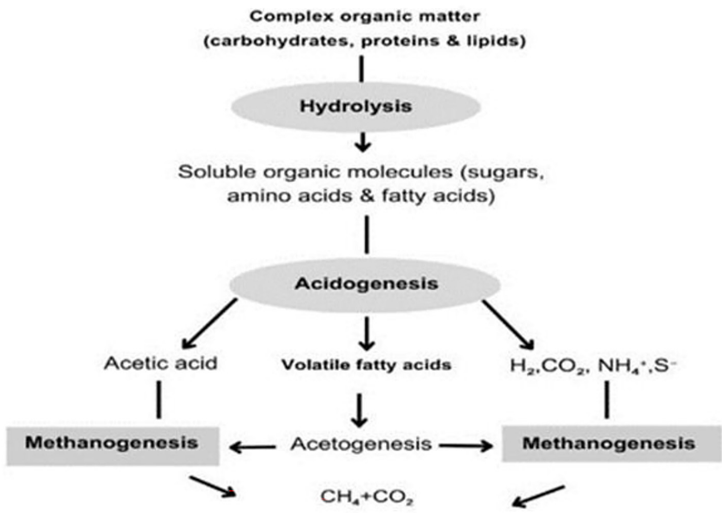

Figure 1. Stages of anaerobic digestion (methane fermentation process) [21]

with bacterial flora. Methanogenic bacteria, which are crucial in the biogas production process, cannot process fats, proteins, and carbohydrates in their pure form. They require the presence of nitrogenous substances and microorganisms, which are abundantly found in manure and animal slurry. Therefore, materials such as straw, long grass, and other biological waste, need to be shredded to facilitate the fermentation process, which would otherwise take too long [23, 24]. It is estimated that approximately 180 million tons of anaerobic digestate are produced annually in the European Union, most of which is used as organic fertilizer [25]. The agricultural use of digestate from biogas plants is a key factor ensuring the profitability of biogas plants, as it produces a large amount of high-energy biogas while eliminating the waste that would otherwise negatively impact the environment and incur high storage costs [26].

The composition of digestate primarily includes undigested organic residues, mineral components (in quantities comparable to their content in the substrates), and the biomass of methanogenic bacteria. The main characteristics of digestate mass include the pH, content of dry matter, organic substances, nitrogen, phosphorus, calcium, and magnesium, as well as the presence of heavy metals [27]. The average chemical composition of digestate is presented in Table 1.

METHODS OF DIGESTATE APPLICATION

The equipment used for applying raw slurry and separated liquid can also be utilized for distributing digestate. Machines designed for spreading manure are also suitable for applying the solid form of digestate. To ensure optimal use of digestate as a fertilizer, it should be applied during the plant growing season using the equipment that enables even distribution across the field and precise dosing. This approach also helps minimize ammonia volatilization [29].

A comparison between slurry and digestate indicated that digestate can be used directly as a fertilizer, similar to slurry. The value of digestate as an

Table 1. Average composition of solid and liquid fractions from Polish biogas plants [28]

Examined feature	Solid fraction	Liquid fraction
Dry matter content (%)	22–27	27–43
Organic dry matter content (%)	89–945	58–62
Total nitrogen (N) (%)	0.4–0.8	0.29–0.75
Ammonium nitrogen ($N-NH_4$) (%)	0.08–0.52	0.28–0.38
Phosphorus (P) (%)	0.1–0.28	0.03–0.05
Potassium (K) (%)	0.12–0.69	0.05–0.62
Calcium (Ca) (%)	0.22–0.43	0.05–0.07
Magnesium (Mg) (%)	0.06–0.17	0.01–0.02

alternative to conventional fertilizers was emphasized due to its ability to comprehensively support plant growth. Additionally, it was noted that the use of digestate brings numerous agronomic and environmental benefits. Owing to its rich nutrient content, digestate not only improves soil fertility but also contributes to reducing greenhouse gas emissions, compared to traditional fertilizers [30].

Four methods of slurry application on cultivated fields were compared: hose spreading, trailing shoe method, injection method, and disk method. The analysis showed that hose spreading and the trailing shoe method ensure even distribution of substances, which promotes more efficient nutrient uptake by plants. The injection method, although effective, can cause mechanical damage to crops. This is a more advanced and effective method. The main advantages of this method include significantly reducing ammonia and other greenhouse gas emissions, thereby minimizing air pollution and maximizing nutrient availability for plants [31]. The disk method proved to be the least uniform, which can affect the even availability of nutrients. The aspect of ammonia volatilization is crucial due to its impact on air quality and greenhouse gas emissions. The injection method has the lowest risk of ammonia volatilization, whereas the disk method has the highest. The risk of crop contamination indicates the potential impact of application methods on the quality and safety of agricultural products. The disk method, due to its nature, carries the greatest risk of contamination, which requires careful consideration in the context of consumer agriculture [30].

In summary, the choice of organic fertilizer application method, including digestate, is a complex decision. It should balance agronomic efficiency, environmental impact, and economic factors, which are key to the sustainable development of agricultural practices.To better utilize the methane potential and nutrient content of digestate, research has been conducted on various fractions of this material, such as solid and liquid, which have different properties. This chapter presents the results of these studies as well as their implications for agricultural and industrial practice.

Solid and liquid fraction of digestate

The solid fraction of digestate can undergo a certification process and be used as a fertilizer, which is one of its applications after separation [22]. Additionally, it can be utilized as a solid fuel through combustion, allowing for the efficient use of the energy contained in this material. Other uses of the solid fraction include feed additives, which can positively impact the nutritional value of food produced from cultivated plants, and composting, which can be employed in ornamental plant nurseries as a peat substitute [32]. This process improves the quality of the raw material and reduces unpleasant odor, moisture, as well as potential phytotoxicity.

The liquid fraction of digestate can be spread on fields, complying with relevant recovery regulations. Alternatively, it can be reprocessed as a technological liquid, enabling its use for various industrial purposes. Research results have also shown that the application of digestate, in both solid and liquid forms, brings significant benefits to soil quality and plant growth. The fertilizing potential of the solid and liquid fractions of digestate was examined on two different soil types with varied chemical and biological properties. It was found that the solid fraction of digestate was particularly effective in improving organic matter content (OM), microbial biomass (MBC), and cation exchange capacity (CEC) in the soils with neutral pH. In contrast, the soils with alkaline pH showed lesser improvements, mainly limited to soil oxidative activity and bacterial colonies. The solid fraction demonstrated higher fertilizing potential than the liquid fraction, resulting in more significant agronomic benefits [33].

The environmental impact of digestate application methods

Considering environmental pollution, studies conducted [34] analyzed the impact of different digestate application methods on methane, ammonia, and carbon dioxide emissions, as well as on plant condition. Two application methods were used: disk unit and strip-till technology. Both methods were tested at different digestate application rates: 0, 10, 20, 30, and 40 m^3/ha. The results showed that strip-till technology at an application rate of around 20 m^3/ha was the most effective. This method minimized greenhouse gas emissions and maximized the yields of silage maize. The use of the disk unit also produced positive effects, but strip-till proved to be more efficient in terms of both ecological and agronomic benefits. The broadcast spreading method demonstrated that odor emissions from this technique are significantly higher compared to more advanced application techniques, such as direct soil injection. It has been shown that the injection method can reduce odor emissions by 23–94% with shallow injection and by 95–99% with deep injection, compared to broadcast spreading. The direct injection method is more effective in reducing the negative environmental impact, particularly in terms of odor and greenhouse gas emissions [31].

Using digestate as a fertilizer in the cultivation of crops with high nutrient demands, such as winter oilseed rape, brings significant benefits both for crop quality and soil. It was found that the application of digestate at a rate of 50,000 L/ha significantly increases the fat and protein content in rapeseed, resulting in better crop quality. Moreover, scientists observed improvements in soil parameters and increased plant resistance to biotic and abiotic stresses, which is particularly important in the context of sustainable agricultural development. These findings are consistent with observations by other researchers, who also note the positive effects of using digestate as part of recycling practices in agriculture. The economic and ecological benefits of this approach can significantly impact sustainable agricultural production [35].

The use of digestate in horticultural crops

Studies conducted over a two-year period evaluated the potential of digestate as a fertilizer in horticultural crops. The impact of digestate addition on soil fertility and plant yield was analyzed, comparing its fertilizing capability with that of mineral fertilizers and traditional organic fertilizers, such as cattle manure [32]:

- physicochemical changes in soil: the impact of digestate on the physicochemical properties of the soil decreased gradually over time, resulting in a minimal residual effect.
- ammonium nitrogen: digestate provided a significant amount of ammonium nitrogen, which quickly underwent nitrification, becoming directly available to plants in the short term.
- phosphorus: the addition of digestate increased the amount of available phosphorus in the soil, suggesting that its use in agricultural practice should be based not only on the nitrogen it provides, but also on phosphorus.

Digestate can be an effective fertilizer, supplying both nitrogen and phosphorus, which can significantly impact soil fertility and plant yield. Its use can be beneficial in agricultural practice; however, both short-term and long-term effects on soil should be considered.

The potential benefits and implications of using digestate in horticultural crops include:

1. Enhanced soil fertility: digestate improves soil structure and nutrient content, contributing to better plant growth.
2. Nutrient availability: the rapid nitrification of ammonium nitrogen and increased phosphorus availability make digestate a valuable nutrient source.
3. Sustainable agriculture: using digestate supports recycling organic waste and reduces reliance on synthetic fertilizers, promoting more sustainable farming practices.

Overall, the studies highlight the effectiveness of digestate in horticultural applications, demonstrating its potential as a sustainable fertilizer alternative.

Safety of digestate use

In the context of heavy metal content, digestate generally exhibits trace amounts of these elements, making it safe for use as a fertilizer in agriculture [6]. The substrates used in biogas plants contain some heavy metals, but the anaerobic fermentation process and the final conversion into digestate do not lead to their accumulation in hazardous amounts. Specifically, lead concentrations in digestate were significantly lower than 5 mg/kg, which is below the threshold considered safe for soil and plants. This suggests that digestate can be effectively used as an eco-friendly fertilizer, providing nutrients without the risk of soil contamination by heavy metals.

Physicochemical and microbiological characteristics of digestate

Considering the evaluation of physicochemical and microbiological properties of digestate derived from single-stage and two-stage fermentation of food waste, various parameters such as pH, moisture content, organic matter content, heavy metals, and pathogen presence were examined. The results indicated that the digestate from two-stage fermentation (D3) had the best physicochemical and microbiological parameters, including low levels of heavy metals and pathogens. D3 also exhibited better stability indicators and a higher potential for agricultural use, which was confirmed by germination tests on radish seeds (*Raphanus sativus*) [36]. Furthermore, it is important to emphasize that the long-term benefits of digestate application have a significant impact on the physical properties of the soil. Studies show that regular use of digestate improves soil structure and increases the availability of nutrients for plants, leading to higher yields. Regular application of digestate positively impacts soil fertility, which is crucial for sustainable agricultural development [37].

CONCLUSIONS

Digestate from agricultural biogas plants is an effective organic fertilizer that improves soil structure and provides essential nutrients. It was shown to enhance soil structure, increase fertility, and support the development of microorganisms. Different fractions of digestate have various applications: solid fractions can be used for energy production and feed, while liquid fractions can be used for field irrigation. The use of digestate can significantly reduce the costs associated with purchasing mineral fertilizers, which is particularly important in the face of rising prices and limited availability of mineral resources. Scientists, after analyzing their research results, suggest that the agronomic efficiency of digestate and its beneficial environmental impact make it an attractive alternative to conventional fertilizers. Digestate, after appropriate certification, can be an efficient and safe organic fertilizer.

The use of digestate supports sustainable development goals by increasing crop yields and protecting the natural environment from contamination by heavy metals and other hazardous substances. To fully understand the impact of digestate on agriculture, soil, plants, and the environment, further research is necessary. These studies should focus on maximizing the benefits of its use and minimizing potential risks. Particular attention should be paid to the long-term effects of digestate application on soil health and crop yields.

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