CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

FACULTY OF ENGINEERING

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SYSTEMS OF LIQUID ORGANIC FERTILIZER APPLICATION WITH RESPECT TO ENVIRONMENTAL IMPACT

MASTER'S THESIS

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DIPLOMA THESIS ASSIGNMENT

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Thesis title

Systems of liquid organic fertilizer application with respect to environmental impact

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Objectives of thesis

The aim of the work is to verify the methods of liquid organic fertilizer application, digastate in particular, into various application depths and at different rates with respect to the need for mitigation of environmental impacts.

Methodology

In-field trials, application variants will be established under different conditions and crops. The trials will include physical and chemical analysis of soil sample, gas emission measurement and crop stand assessment. Technological aspects will be stressed when evaluating the experiment and concluding on recommended application methods.

The proposed extent of the thesis

ca. 55 pages

Keywords

liquid organic fertilizer, digestate, application, ammonia, emission

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Recommended information sources

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Declaration

I hereby declare that I have done this thesis entitled **Systems of liquid organic fertilizer application with respect to environmental impact** independently, all texts in this thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the Faculty of Engineering.

In Prague, 31st March 2022

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Hidayatul Fitri

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ABSTRACT

The use of organic fertilizer is increasing nowadays, and the application must be conducted accurately to provide the right benefits for plants and maintain soil health. Improper application of fertilizers can cause problems for both plants and the environment. This study investigated the liquid organic fertilizer application, particularly digestate, varied into different application doses concerning mitigation of adverse environmental impacts, improving water infiltration ability, and crop yields. The experiment was established into eight variants with different digestate doses, conducted on emission monitoring and soil physical properties. As a result, the digestate application with shallow injection (5 cm in depth) was confirmed as an appropriate technique for applying liquid fertilizer into the soil. Gas emissions resulted in low concentration and declined gradually over time, obviously proved from the experiment conducted under two measurements immediately after application and the next day. Applied various doses of liquid digestate fertilizer affected the emission concentrations of NH_3 volatilization, differing significantly and decreasing about 40% from the first to second measurement. In this study, winter wheat crop production significantly increases under digestate application with additional N fertilizer. This study suggested the long-term application of digestate to obtain more alteration of soil properties such as bulk density, penetration resistance, and hydraulic conductivity.

Keywords: liquid organic fertilizer, digestate, application, ammonia, emission

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1. INTRODUCTION AND LITERATURE REVIEW

This study describes the future agricultural development in line with the confront challenges. This overview informs the current trends in potentially a by-product of biogas for increasing agricultural production and challenges in several environmental risks.

1.1. Introduction

Agricultural trends are increasingly pointing towards using environmentally-friendly products and activities to create a sustainable environment. Agriculture is a major concern in sustainable development due to its impact on food production, widespread use of natural resources, and environmental impact. Organic material sources such as agricultural residues, animal manure and slurries, and organic municipal wastes have potentially functioned as fertilizer, characterized by high nutrient and organic matter as plant and soil demands (Ye et al., 2020). An organic fertilizer plays a vital role in raising crop yields, mitigating environmental pollutants, and maintaining the physical and biological properties of the soil. Furthermore, the organic material source processed through anaerobic digestion produces biogas as renewable energy and digestate products, which can be used as fertilizer.

Europe is the largest producer of biogas production (IEA, 2020). The process of biogas production through anaerobic digestion is known as a renewable energy source. In addition, the anaerobic digestion process results in digestate substrates which can be used as fertilizer and soil enhancer. An investigation evaluated digestate material containing a high nutrient that can substitute the artificial fertilizer (Makdi et al., 2012), which is higher in pollutant emit (Ye et al., 2020). In addition, as reported digestate or natural fertilizer can replace 5-7% of inorganic fertilizer currently in use and mitigate the greenhouse gas (GHG) emission by about 10-13% (WBA, 2019). Therefore, digestate use as organic fertilizer is an alternative to mineral fertilizer to improve sustainability in agriculture and accomplish crop and soil demands.

Digestate as left material from Anaerobic digestion can be a new source of plant nutrients and soil enhancers (Makdi et al., 2012). The most common feedstocks come from agriculture residue, animal slurry and manure, energy crops, and organic municipal waste (Drosg et al., 2015; Makdi et al., 2012). Organic material content potentially increased soil organic matter in the soil (Hu et al., 2021). On the other hand, digestate is related to greenhouse gas (GHG) emission production such as ammonia (NH_3), methane (CH_4), and nitrous oxide (N_2O) (Czubaszek & Wysocka-Czubaszek, 2018; Lu & Xu, 2021; Zilio et al., 2021). Furthermore, a study reported that digestate is rich in nitrogen content, and possibly it volatilizes into the atmosphere as gas (Paolini et al., 2018).

Many studies investigated the potential of digestate as fertilizer as economically and environmentally friendly. As Riva et al., (2016) reported, digestate has potential impacts in reducing undesired pollutants emitted. Fertilizers are designed to provide additional nutrients to the soil to meet the nutritional needs of plants. Fertilizer utilization is essential for farmers to obtain high yield and somehow is challenging in considering the negative environmental impact of undesired pollutants. Fertilizer application must be conducted accurately to provide the right benefits for plants and maintain soil health. Improper application of fertilizers can cause problems for both plants and the environment. Currently, misuse of organic fertilizer has become a problem for today's environment.

Improper application of fertilizers carries the risk of nutrient loss through volatilization or leaching. Land application of fertilizer is the primary factor that impacts the emission released into the atmosphere (Zhang et al., 2021).Therefore, the fertilization technique is crucial to avoid the negative consequences of improper fertilization. Different types and forms of fertilizers also have disparate fertilization methods. For example, solid and liquid fertilizers are applied to plants differently depending on the type of fertilizer. An investigation of liquid fertilizer spreading on the surface (splash spreading) contributed to higher emissions released into the atmosphere and induced nutrient losses (Riva et al., 2016; Seadi et al., 2012). Nevertheless, understanding the properties of organic fertilizer is crucial in consideration to supply adequate nutrients for plants, rebuild soil fertility, and protect the environment from undesired compounds.

This study focuses on the liquid digestate for land applications concerning the emission released into the atmosphere. This research proposed expanding the system application of liquid organic fertilizer without damaging the environment and optimizing fertilizer use. This study aimed to investigate the liquid organic fertilizer application methods, particularly digestate, into different application rates concerning mitigation of adverse environmental impacts. Furthermore, the research concerned the application method used in different application rates performed in winter wheat. By varying the application rates, we tried to determine which application method contributes to the low impact of emissions into the environment. The findings of this study should make a significant contribution for farmers or researchers to improve the use of fertilizers to realize its potential and maintain sustainable agriculture.

1.2. Literature Review

This brief summary discusses about nutrients, fertilizers and its applications and the potential risks of the application. Thus, it can help researchers to understand relevant information and knowledge related to the problem, with the aim of solving the problem and may create development related to the object study.

1.2.1. Liquid Organic Fertilizer

The continuous use of chemical fertilizers causes unbalanced soil biological ecosystems, so fertilization to adequate nutrients in the soil is not achieved. In addition, the excessive amount of artificial fertilizer use leads to the release of greenhouse gases into the atmosphere, reduces soil fertility, and causes many diseases for human life. The use of organic fertilizers contributes to the protection of the environment and the safety of ecosystems. Organic fertilizer emitted lower pollutants to the atmosphere than inorganic fertilizer (Ye et al., 2020). On the other hand, the use of organic fertilizers can maintain soil balance, increase land productivity, and reduce the environmental impact of the soil.

Liquid organic fertilizer (LOF) has essential nutrients for increasing plant growth and soil fertility. Organic fertilizer is produced from natural sources, for instance, agricultural wastes, animal manures, and household wastes. Thus, the nutrient content is differed depending on the feedstock of the material used. A study Martínez-Alcántara et al., (Martínez-Alcántara et al., 2016) reported that organic fertilizer increased macronutrient and micronutrient uptake. Soil nutrients strongly influence the plant growth processes. The liquid fertilizer immediately penetrates the soil, giving the plants quick and easy access to the nutrients they need.

Liquid organic fertilizer is a soluble solution containing one or more nutrient carriers that the plant needs. LOF has a dual effect on the soil, promoting crop growth and health and improving soil structure. The benefit of using liquid organic fertilizer is that it is easily absorbed from the soil by the plant root as it releases dissolved nutrients. A paper by Martínez-Alcántara et al., (2016) demonstrated that liquid fertilizer improved nutrient uptake and raised total biomass yields. Another advantage of these fertilizers is that liquid fertilizers can balance the soil's pH level depending on the nutrients they deliver (Li et al., 2021). Because the organic matter of organic fertilizer resulted in the promotion of soil microbial activity, thus influencing the improvement of plant growth (Li et al., 2021). Nevertheless, adding fertilizer should consider the amount of nutrients amendments to avoid nutrient leaching and release into the environment. Management of liquid fertilizer application needs to consider nutrient demand, application equipment, and application methods. Adopting best nutrient management practices (BMPs) leads to achieving nutrient use efficiency (G. Liu et al., 2021).

1.2.2. Biogas Digestate

Digestate is a valuable product of anaerobic digestion. It is containing nutrient-rich and therefore applies as fertilizer to agricultural land. As a fertilizer that releases nutrients for plants, digestate also maintains soil fertility due to its characteristics. Therefore, considering the potential of biogas digestate as organic fertilizer was evaluated as a nutrient source for plants (Barbosa et al., 2014).

The critical factors affected the quality of biogas digestate, including feedstocks, anaerobic processes, and separation methods. The sources materials factor influenced digestate composition in solid-liquid digestate characteristics and compositions (Makdi et al., 2012). In Europe, the most common feedstock comes from agriculture residue, animal slurry and manure, energy crops, and organic municipal waste (Drosg et al., 2015; Makdi et al., 2012). In addition, feedstock from animal slurries produced lower biogas than feedstock from agricultural wastes (Mucha et al., 2019). Plant waste feedstock with a high fiber content results in a digestate with a high dry matter content (Lamolinara et al., 2022). Furthermore, commonly used AD from animal manure and agricultural waste derives high biogas yields and digestate products rich in nutrients.

A range of materials is considered physical and chemical impurities in AD feedstock material. The unwanted impurities strip cannot be guaranteed by pretreatment or through the AD process. The respective material must not be used as feedstock in biogas plants where digestate is used as fertilizer or for other agricultural purposes (Seadi et al., 2012). Such materials are crucial in affecting AD product quality as fertilizer corresponding to plant, soil, and human safety.

Another factor influencing digestate quality is biogas management processes through anaerobic digestion. Digestate quality management involves various clearances and quality standards to ensure the safety and value of digestate as a fertilizer, soil conditioner, or growing medium. Digestate management strategies are designed not only for safe disposal but also to increase value and selling power. Fermentation and technology used in AD processes play an essential role in producing the desired quality (Czekała et al., 2020).

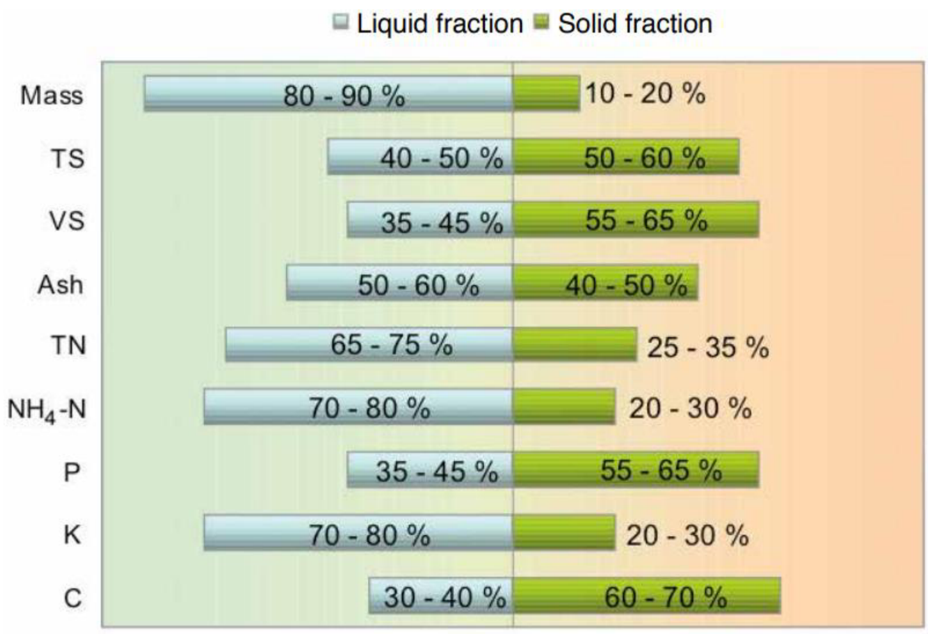


Figure 1. Different characteristics of the solid and liquid fractions of digestate (Source: Bauer 2009)

Solid-liquid separation is the first step after the anaerobic digestion process to obtain a better quality of its fraction. As defined, both fractions had fertilizing potentials for soil and plant demands. A study of digestate management (Visvanathan, 2014) stated that digestate needs further treatment (separation and storage) if the C/N ratio is higher than the safe range as nutrient demand for land application. However, separated into solid and liquid fractions has many advantages due to the purpose of application in different usage. For example, the solid-liquid separation process also reduces volatile ammonia potential (Tiwary et al., 2015).

Post-treatment of AD process aimed to improve the quality of nutrient recovery in both fractions. Many technological processes used for separation include mechanical, chemical, thermal, and biochemical techniques (Monfet et al., 2018; Mucha et al., 2019). Moreover, several technologies have been developed for liquid digestate treatment to concentrate nutrients into liquid fertilizer products (Tampio et al., 2016).

1.2.2.1. Digestate Properties

The characteristics of digestate depend on the source of materials and the digestion process (Makdi et al., 2012) and affect the quality of digestate products. Agricultural/livestock residues, energy crops, residue from food and agroindustry, biogenic waste are major substrates in anaerobic digestion (Drosg et al., 2015). Those materials influenced the anaerobic digestion process, which determined the composition and characteristics of digestate, primarily organic matter content, chemical composition, pH, and the presence of impurities. For instance, alkalinity always characterizes the distinctive properties of digestate due to its high pH of approximately >7 (average pH 7-10) (Czekała, 2019; Drosg et al., 2015; Koszel & Lorencowicz, 2015). In addition, residue and waste source of feedstock utilization directly affected the environment as waste management improvement (IEA, 2020).

A study of biogas-digestate presented the practical potential of digestate was similar to NPK fertilizer according to the contains such as Nitrogen, Carbon, and Phosphorous. Hence, this potential of digestate leads to mitigation of mineral fertilizer use due to its similarity. The nitrogen and carbon (C/N) ratio characterized the liquid digestate (Visvanathan, 2014), which influences the growth of microbial activities (Mucha et al., 2019). The soil microbial community indicated the soil quality. They maintained the soil stabilization by sustaining the nutrient cycles and organic matter decomposition. The pH value of fresh digestate typically ranges from 7.5 to 8.0 pH (Drosg et al., 2015). This characteristic role indicates soil acidity, directly affecting physical, chemical, and biological properties. Strongly acidic soil decreases nutrients, inhibits plant growth, and decreases crop yield. As described above, solid-liquid separation is essential for nutrient recovery considering nitrogen is the foremost plant demand, absorbed in nitrate (NO_3-) and ammonium (NH_4^+) form.

The critical role of digestate is reducing greenhouse gases (GHGs) associated with manure management and improving nutrient management on the farm. This characteristic is according to lower volatile compound content compared to inorganic fertilizers. An Assessment resulted that NH_4^+ allocated into liquid fraction during the separation process (Petrova et al., 2021) as the total amount of N content in liquid is higher than solid. Analysis of liquid digestate reported that it released undesired pollutants, yet low potential (Riva et al., 2016).

1.2.2.2. Content of Digestate

The biogas digestate contains all nutrients, both macro and micronutrient needs for modern farming (Kumar et al., 2015; Makdi et al., 2012), including Nitrogen, Phosphate, and Potassium. Its nutrient-rich content induces growth promoters essential not only for the crops but also for soil microorganisms. Digestate content depends on the feedstocks used, such as agricultural waste (manure and plant residues), organic municipal waste, and animal waste. For instance, digestate from cattle slurry has higher GHGs than digestate from crop residue It also has higher dry matter content in separated fractions (particularly in solid fractions) due to fiber content from the plants.

Digestate used as a fertilizer or soil enhancer, the digestate must have specific criteria and composition of dry matter and organic matter, minerals, nutrients, and indeed free of unwanted compounds. Drosg et al. (Drosg et al., 2015) reported that the percentage of digestate, divided into solid and liquid, is 10-20 % and 80-90%, respectively. The higher carbon was found in a solid phase (Drosg et al., 2015) and higher nitrogen was found in the liquid phase (Czekała, 2019; Koszel & Lorencowicz, 2015).

Table 1. Digestate contents from several feedstocks (maize and chicken manure, Liquid digestate; manure-based, Broiler)

Parameter	Feedstocks		
	Maize and chicken manure[1]	Liquid digestate[2]	Broiler[3]
C %	41.1	36	-
N %	3.20	8.4	2.84
P %	1.50	-	-
K %	3.75	-	3.45
NH_4^+ %	-	4.4	-
NO_3^- %	-	0.024.3	-
P_2O_5 %	-	10.7	-
K_2O %	-	-	-
Ca %	3.21	-	-
Mg %	0.57	-	-
S %	0.39	-	-
Al %	0.09	-	-
Na %	0.15	-	-
Cu %	<0.01	<0.01	<0.01
Mn %	0.03	0.36	-
Mo %	<0.01	-	-
Zn %	0.03	<0.01	<0.01
pH	8.35	-	8

[1]Barbosa et al., 2014

[2]Valentinuzzi et al., 2020

[3]Aladjadjiyan et al., 2016

Organic Matter (OM) and Dry Matter (DM) Content

Organic matter is substances formed from weathering or decaying the remains of plants and animals. Organic material in the soil can vary depending on the type of soil. Adding organic material into soil that lacks organic substances improves soil structure and quality. Organic substances will be broken down into simpler forms, building elements that fuse soil. Abiotic factors such as the size and diversity of the microbial community, temperature of abiotic factors, soil moisture content, and temperature are directly related to the regulation of mineralization of soil organic compounds (Anas et al., 2020).

Soil fertility is the most affected by the amount of organic matter in the soil. Therefore, the content of organic matter in the soil is determined by management in land management. Organic matter from anaerobic digestion is a biodegradable compound (Slepetiene et al., 2020) and is a good amendment for soil maintenance (Makdi et al., 2012; Pigoli et al., 2021). Adding the OM plays a vital role as the source of soil organic matter (SOM). The organic matter and dry matter content indeed depend on material sources. Mainly they are high produced from agricultural residues (see table 1). Many studies of digestates analyzed that proportion of dry matter content is constantly higher in solid-separation of digestate. Rich dry matter content indicated biogas digestate from animal waste (Czekała et al., 2020).

Carbon (C) was found in digestate with different percentages after solid-liquid separation, whereas approximately two times higher in solid than liquid (Drosg et al., 2015). The percentage of undegraded carbon in AD stabilized the organic matter in the soil to which the digestate was applied (Lamolinara et al., 2022). Digestate containing high N and low C can improve soil fertility due to its function as a promotor for microbial activities such as the nitrogen cycle. The digestate carbon (C) content may decrease during anaerobic digestion and cause a reduced input of organic C into the soil (Möller et al., 2008). The experiment by Sulok et al., (2021) stated that C content was characterized by brown feedstock material. The study result by Petrova et al. (2021) showed high N in the liquid phase and high C in the solid phase, whereby C was crucial in decomposition N via denitrification.

Macronutrients (NPK)

Plants need essential elements for the growth process. Macronutrients include Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), Phosphorus (P), Potassium (K), Magnesium (Mg), Calcium (Ca), Sulfur (S). Elements C, H, and O are obtained by plants from the air. Other macronutrient elements are obtained from the decomposition or weathering of minerals in the soil. The deficiency of essential nutrients can disrupt plant growth and weaken even cause death. The soil already has all the nutrient elements that plants need to grow. However, the amount of nutrients available in the soil is limited, so it takes a considerable amount of time to decompose the nutrients available naturally. If the soil does not provide sufficient nutrients, adding fertilizer should be a solution to complete the nutritional needs. The additional nutrients should not be excessive because they will harm and even poison the plants.

Biogas digestate can be a new source of plant nutrients and soil enhancers (Makdi et al., 2012). Digestate fertilizer contains several nutrients, which can fluctuate in amounts depending on the type of material sources; food-based, biomass, pig, or cattle. A study found that the total mass of nutrients such as nitrogen, phosphorus, and potassium that enters the digester is equal to the mass that leaves as digestate (Logan & Visvanathan, 2019). In addition, the organic material content in digestate potentially increased soil organic matter (Hu et al., 2021), an alternative to supplying sufficient nutrients for a long-term period. Hence, the plants grow well and produce yields optimally.

Nitrogen (N)

Nitrogen (N) is one of the primary plant nutrients in the soil, which plays a significant role in stimulating growth and giving green color to leaves. Lack of nitrogen in the soil may disrupt plant growth and decrease crop yields because it directly affects chlorophyll, essential for photosynthesis. Nitrogen fertilization is one of the most critical factors of agricultural production. Anaerobic digestion refers to nutrient recovery (Monfet et al., 2018; WBA, 2019) as the potential of digestate products containing nutrient-rich, particularly in nitrogen.

The primary nitrogen source for fertilizer production is derived from organic materials such as plants, animals, food waste, and other materials (see figure 2). Plant residues are the primary source of resulting N content (Makdi et al., 2012). Many studies reported that liquid fraction has higher nitrogen content, particularly after solid-liquid separation (Drosg et al., 2015; Koszel & Lorencowicz, 2015; Nkoa, 2014). Whereas nitrogen is responsible for plant growth, such as leaves function for building the leaf structure. For instance, an analysis of fertilized digestate of alfalfa showed the macro-element percentage, which increases in the highest nitrogen and potassium of leaves compared with mineral fertilizer (Koszel & Lorencowicz, 2015).

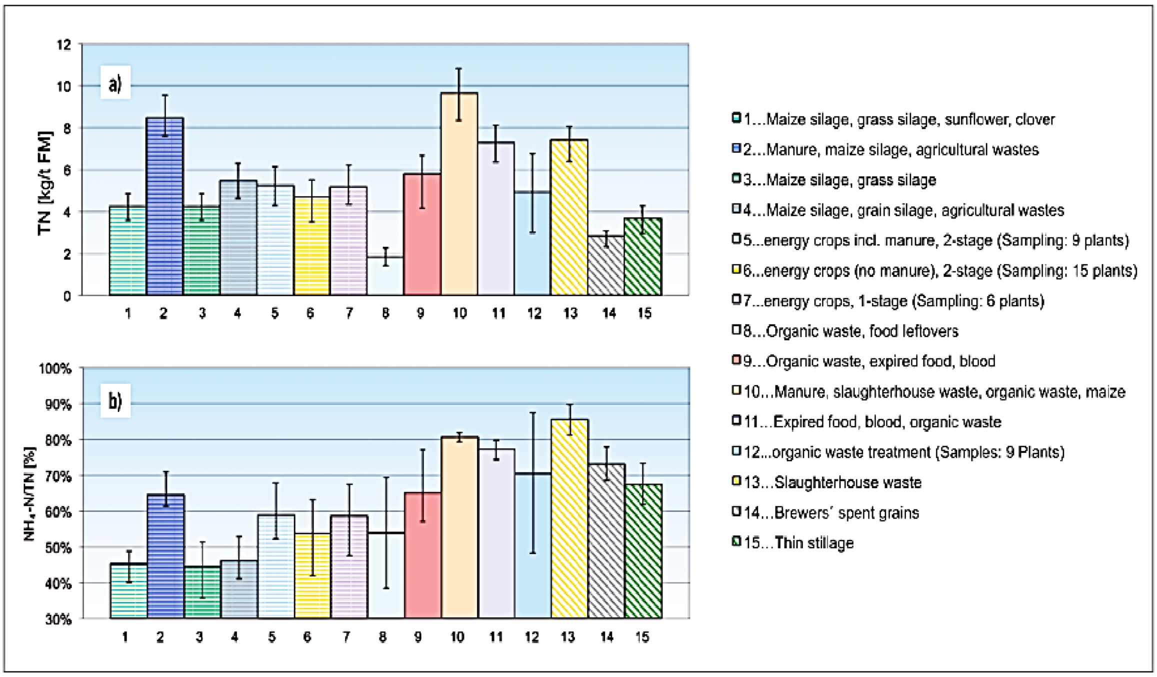


Figure 2. Nitrogen source from several different feedstocks (Source: Drosg et al., 2015)

Nitrogen is readily available in N as ammonium nitrogen (NH_4^+-N) and organic-N (Drosg et al., 2015; Makdi et al., 2012; Pigoli et al., 2021). NH_4^+ and NH3- are available in N form whereas absorbed by the plants from the soil directly. Nitrogen is one of the soil nutrients, depending on the nitrogen cycle (see figure 3) through the leaching process, volatilization, mineral fixation, and microbial activities. Nitrogen is converted into ammonium through nitrogen fixation by nitrifying bacteria. At the same time, the organic N is breaking down slowly and provided N in prolonged time for crop uptake. Nitrate (NO_3-) is another form of nitrogen through the nitrogen cycles (see figure 3). Nitrifying bacteria need oxygen, low organic carbon, favorable temperature, and a growth phase before sufficient numbers are present for effective nitrification (Szogi et al., 2015). Thus, the plant root can easily absorb the simple form of N as NH_4^+ and NO_3-.

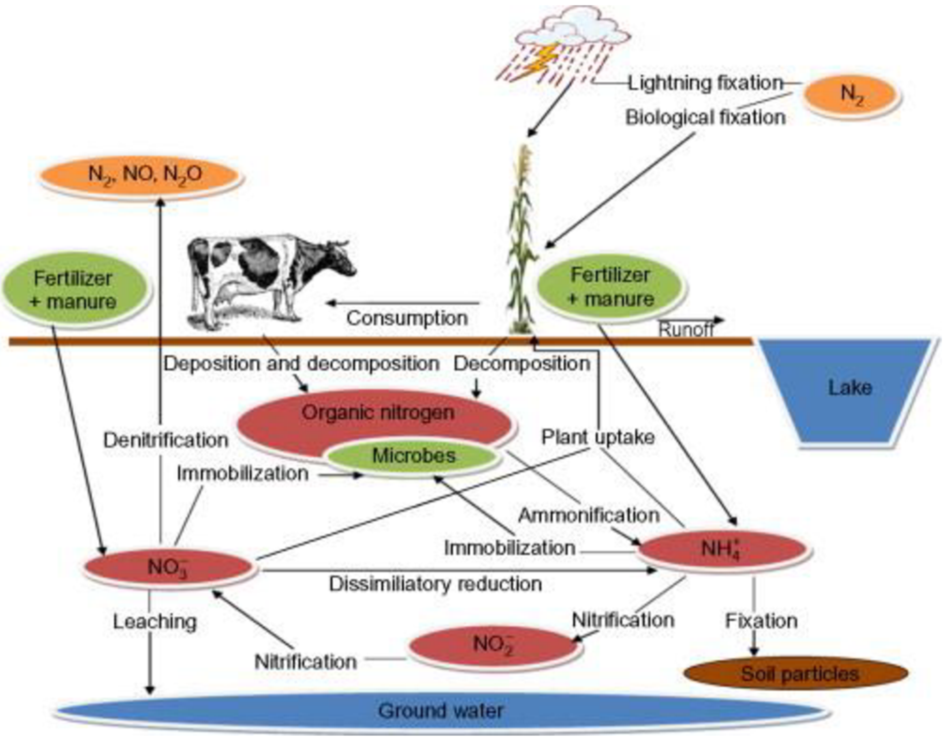


Figure 3. Illustration of nitrogen cycle in nature (Source:St. Luce et al., 2011)

A study resulted in available nitrogen presented in digestate with ammonium (NH_4^+-N) form (Drosg et al., 2015; Makdi et al., 2012; Pigoli et al., 2021). Presented N content in liquid was found approximately 40-80% as NH_4^+-N (Möller & Müller, 2012), which is easily uptake by the plant from the soil. Therefore, the total amount of ammonium in digestate is related to the total N from the material source, released immediately for growing plants (Drosg et al., 2015).

Phosphorous (P) and Potassium (K)

The characteristic of phosphorus is not easily dissolved in water distinguishes it from other elements and is usually available in the soil. Soil with digestate fertilization provided P and K in the long-term period for the plant (Meyer-aurich et al., 2012). For this reason, this element can be contained in large quantities in the ground compared to other macroelements. Phosphorous (P) is crucial for biochemical reactions as a part of plant structure compounds found in a high percentage of digestate. Additionally, Monfet et al., (2018) reported that solid-phase contained higher P, while K content is higher in the liquid phase (Monfet et al., 2018; Tampio et al., 2016). Sources of organic phosphorus elements are derived from green manure made from plants residues which regularly contain a high phosphorus content. Nutrient analysis of digestate from different feedstock resulted in the other total amounts of P (see table 1).

One of the macronutrients available and sufficient for plants is potassium (K). Potassium increases plant resistance to disease and drought and expands root tissue. Potassium promotes enzyme activation for growing plants, and phosphorous stimulates root and shoot growth. Thus, applied P and K as fertilizer increased crop yield and its quality (Slepetiene et al., 2020). Several sources, such as animal-based and plant ashes, provide high potassium. Plants absorb the potassium elemental from the soil in the ion form of K^{+}. Relatively, the needs of element K are more significant than element P. Makdi (2012) suggested that P:K ratio for land application is about 1:3 for a nutrient complement.

Impurities of Digestate

The feedstock used for the digestion process influences the AD digestate. Therefore, it is crucial to characterize and determine the feedstock's quality, impurities, and microbiological and pathogen content (Lamolinara et al., 2022). However, Kupper et al. (2014) found that the input materials may have a minor impact on the heavy metal content of compost and digestate. Two categories of chemicals are of particular concern for the quality of digestate used as fertilizer, heavy metals, and organic pollutants (Seadi et al., 2012). The decomposition process cannot decompose all potential chemical contaminants supplied with the raw material. It means that the only way to produce high-quality digestate is to use AD feedstock free of harmful impurities. Heavy metals like cadmium (Cd), chromium (Cr), mercury (Hg) and lead (Pb) are toxic to plants, animals and humans (Makdi et al., 2012). It is necessary to check the safety of the material and the effect of toxic compounds that may harm humans and the environment and affect crop quality, crop yield and soil fertility.

Organic pollutants are unwanted compounds in AD processes from undigestible materials (Seadi et al., 2012). Organic pollutants are toxic molecular compounds and, if the permissible limits are exceeded, can cause various diseases in humans. The range of national limits and regulated organic pollutants depends on the legal priorities of different countries. Directive 86/278 of the European Parliament was issued to regulate the use of waste products as fertilizers and prevent possible adverse effects on soil, vegetation, and human and animal health (Seadi et al., 2012).

1.2.3. System Application of Digestate Fertilizer

In cultivated plants, fertilization is a necessary process that supports plant growth. Fertilizers are designed to provide additional nutrients to the soil to meet the nutritional needs of plants. The use of organic fertilizer is increasing nowadays due to its benefits for crops as the nutrient supplier and soil fertility as organic matter enhancement. However, fertilizer application must be conducted accurately to provide the right benefits for plants and maintain soil health. Improper application of fertilizers can cause problems for both plants and the environment. For example, the unsuitable spreading method of liquid fertilizer on soil surface promoted higher emissions (Riva et al., 2016). Those are the importance of regarding the proper technique in applying fertilizer. Achieving the effectiveness and efficiency of fertilization refers to several following factors.

1.2.3.1. Plant and Soil Demand

In terms of nutrients, crop production requires a large amount of N, which is the widely determinant of crop growth, development and production (Anas et al., 2020). Plant productivity depends on nutrients, which is limited by the minimum availability of nutrients in the soil. Agricultural management processes, such as cultivation and fertilizer application, are key factors influencing farming soils and their properties to increase the yield and quality of food (Singh & Ryan, 2015). Soil is essential for crop production and thus are the natural resource that provides humanity with most of its food and nutrients. It is important to remember that plants get nutrients from soil and fertilizer.

Digestate application mainly depends on soil characteristics (Panuccio et al., 2021) to provide nutrients for plants regarding nutrient leaching and odors volatilization. However, misuse of the digestate application into soil contributed the greenhouse gas (GHG) emission. Furthermore, the application must consider the appropriate management according to the soil properties and digestate feedstock. Therefore, before applying digestate, a farmer should know material sources of fertilizer and soil characteristics to determine the nutrient ratio to apply. This strategy can avoid nutrient volatilization converted as emission and nutrient leaching.

1.2.3.1. Type of Fertilizer Used

Fertilizer differs according to different types and form. Generally, it is varied into synthetic and organic fertilizer. Choosing the right fertilizer source requires understanding the soil, time, and crop growing conditions to make the right decisions. Plant nutrition requirements, soil conditions, and environmental risks are essential considerations in selecting the most appropriate fertilizer source. Farmers usually use synthetic fertilizer to obtain higher yields of harvesting crops production. However, the long-term application of chemical fertilizers will eventually decrease the bacterial community within the soil (Chew et al., 2019). Thus, using organic fertilizer contributes to sustainable agriculture, yields high crop production, and maintains soil fertility.

Organic and synthetic fertilizers have a role in soil properties and agriculture, and their advantages should be recognized (Assefa, 2019). In terms of organic, fertilizer composition and properties are the most critical factor to determine which is suitable for the plants and soil demands to apply (Visvanathan, 2014). Availability and application of N fertilizers have been the most important determinant of yield in all major crops (Singh & Ryan, 2015). The use of organic fertilizers can enhance the absorption of nutrients, especially N, by reducing mineral leaching (Martínez-Alcántara et al., 2016).

Based on the form, fertilizers are available in solid and liquid forms, each of which has a different application. Urea (solid form) is the most commonly used for fertilization. Liquid fertilizer primarily addresses losses via ammonia volatilization, which occurs from the surface of applied slurries. LOF commonly applies via shallow injection to avoid volatilization. Thus, several analyses of fertilizer characteristics should be conducted before applying fertilizer corresponding to any possible negative impact causes. The reason is that plants can optimally utilize nutrients from the soil. For example, solid-liquid separation of biogas digestate differed in characteristics and application methods.

1.2.3.2. Rate Application

The proper application rate of a liquid or solid digestate depends on the plant nitrogen demand (Makdi et al., 2012) . Every plant has different mineral and nutrient requirements at various stages of development and time. Determining an appropriate application rate requires knowledge of the generally known N content of the fertilizer and the amount of product to be applied. The adjustment of N application rates, aim of reducing excess N, is based on two measures: (1) the calculation of the crop's N demand (2) the analysis of N_{min} at the time of fertilization (Edward et al., 2015). High doses of fertilizer do not guarantee high yields because the appropriate quantity of given fertilizer and demand is significant to avoid loss of nutrients (Costa et al., 2018). The excessive fertilizer dose may cause plant damage. The deficiency of nutrients stunted plant growth and led to diseases. The essential management technique to avoid inadequate nutrient and environmental problems is to develop a nutritional management plan based on soil testing of the application rate.

Consider N content-based, and it is crucial to determine the application rate (Czekała et al., 2020), because the exceeded amount of N application is the primary emission factor (NH_3, N_2O). This emission is also related to the C/N ratio. It influences the CO_2 volatilization from microbial activities as higher C, usually in the solid fraction. C content in fertilizer triggered N immobilization after application (Alburquerque et al., 2012). Therefore, a high amount of C can induce N losses during storage or application. Visvanathan (2014) suggested that a C/N ratio of 15-20 is a safe land application. The N:P:K ratio is essential for reduced leaching of exceeding nutrient use.

1.2.3.3. Time Application

The application of digestate fertilizer also must be considered to the spreading time of period. Fertilizer should be applied when the crop has high nutrient uptake to avoid nutrient leaching. Nutrient uptake depends on the environmental condition among plants and soil, including growing season and available nutrients. Plants absorb the nutrients to comply with the nutrient demand of cellular processes for their growth. The amount of fertilizer and the time of fertilization affected nutrient leaching (Delin & Stenberg, 2014). Therefore, due to the high nutrient requirements of plant growth, fertilization during the growing season in spring resulted in low emissions (Rodhe et al., 2015).

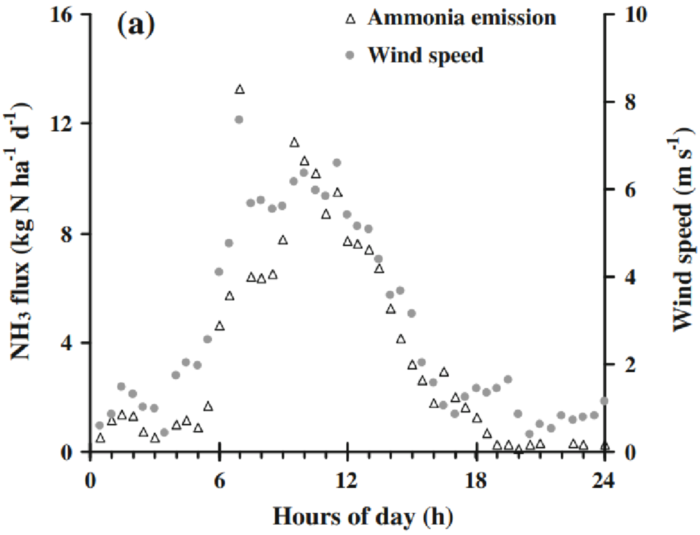


Figure 4. Effect of wind speed in ammonia flux after fertilization on winter wheat (Source: Yang et al., 2014)

The time application is also vital to avoid and minimize volatilization and reduce nutrient leaching. The nitrogen application is more important than any other nutrients because it is applied in large quantities for almost all crops. The right time to apply N fertilizer is in the morning because the temperature and wind speed is stable. The experiment result by Yang et al. (2014) showed that the ammonia flux increases with increasing wind speed (see figure 4). Therefore, the primary factors affecting the volatilization of fertilizers are soil temperature and wind speed. In addition, applied liquid fertilizer into the soil in the rainy season may occur nutrient leaching into nearby groundwater and affect the surface water quality. Therefore, liquid fertilizer is suggested to apply in late winter until early summer to enhance nutrient efficiency (Möller & Müller, 2012).

1.2.3.4. Application (Spreading) Method

Generally, fertilization can be applied by the roots (ground) or leaves of plants depending on fertilizer types and soil conditions. The four main application methods consist of broadcasting, foliar, placement, and fertigation. A technique of feeding plants characterizes foliar application by applying liquid fertilizer directly to their leaves (Alshaal & El-Ramady, 2017). This method aims to provide nutrients for easy fertilizer absorption into the stomata. Mechanically deep placement of N fertilizer enhanced nutrient use efficiency (NUE) and grain yield significantly compared to surface broadcasting (Pan et al., 2017). Some of the problems observed in traditional centrifugal fertilizer application methods or manual spreading (dressing) are nutrient losses due to rain or irrigation and sublimation of solar radiation (Bakhtiari et al., 2014). Therefore, choosing the proper fertilization method is essential to avoid nutrient losses and increase crop production yield.

In order to improve the efficiency of nitrogen utilization in crop growth, it is essential to change the fertilizer rate according to the demand of plants and the lateral arrangement of roots (depth 50-100 mm) (da Silva & Magalhães, 2019). Plants quickly absorb the dissolved nutrients provided by liquid fertilizers. Therefore, liquid fertilizers are commonly used by farmers to nourish their crops. However, liquid fertilizers are often applied by injection into the topsoil in a concentrated form to maximize the fertilizer's stability regarding several potential impacts on the environment.

Liquid digestate application must use a suitable method by avoiding the surface area contact to air to minimize the volatilization of odor emissions. Measurement of ammonia emission was derived higher in digestate application by the surface area (Riva et al., 2016), and CO_2 decreased significantly when injection depth increased (Maucieri et al., 2016). On the contrary, Severin et al. (2016) found no significant effect on emission between injection depths after digestate application. Therefore, most studies recommended liquid digestate application for manure or slurry by trailing shoes or direct injection into topsoil (Nkoa, 2014; Seadi et al., 2012). A study of the liquid fraction of digestate also resulted in that digestate had low emission due to its treatment in spreading whereas injected into the top layer of soil (Verdi et al., 2019). Furthermore, liquid fertilizer injection into topsoil directly eases the nutrient uptake by crop roots. This application method aimed to avoid unpleasant odors volatilization and provide nutrients for the plants into the soil root immediately.

1.2.4. Environmental Impact of Improper Fertilizer Application

Improper use of fertilizers can damage the environment (as water and soil pollution), be toxic to plants, reduce soil fertility, and reduce crop productivity and crop yields. However, the direct impact from fertilizer application is considering emission released into the atmosphere and nutrient leaching triggered as a pollutant in groundwater. Nevertheless, an investigation of the organic pollutants was measured much lower than the limits required for agriculture use (Pigoli et al., 2021) and digestate emissions.

1.2.4.1. Emission

Global warming currently results from increasing greenhouse gas (GHG) emissions in the atmosphere, both from natural and artificial ecosystems, including the agricultural sector. The dominant greenhouse gases in the atmosphere are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The agricultural sector contributes to anthropogenic GHG emissions in global warming. One of the sources of GHG emissions contribution comes from agricultural activities such as fertilizer production, land application, and transportation (see figure 2). Microbial mineralization of organic fertilizers N, reactive N compounds such as ammonia (NH_3), and nitrates (N_2O) are present in the soil through subsequent NH_3 oxidation (Szogi et al., 2015). Plant growth requires a soluble form of nitrogen. However, losing to the environment can adversely affect air and water quality.

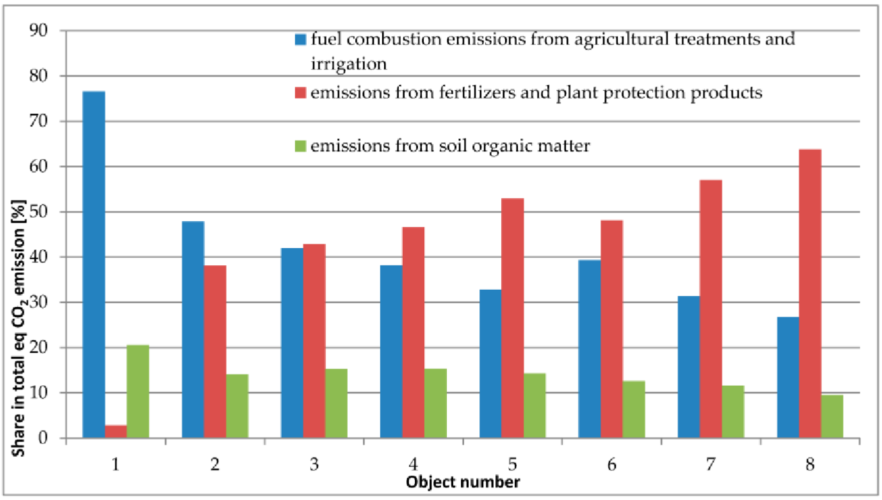


Figure 5. Percentage of GHG emission (CO_2) from agricultural field (source: Sikora et al., 2020)

Emission of digestate depends on the land application, temperature (according to time application, such as in the spring or autumn period), and soil nutrient demands (Zhang et al., 2021). The feedstock, such as animal manures and many organic wastes, contained volatile organic compounds that can produce unpleasant odors.

Digestate released lower emissions than undigested material like the animal slurry (Johansen et al., 2013; Riva et al., 2016). A study of digestate resulted in emissions including ammonia (NH_3) which contributed to matter formation in the atmosphere (Zilio et al., 2021). Also, carbon dioxide (CO_2) and methane (CH_3) are released but gradually decrease after spreading (Czubaszek & Wysocka-Czubaszek, 2018). Raw digestate was investigated, resulting in the high potential of GHG emissions (Visvanathan, 2014). However, proper management, either in processes, stored or land application, is essential for emission minimalization.

1.2.4.2. Ammonia (NH_3)

The emission of NH_3 is the most air pollutant from the agricultural sector. As nitrogen is known as the essential nutrient for plant growth and production, it is also challenging for the farmers in agriculture nowadays. Nitrogen is the highest content of digestate (Makdi et al., 2012), which releases in ammonia (NH_3) form as emission. This primary factor of NH_3 emission to measure from the land application (Zhang et al., 2021). For instance, measurement in digestate showed that emissions, including ammonia (NH_3), contributed to matter formation in the atmosphere (Zilio et al., 2021) after the application. Also, NH_3 emissions were obtained high from field application of digestate cattle slurry in spring (Rodhe et al., 2015). The NH_3 emitted from the agriculture field is related to the C/N ratio.

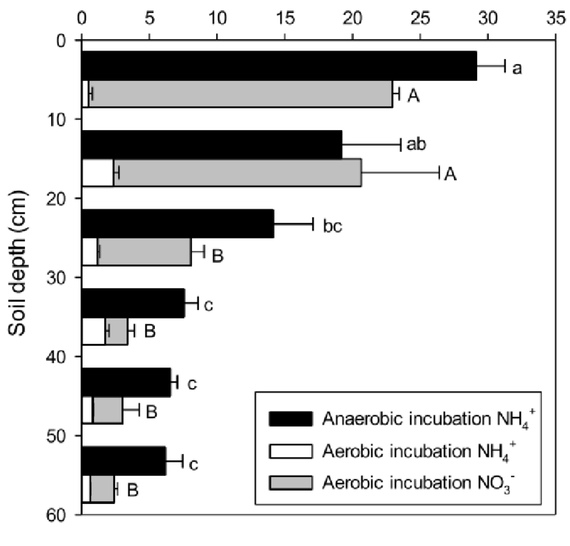


Figure 6. Mineralization (ammonification and nitrification) after incubation at different soil depths in an agricultural wheat cropping soil (source: Jones et al., 2018)

NH_4^+ is an essential nitrogen source for plants presented in soil, water, and air. The high content of NH_4^+ and the pH of the digestate facilitate nitrogen losses due to NH_3 volatilization (Möller & Müller, 2012). However, NH_3 is a harmful nitrogen form that plants and animals cannot directly use in the air. To grow, plants require nitrogen compounds from the soil, produced naturally or provided by fertilizers. Plants absorb N from the soil in NH_4^+ and NO_3- form. The nitrogen converts through denitrification and nitrification. Thus, the immobilization of N produced the NH_3 during its processes. Most microbial activities are abundant in the topsoil and subsoil as mineralization and soil respiration decline with increasing soil depth (Jones et al., 2018).

1.2.4.3. Methane (CH_4)

Methane (CH_4) is the simplest form of hydrocarbon, odorless. So naturally, anaerobic respiration (methanogenesis) is a process that produces CH_4 used by organisms as a source of energy. The utilization of methane gas (CH_4) from the waste of agriculture and livestock can be processed through AD by microorganisms into biogas as renewable energy. Digestate with a higher dry matter content, deriving from dry AD processes, might give rise to higher emissions of CH_4 in the field (Dieterich et al., 2012). As previously described, a by-product from biogas is utilized as a source of nutrition. However, after the land application of fertilizer, it remained to release methane. CH_4 concentration was examined in a lower value, characterized the liquid phase of digestate (Czekała, 2019).

Studies of methane emission from soil investigated several factors influencing elevated concentration, such as N fertilizer, SOM, microbes' activities, temperature, and soil moisture content. Abundant microbe activities induce this emission during the transformation of organic matter into CH_4 (Meyer-aurich et al., 2012). Thereby, methane (CH_4) is generated from soil organic matter, using a C source for CH_4 production, contributing to GHG emissions. Also, the most critical factor controlling methane production activity is soil temperature, which increases methanogenesis exponentially with increased temperature (Malyan et al., 2016). Then, an elevated high temperature decreased CH_4 oxidation, which converted CH_4 to CO_2.

On the other hand, low soil moisture content influenced CH_4 emission by inhibiting its production process (Doyeni et al., 2021). Whereby microbial activities in decomposing SOM decrease with decreased soil moisture. In the case of CH_4 emission, the production requires anaerobic conditions for fermentation while sinking in aerobic conditions. thus, oxygen is a limiting factor for methane oxidation as aerobic methane oxidation is the most critical process of soil methane consumption (Serrano-Silva et al., 2014)

1.2.4.4. Nitrous Oxide (N_2O)

Important factors that affect the formation and emission of N_2O gas include ammonia and nitrate content in the soil, soil aeration, soil water content, soil pH, and soil temperature. N_2O emissions are caused by the compound of nitrogen and oxygen nutrients. Increased human activity in agricultural land management can increase the nitrogen content available in the soil through nitrogen fertilization and the application of organic matter. The possible explanation of N_2O emission depends on N content as the primary source of microbial production. In addition, microbiological processes stimulate the increase in N_2O emissions directly and indirectly. In the aerobic process, the microbial process primarily caused nitrous oxide (N_2O) emission through the nitrogen cycle (Meyer-aurich et al., 2012; Zhang et al., 2021). N_2O gas emissions tend to increase in wet soil conditions but not flooded.

A study by Verdi et al. (2019), observed high N_2O emission after digestate application that may cause the combined effect of several factors such as organic C, soil moisture, and distribution method. Soil moisture increased in the rainy season, is induced N_2O flux peaked (Rodhe et al., 2015). In terms of N, additional into the soil may consider the source of fertilizer material. A paper by Doyeni et al. (2021) reported highest N_2O emission was released from pig slurry compared to cow and chicken slurry, yet was in the low stage of the limit. However, nitrogen gas emissions are much lower than atmospheric CO_2 emissions.

1.2.4.5. Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) is the main factor of greenhouse gases greenhouse gases because the amount of CO_2 emissions is constantly increasing in the atmosphere and induces accelerated global warming. CO_2 emissions are produced from the soil and released into the atmosphere. Soil microbial activities are the prime factor in the biodegradable organic carbon decomposition process (Czubaszek & Wysocka-

Czubaszek, 2018), which triggered releasing CO_2-C rapidly (Alburquerque et al., 2012). In addition, destroying soil aggregation by land plowing triggered the loss of soil particles and carbon by the erosion also stimulates the oxidation of soil organic matter, resulting in increased CO_2 emissions. As the study found, organic matter enhancement referred to microbial activity (Severin et al., 2016).

Carbon dioxide (CO_2) released from the soil is referred to soil respiration. This carbon dioxide comes from various sources, including aerobic microbial decomposition of soil organic matter (SOM) for energy (microbial respiration). Soil moisture can affect soil respiration both directly and indirectly. An increase in soil temperature leads to increased emissions and increased soil respiration rates as a result of the positive feedback of increased microbial metabolism (Oertel et al., 2016). Soil respiration is low in dry conditions and increases to a maximum at an intermediate moisture level until it begins to decrease when moisture content excludes oxygen (Xu & Shang, 2016). Soil respiration is a measure of biological activity and decomposition. Low soil respiration rates indicate little or no aerobic or soil microbial activity. It may also indicate that soil properties that contribute to soil respiration (soil temperature, moisture, aeration, available nitrogen) limit biological activity and decomposition of SOM.

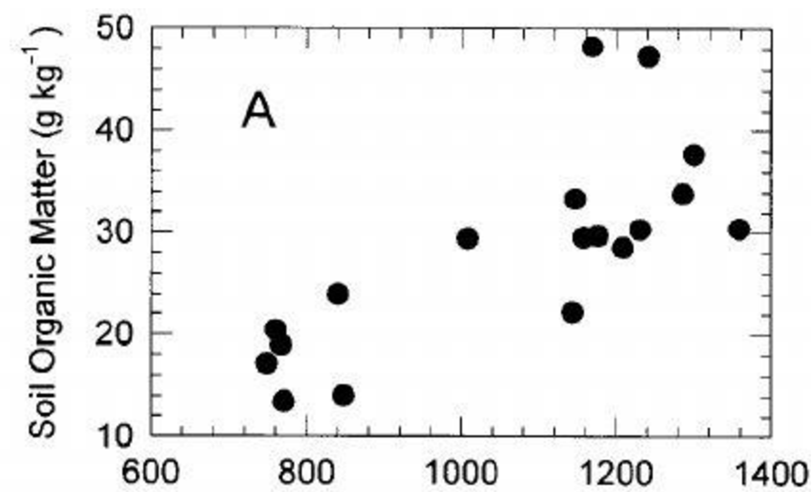


Figure 7. Annual values of soil respiration related to SOM (0-30 cm in depth) (source: Grandgirard et al., 2002)

Organic fertilizer is the primary source of rich organic matter, including biogas digestate fertilizer. For instance, Maucieri (2016) investigated CO_2 emitted in the experimental plot after applying liquid digestate fertilizer. Doyeni et al. (2021) also found that soil under pig digestate treatment had consistently released CO_2 emissions compared to the other digestates (cow and chicken manure). Therefore, it is necessary to have GHG mitigation through sustainable land management, increasing carbon sequestration, and reducing CO_2 gas emissions from the agricultural sector. Increasing carbon in soil will help reduce GHG emissions and increase soil fertility.

1.2.4.6. Leaching of Nutrient

Loss of soil nutrients occurs through leaching through the surface runoff or stream into groundwater. Soil structures such as soil hydraulic properties, porosity, infiltration capacity, and hydraulic conductivity regulate nutrient leaching (Dar et al., 2017). Leaching through surface runoff occurs when the soil becomes saturated and cannot retain water. The nutrient washed into the groundwater is promoted by very high soil porosity, commonly indicated in sandy soil. Surface runoff is the amount of water contained in rainfall and runoff received from higher altitudes that do not infiltrate the soil. Compaction or drought soil is also another factor that affects nutrient leaching. Thus, the water is difficult to penetrate the soil then flow over the surface due to the low infiltration capability in dry soils.

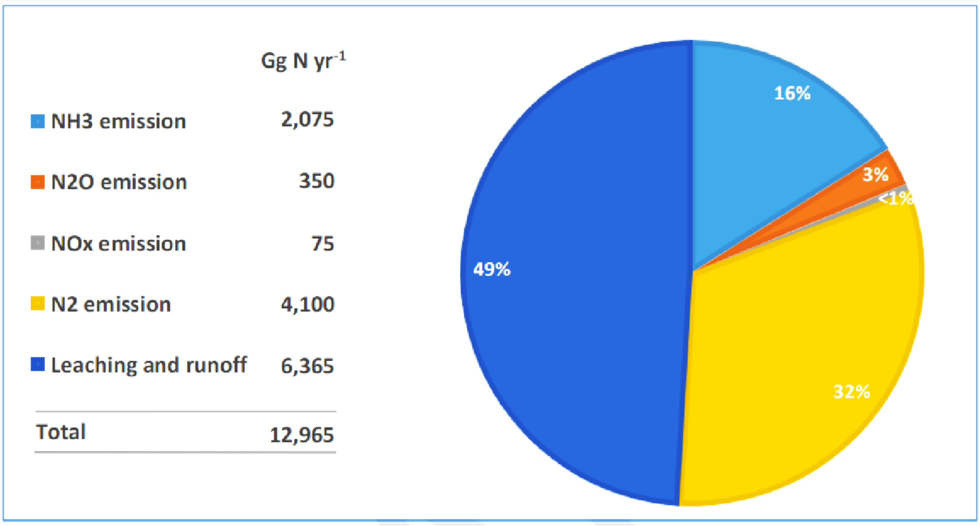


Figure 8. Estimates of N losses from agricultural soils in EU28 (UNECE, 2014)

A large proportion of applied nitrogen in agricultural land consequently loses the nitrogen from soil (see figure 8). N losses through leaching and runoff contributed to water and ground contamination, potentially affecting water quality (see figure 8).

Notably, nitrate (NH_3-) leaching is a critical point for soil and water pollutants (Misselbrook et al., 2019). Particularly, the nitrate (NH_3-) leaching is critical point for soil and water as pollutant (Paolini et al., 2018; Sánchez-Rodríguez et al., 2018). Nitrogen loss is usually in nitrate form stream down vertically to groundwater or horizontally by runoff in the soil surface (Powlson & Addiscott, 2005). Matching fertilizer application to crop nutrient demands can reduce the risk of nutrient leaching. The amount of fertilizer and the time of fertilization affected nutrient leaching (Delin & Stenberg, 2014).

2. AIM OF THE THESIS

The research is aimed at investigating the effect of different digestate rates on gas emission, water infiltration ability, and yield attained. The vegetative disk unit is used that applies the digestate under the soil surface. Mitigation of environmental impacts is therefore assumed.

3. MATERIAL AND METHODS

In this section, the author describes the processes in research, including data collection and the analysis process. So that all research processes will be transparent and can be developed by other researchers.

3.1. Material

The digested substrate for fertilization was carried out from the agricultural biogas station in Bořetice. Biogas materials were derived from 51 % maize silage, 15 % slurry, 2 % grass silage, and other substrates. The fermentation test methodology referred to the German standard VDI 4630. Product fermentation is carried out for a minimum of 21 days. An extended storage period is required if the yield has not obtained relevant application results. It was measured using a Biogas analyzer from Geotech for biogas digestate quality test before field application.

3.2. Methods

The digestate fertilizer application was on 30.03.2021 in Cechtice, Central Bohemian Czech Republic. The application of digestate slurry was performed in the growing season of winter wheat *(Triticum aestivum L)* by a Vredo self-propelled machine (type VT4556) equipped with a vegetation applicator with a working width of 8 m. The experiment was established in eight variants with different digestate doses. The investigation was conducted on emission released and soil physical properties, including infiltration, bulk density, and penetration resistance. Then, we processed the data collection from measurement by analyzing using ANOVA (analysis of variant) and post-hoc test (Tukey's HSD test).

3.3. Digestate Application

The digestate application took place in the agriculture field "Za Sady" (8.81 ha, No. 3101, district Čechtice, GPS:49.6162719N,15.0742658E), where winter wheat was grown in the season 2020/21. The application was carried out in the spring season in March 2021. We established 8 (eight) plots as variants and control from the selected locations.

Digestate fertilizer was injected into the soil using Vredo self-propelled machine (type VT4556) equipped with a vegetation applicator. Digestate was applied to all variants, excluding the control. Then fertilizer is applied again for variants 4 to 8, the so-called regenerative application. This reapplication used N industrial fertilizer with a 60 kg/ha application rate. The table below shows detailed application doses.

Table 2. Variants of the field experiment with different doses applied on winter wheat

Variant	Dose ($t\ h^{-1}$)	Depth (cm)	Regeneration
1	0	5	No
2	15	5	No
3	20	5	No
4	10	5	Yes
5	15	5	Yes
6	20	5	Yes
7	25	5	Yes
8	0	5	Yes

3.4. Gas Emissions Monitoring

The emission measurement was taken two days after digestate application into the soil around 30.03.2021. Particularly, consider that high ammonia volatilization will take place after the application. The device for the emission monitoring was used the INOVA 1412 gas analyzer. Five closed chambers set on the soil's surface connect to the device. The closed chamber/box was constructed in a surface area of 0.175 m2 with an inlet diameter of 0.072 m accomplished with a wind tunnel at the side of the box. Gas monitored was conducted for variants 4-8 because variants 2 and 3 are similar in dose application to variants 5 and 6. Then, it intended to avoid the repeated measurement of the same doses.

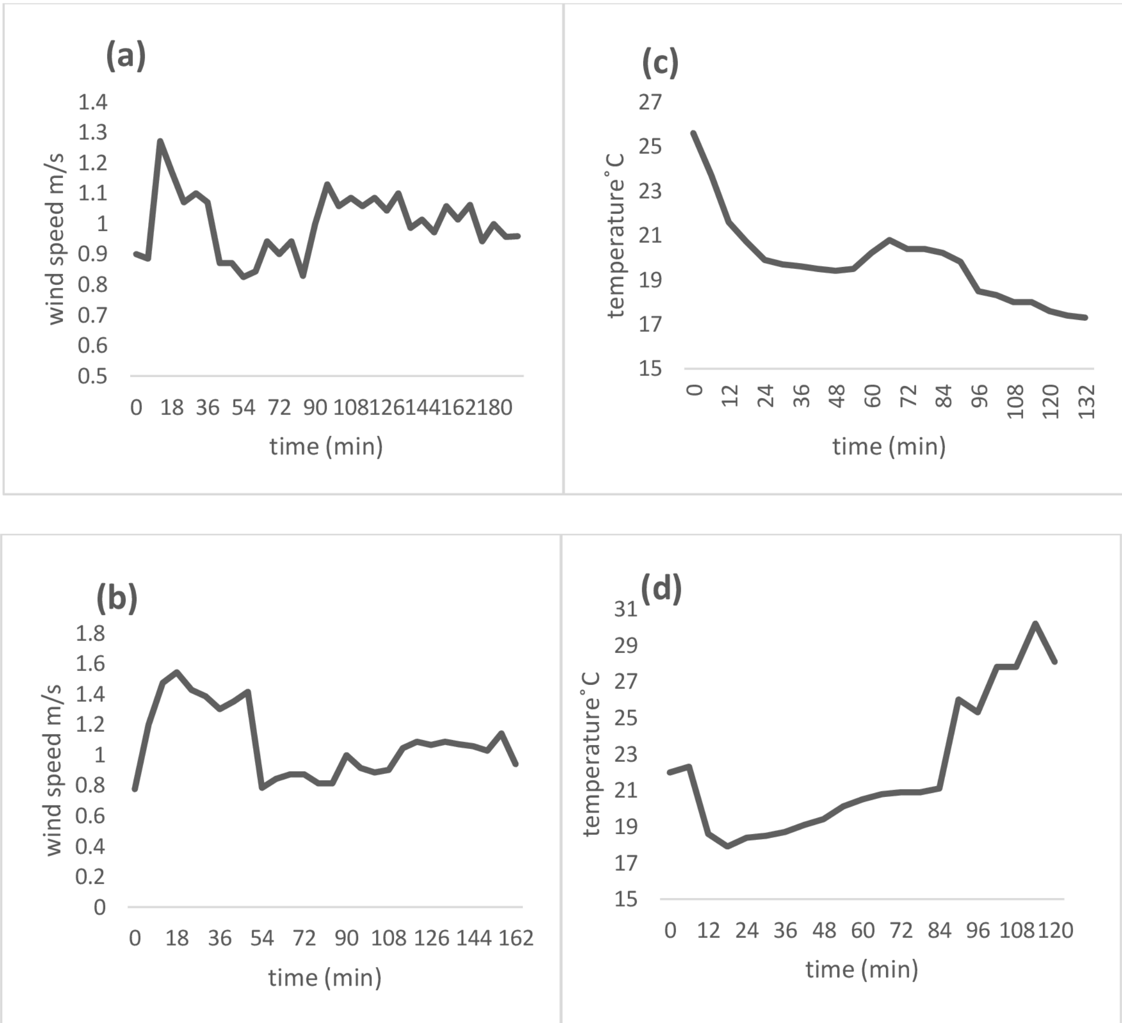


Figure 9. Atmospheric condition during measurement, (a) wind speed m/s and (c) temperature ^{0}C after application and (b) wind speed m/s and (d) temperature ^{0}C in next day.

The first emission monitoring was conducted after the digestate application immediately. During gas monitoring, the average temperature was measured at around 19 ^{0}C. The second measurement was continued on the following day, around 10.00, to see the differences in emission values compared to the first measurement. The temperature was approximately the same as the first measurement. ANOVA statistical analysis was used to determine the effect of the different rate applications on emission to understand the relationship between attributes of soil entities and the environment.

Then, further analysis was conducted to post-hoc test (Tukey's HSD test) corresponding to correlative between the group of variants.

3.5. Soil Properties Measurement

Analysis of Physical properties was established by measuring infiltration, bulk density, and soil moisture content to investigate digestate impact in soil aggregate. Physical properties were measured to analyze the soil condition after applying digestate fertilizer. The statistical analysis also used analysis of variant (ANOVA), which is commonly used to study the environmental effect on soil properties. The infiltration experiment used the Simplified Falling Head (SFH) method with a ring of 0.15 m in diameter and 0.5 L of water. This experiment used a minor diameter of the ring instead of a bigger diameter. Due to the measurement results, the big diameter of the ring used to be fragile to an insignificant result and requires large amounts of water, and is challenging to install. This gauge used a circular device that allowed water to pond on the soil surface. Then the ring filled with water during measurement of time was taken to the permeated water into the soil. The repetition of measurement was taken five times for each treatment. There was also soil moisture content measurement, which took place for dry and wet moisture content.

Infiltration with SFH method investigation was used to calculate the value of Saturated Hydraulic Conductivity (SHC). According to Bagarelo (2006) and Elrick (1989), this calculation approach estimated reliable Soil Hydraulic Conductivity, K_{fs} (LT^{-1}) value using single ring infiltration technique.

Equation (1) for calculating soil conductivity based on analysis by Philip (1992):

$$K_{fs} = \frac{\Delta\theta}{(1-\Delta\theta)t_a}\left[\frac{D}{\Delta\theta} - \frac{\left(D+\frac{1}{\alpha^{\circ}}\right)}{1-\Delta\theta}\ln\left(1 + \frac{(1-\Delta\theta)D}{\Delta\theta\left(D+\frac{1}{\alpha^{\circ}}\right)}\right)\right] \quad (1)$$

Equation (1) indicates that the infiltration (queasy-steady state infiltration) is determined by the hydraulic conductivity of the soil in saturation state (Kfs). θ (L^3L^{-3}) is thedifference between volumetric dry and wet soil water content. t (T) is time-consumed for water runoff into the soil. α (L^{-1}) is a different type of soil texture (soil macroscopic capillary length) according to Elrick et al. (1989). D (L) is the ratio of water volume, V (L^3), and area of the ring, A (L^2).

SHC values were estimated by the SFH method and the equation based on analysis by Philip (1992) (see equation 1). Determined K_{fs} value depended on α* parameter (Elrick et al. 1989) where the field experimental characterized by brown aluminous sandy/sandy soil.

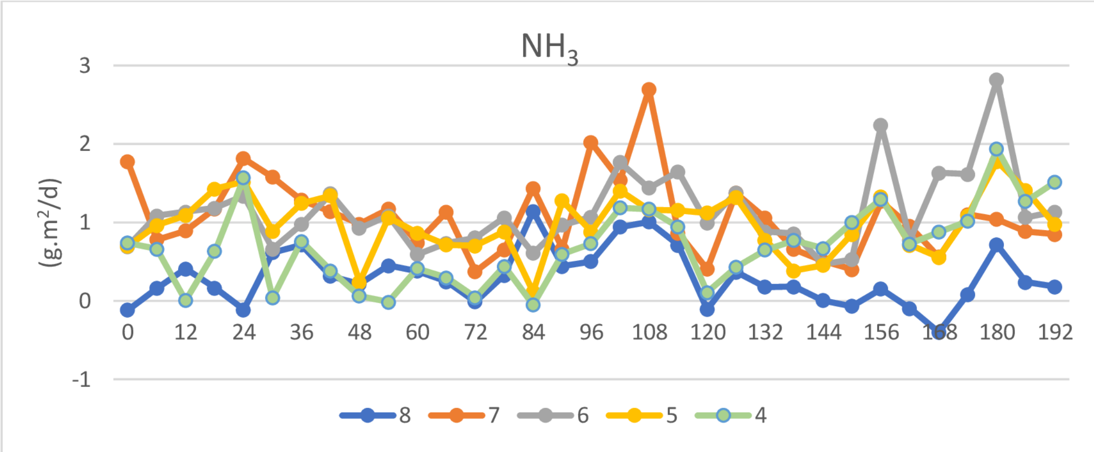
Another essential measurement that should take is detecting the compaction of the soil. Therefore, bulk density and penetration were also measured to investigate the density of soil conditions that determine the growth of plant roots. The Cone Penetration test is a standard test that is used to determine the geotechnical properties. Soil penetration resistance was measured by cone penetrometer in several depths from 4 cm to 32 cm in each variant randomly. At the same time, bulk density also was measured with a roller with a volume of 100 cm^3. Soil sampling was collected in three replications from each variant. Then samples were carried on and analyzed in the Czech University of Life Sciences Prague laboratory.

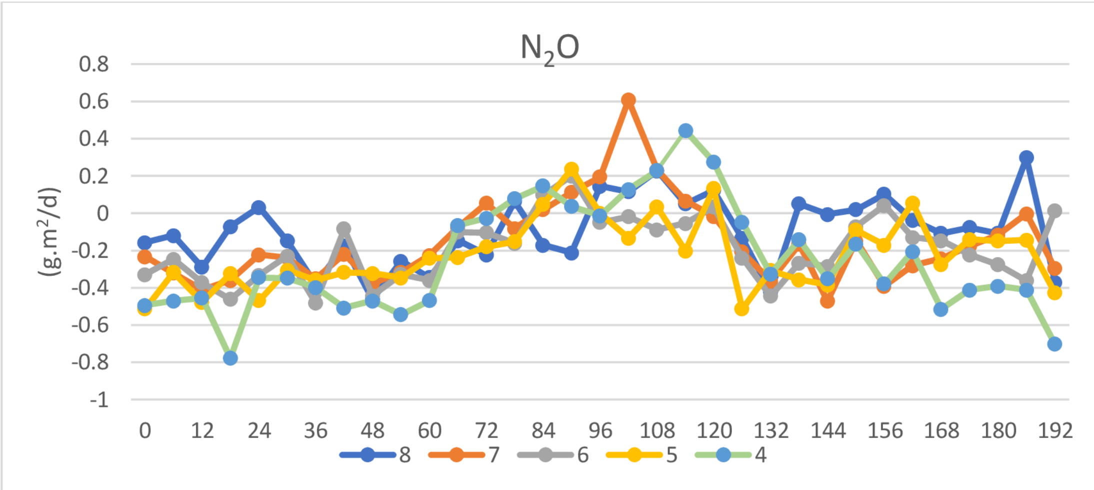
4. RESULTS

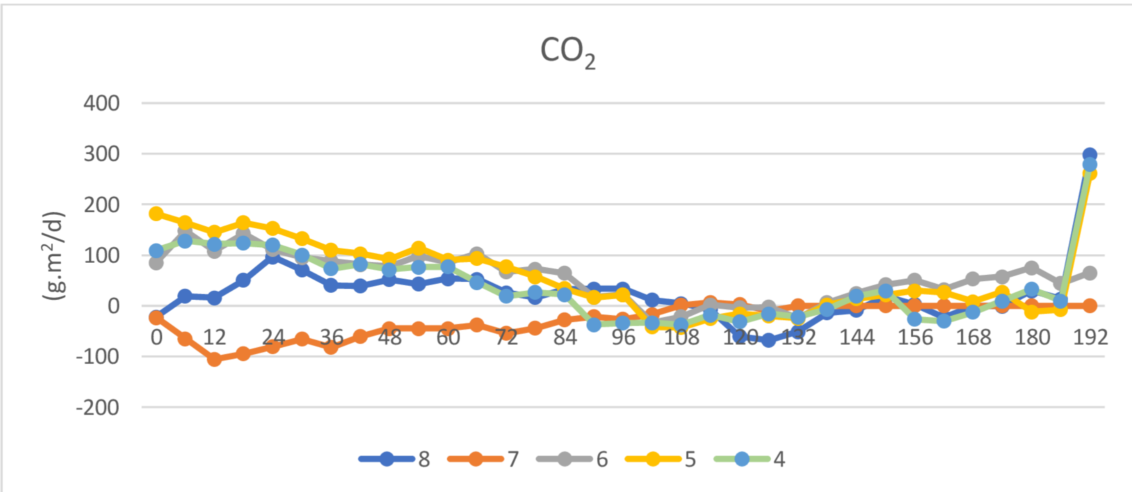
This work resulted in many data measurements from field experiments to assess the liquid organic fertilizer in particular digestate. We obtained the emission concentration values from the shallow injection method used in the study. Also, crop yield and soil properties assessments were conducted to see the digestate effect on plants and soil.

4.1. Emission

Assessment of emission monitoring is shown in figure 1. and figure 2. Emission measurements after digestate application found that each emission gas has a varied concentration. Gas emission was monitored at 14.00 after the digestate application. The average temperature and humidity were measured at 19 ^{0}C and 54% during the emission monitoring. Then the second monitoring took place on the following day at 10.00 in the morning with the same condition but a slightly warmer with an average temperature of 22 ^{0}C.


NH3
(g.m2/d)
3
2
1
0
-1
0 12 24 36 48 60 72 84 96 108 120 132 144 156 168 180 192
8 7 6 5 4


N2O
(g.m2/d)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0 12 24 36 48 60 72 84 96 108 120 132 144 156 168 180 192
8 7 6 5 4


CO2
(g.m2/d)
400
300
200
100
0
-100
-200
0 12 24 36 48 60 72 84 96 108 120 132 144 156 168 180 192
8 7 6 5 4

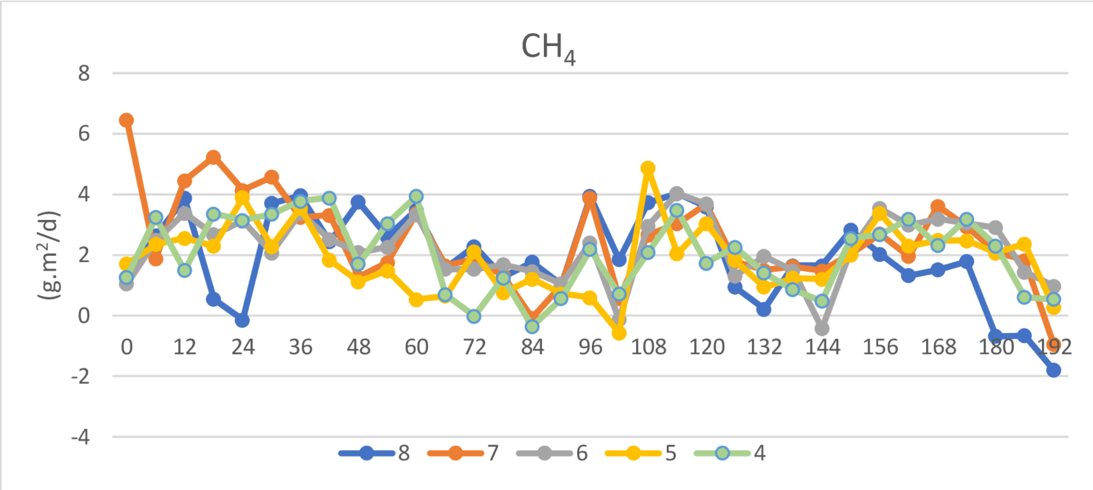


Figure 10. The dynamic flux of gas emissions (based on time (min) of measurement) from measurement immediately after the liquid digestate application

Variant: 4 – 10 t ha^{-1} + reg., 5 – 15 t ha^{-1} + reg., 6 – 20 t ha^{-1}+ reg., 7 – 25 t ha^{-1}+ reg., 8 – control + reg.

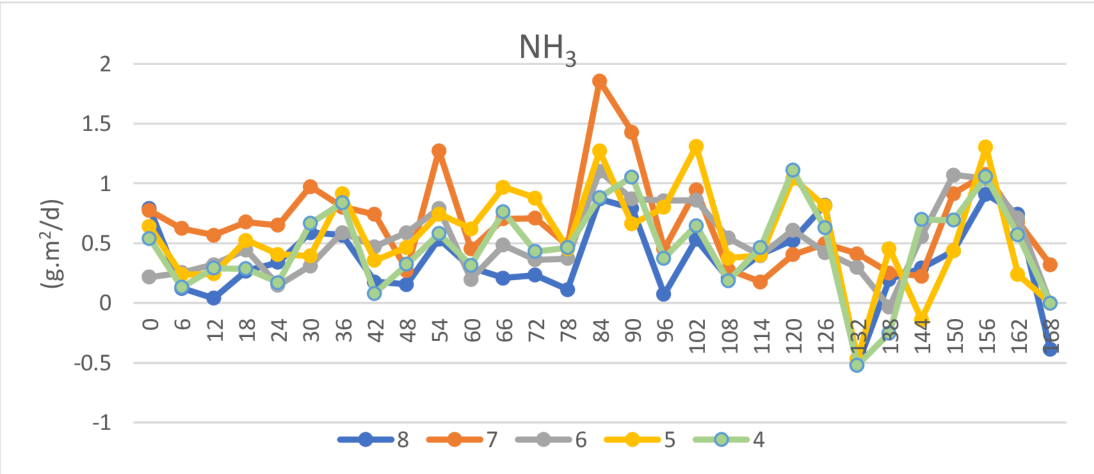
Emission of NH_3 showed that between the control and the variants indicated a significant difference. Variant 4 with lowest dose (10 t ha^{-1}) released ammonia in the lowest concentration level compared to variant 6 (20 t ha^{-1}) and 7 (25 t ha^{-1}). This result was expected that variants with lower fertilizer doses induced lower emissions released into the air than variants with higher fertilizer doses. Variant 5 was not statistically different from other variants, it however differed only from the control. Given various doses of liquid digestate fertilizer affected the emission concentrations of NH_3 volatilization from soil. Figure 10 shows the dynamic flux of emissions from the first measurement. The dynamic flux of NH_3 was synchronized to the fluctuating wind speed (see figure 9). This result indicated that wind speed influenced the NH_3 emission, reaching three peaks between 24, 108, and 156. On the contrary, the dynamic temperature was not synchronized with the dynamic flux of NH_3 emissions.

N_2O emission resulted in an insignificant difference between control and variants. However, the average concentration of N_2O emission was reported with low rates and negative values, indicating the proper application method. Therefore, the application of digestate in the growth period had no meaningful impact on N_2O emissions released in this work. Nevertheless, the dynamic flux of N_2O emission showed that it reaches the peak when wind speed increases at 100 h after application while the temperature decrease.

CO_2 had the highest emission compared to other emissions monitoring. The average values of CO_2 emission between variants with digestate application with the control are not significant. However, the emission concentration for variants 4, 5, 6 showed insignificant differences. Microbe's activities in organic matter decomposition most likely triggered the high emission of CO_2. However, the emission flux of CO_2 gas showed that increase in initial measurement after digestate application and gradually decreased. The dynamic flux of CO_2 is related to the dynamic change in temperature. Soil with high water content may disrupt oxygen absorption, inhibiting the aerobic process and indirectly declining CO_2 gas.

All variants showed there was no significant difference for CH_4 emission. Although it seemed to increase slightly at the initial assessment, the CH_4 flux decreased over time. Nevertheless, the average CH_4 concentration remaining yields low emission. Even though CH_4 gas was unstably increased again after 2 hours, it possibly occurred by the high temperature and wind speed in the atmosphere.

Different doses application did not show any significant difference in CH_4 and N_2O emissions. Using the proper application method in spreading fertilizer may have affected these results. Emission of NH_3 and CO_2 showed a statistical difference between variants and control. NH_3 emission for variant 4 differed significantly from variants 6 and 7.



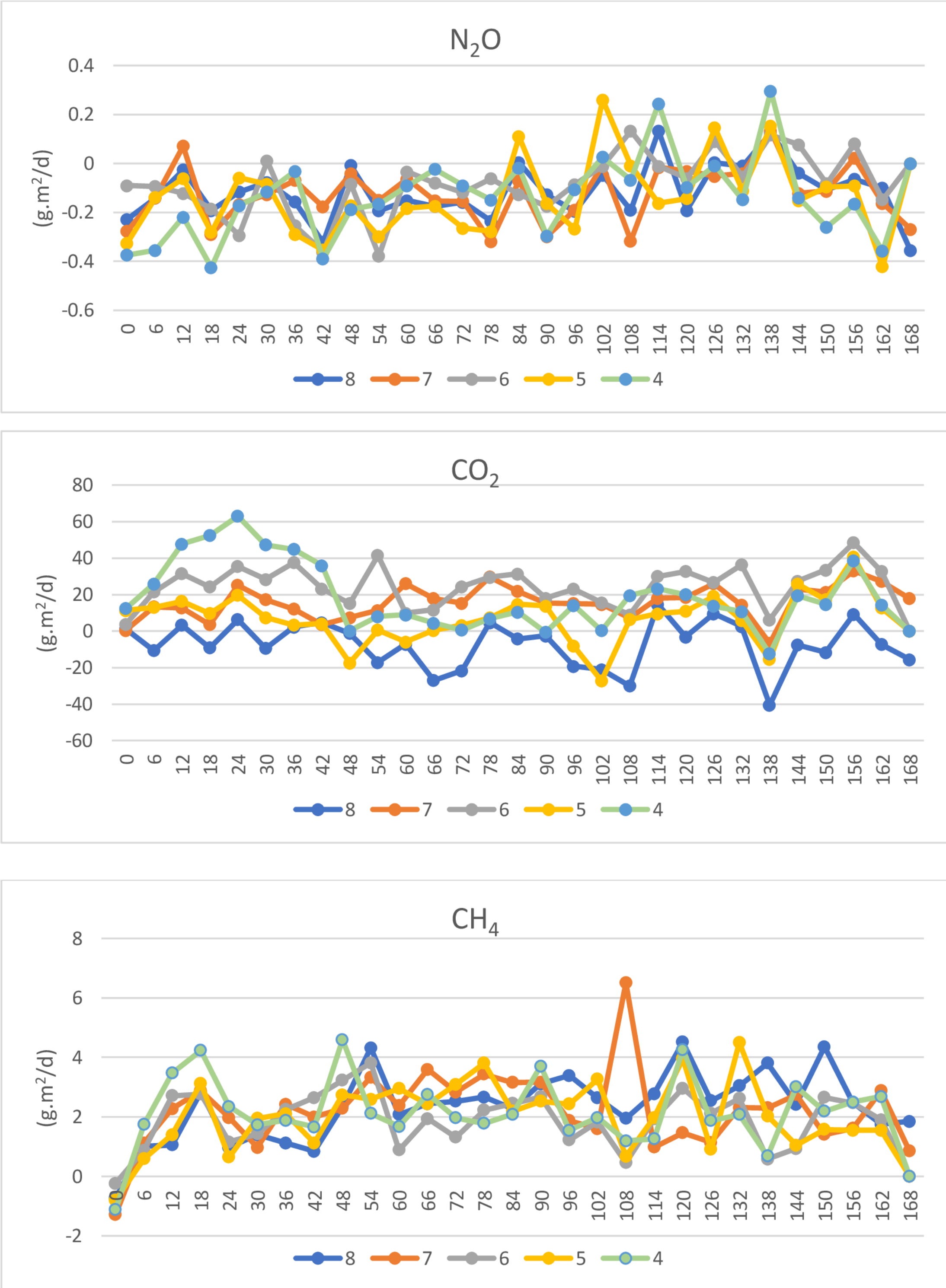


Figure 11. The dynamic flux of gas emission (based on time (min) of measurement) *from* measurement the next day *after* liquid digestate application on winter wheat

Variant: 4 – 10 t ha^{-1} + reg., 5 – 15 t ha^{-1} + reg., 6 – 20 t ha^{-1}+ reg., 7 – 25 t ha^{-1}+ reg., 8 – control + reg.

The second monitoring resulted in a lower emission released from all variants. NH_3 emissions for variants 4, 5, 6, 7, and 8 have decreased by 44%, 44%, 49%, 38%, and 15%, respectively, compared to the concentration values from the previous measurement. N_2O emission was measured constantly in low emission with negative values. NH_3 emission showed significant differences between the variants and control. Figure 11 shows that variant 7 resulted in the highest concentration of NH_3 emissions applied by 25 t ha^{-1} the highest dose. CO_2 also significantly differed among variants and control. Variant 5 with dose of 15 t ha^{-1} differed from variants 4 and 6. However, variant 7 is not significantly different from other variants. Thus, the average concentration level of emissions remains lower than the previous monitoring. It meant that emission was declining slightly over time.

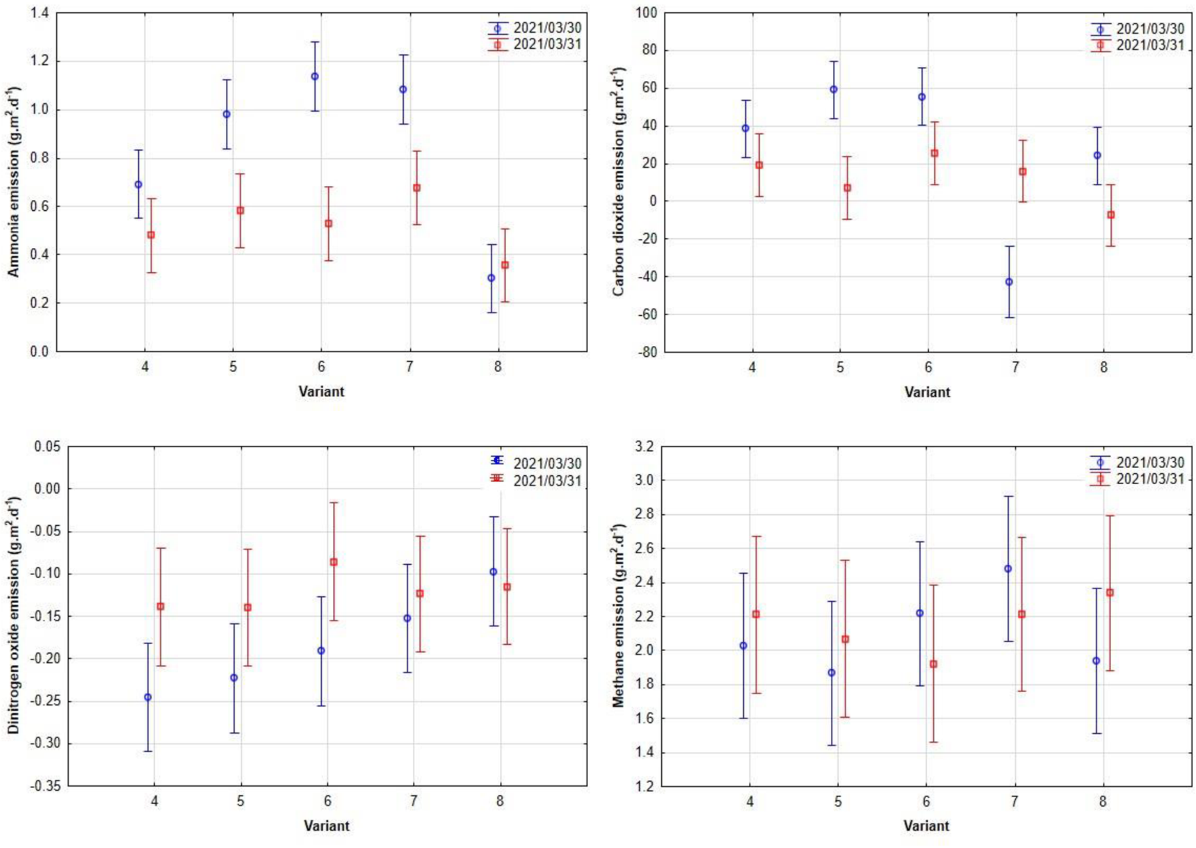


Figure 12. Comparison of emission concentration between measurement after application and measurement in the next day was analyzed by Tukey's HSD test

Figure 12 shows different results from the first measurement after fertilizer application and the second measurement the next day after application. Concentration values of NH_3, N_2O, and CO_2 emissions differed significantly between the two measurements. Nevertheless, for CH_4 measurement did not show significant values among the two measurements. NH_3 shows emission flux declining about 40 % from the previous measurement. Variant 5, 6 and 7 from first and second measurement was statistically different for NH_3 emission. The emission values also varied according to the given application doses described in the previous paragraph. N_2O emissions constantly resulted in low and negative emission values. It may have indicated using the proper method and time for the liquid application. Thus, applying liquid fertilizer in the growing season of wheat established the efficiency of NH_4^+-N uptake, which is contained in liquid digestate. Nevertheless, variant 7 was detected as an unknown erroneous measurement. CO_2 also slightly differed for variants 5 and 7 from the two measurements.

4.2. Soil Properties

Agriculture agronomic activities that are applied emissions continuously can affect the physical, chemical, and biological soil properties. This work measured physical properties such as soil infiltration, bulk density, and penetration resistance. The SFH method was used for infiltration measurement with a single ring infiltrometer. The time for water to permeate the soil is mostly influenced by the type and soil moisture. According to the KKP survey, soil type was classified as aluminous sandy/sandy, HP brown acid soil, the most common type in Czech.

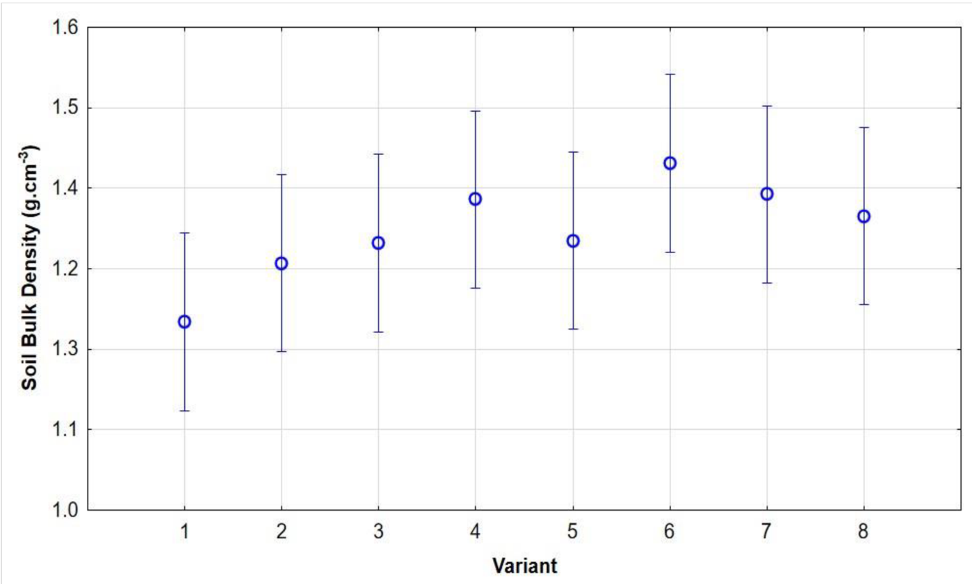


Figure 13. Bulk density was collected in three replications from each variant measured with a roller with a volume of 100 cm^3

Figure 13 shows that bulk density is insignificantly different between the variants. However, the bulk density shows low values for variants 5 and 7 (with N regeneration) compared to variants 1-3 (with no regeneration) (see figure 13). Any land preparation practice will change the soil profile after treatment. In this work, bulk density values may regulate according to the land preparation conducted with shallow tillage. However, soil bulk density values may be temporary.

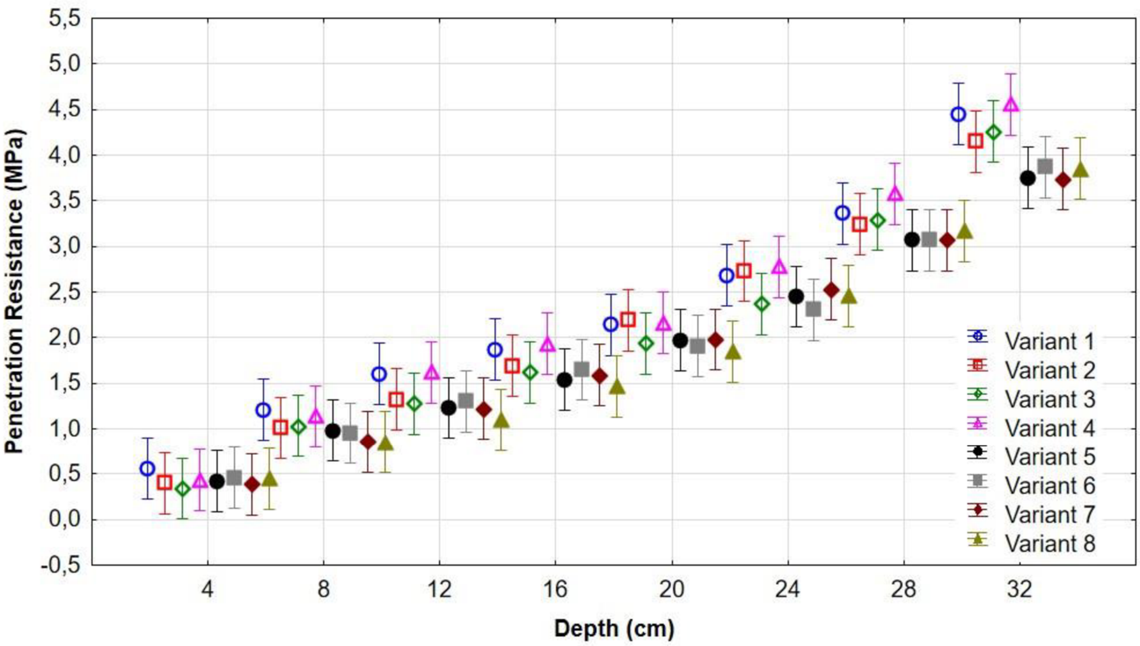


Figure 14. Penetration resistance measured at 4 - 32 cm in depth in each variant

Figure 14 shows the mean values of penetration resistance for each depth in all variants according to ANOVA significance at 5% level differed insignificantly. However, there were relatively higher resistance shows in variants 1 to 4 than variant 5 (see figure 14). Penetration resistance is related to bulk density concerning soil compaction. Therefore, penetration resistance and bulk density can promote soil structure, directly impacting root growth. Both BD and PR values are not statistically significant. These soil physical properties were measured to describe the soil condition of the experiment field. Because BD and PR are associated with soil health and compaction, which is the restriction of crop growth, especially for root growth.

Therefore, soil structure may have been the most influenced factor that governs bulk density values. In this case, the sandy soil of our experiment field has a large particle size compared to other soil types. Furthermore, applying various doses of liquid fertilizer may trigger any soil characteristic change. Particularly for liquid digestate, which can change the soil moisture content of the soil.

Table 3. Mean values of Infiltration using SFH (Simplified Falling Head) method with SHC ($mm.h^{-1}$) calculation

Variant	Dose ($t\ h^{-1}$)	M θ_0 (mm^3mm^{-3})	M θ_1 (mm^3mm^{-3})	M K_{fs} ($mm\ h^{-1}$)
1	0	0.28	0.43	644.763^{b}
2	10	0.31	0.41	197.997^{a}
3	15	0.30	0.41	266.163^{a}
4	10	0.29	0.43	285.419^{a}
5	15	0.31	0.42	695.626^{b}
6	20	0.29	0.39	129.901^{a}
7	25	0.29	0.39	208.435^{a}
8	0	0.28	0.40	216.157^{a}

θ_0: dry volumetric of soil water content (mm^3mm^{-3}), θ_1: wet volumetric of soil water content (mm^3mm^{-3}), K_{fs}: Soil hydraulic conductivity ($mm\ h^{-1}$), values with different letter show significant difference between variant according to Tukey's HSD test

Water flows into the soil through the soil pores. In saturated soil, the ability of the soil to store water is decreasing due to water-filled soil pores. When the soil has low water content, the water flows into the ground quickly and needs less time. Therefore, the soil water content must affect the infiltration rate of water.

Consequently, SCH values are most affected by the amount of water filled into the soil. Variant 3, 4, 7, and 8 showed lower *Kfs* values due to the low volumetric water content (see table 3). High values may have been caused by soil water content in the field measurement. The soil was slightly moist due to the measurement time conducted in early spring. Other variants (1, 2, 5, and 6) shown in high SHC values were caused not only by soil water content but also should be promoted by soil types. In this case, the soil type of field measurement was known as aluminous sandy soil, which has a low ability to retain water.

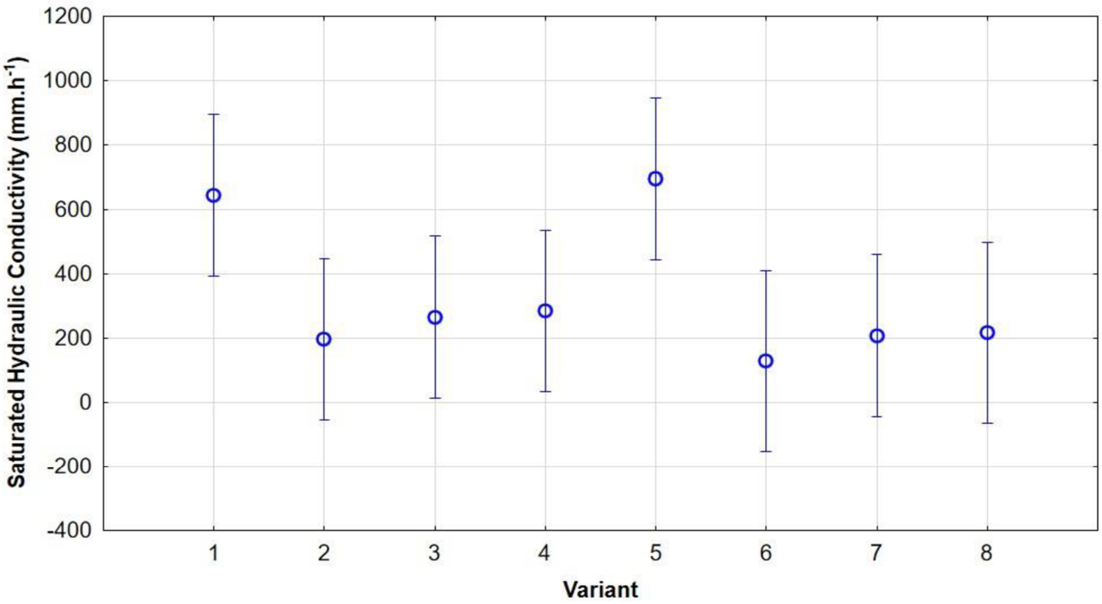


Figure 15. Mean values of SHC in different variants of dose digestate application analyzed with Tukey's HSD test

Figure 15 shows SHC values were slightly significant differences between variants and control. In addition, there is a significant difference between two homogenous groups of variants. All variants with various dose applications were homogenous, excluding the control (variant 1) and variant 5. However, mean values of variants 5 and 1 significantly differed from other variants analyzed with Tukey's HSD test (significance at 5%). Variant 1 and 5 may have been affected by soil moisture content, which indirectly influenced the water infiltration time. Thus, those factors are crucial in influencing the SHC values.

4.3. Crop Yields

Table 4. Evaluation of growth parameters of the digestate application for winter wheat yield in 2021 using Tukey's HSD test

Variant	Sample identification	Dose t ha^{-1}	Fertilizer	II. regeneration	Height of 1 plant cm (30.3.)	cm (26.6.)	Yield t ha^{-1}
1	GRAIN 0	0	DIG	NO	13.3	93.3	7.90^{d}
2	GRAIN 1	15	DIG	NO	13.0	97.5	8.71^{cd}
3	GRAIN 2	20	DIG	NO	14.2	99.6	9.08^{bcd}
4	GRAIN 3	10	DIG	YES	13.3	100.6	9.39^{abc}
5	GRAIN 4	15	DIG	YES	13.0	104.3	9.63^{abc}
6	GRAIN 5	20	DIG	YES	13.2	105.6	9.89^{abc}
7	GRAIN 6	25	DIG	YES	13.6	108.7	10.15^{ab}
8	GRAIN 7	0	DIG	YES	13.7	96.5	8.92^{bcd}

Table 4 clearly shows the highest yield in variant 7 with the highest fertilizer dose (25 t ha^{-1}). The lowest crop yield is shown in variant 1 as a control (0 t ha^{-1}). In addition, it showed an increase in grain yields for treatment with regeneration fertilizer compared to variants without regeneration. However, there was an insignificant difference for all variants, excluding control (variant 1). Grain yields show a significant difference only between variants with regeneration (4, 5, 6, and 7) and control (1). Fertilizer application in the growing season is an appropriate time selection. Nevertheless, the increasing yields of the crop according to dose application was influenced by nitrogen-rich of digestate and with additional N fertilizer for the regeneration.

5. DISCUSSION

This section will discuss the study results and explain the relationship between our results and previous related or unrelated studies. Finding results of this study describe in this part, and we will confirm the compatibility of the study results with the objectives of this study.

5.1.Application System

The current management practice involves the utilization of digestate for land application either as fertilizer or soil enhancer (Logan & Visvanathan, 2019). Accurate management practice for digestate land application is essential to consider that high nitrogen availability applied into the soil may not cause pollution (Zhang et al., 2021). Fertilizer application is based on plant nutritional needs (Makdi et al., 2012) and soil nutrient status otherwise to maximize fertilizer efficiency. However, the improper application may cause several impacts for plants and the environment. For instance, excessive fertilizer contributes to soil acidification that promotes a harmful condition for plant growth. In addition, the wrong time and technique application induced potential pollution emission. For example, applying liquid fertilizer during a high rainfall may cause nutrient loss through leaching into groundwater and surface runoff. Moreover, the liquid fertilizer application on the soil surface promotes more potential odor emissions.

Plants utilize the nutrients optimally during the growth period to improve crop production. The Spring season (especially in early spring) is a proper time for applying fertilizer to supply the nutrient required. Thus, the nutrient loss can be avoided due to nutrient volatilization in gaseous form. The experiment was conducted in the spring, which retained a slightly cold temperature of about 19 ^{0}C. Fertilization in spring stimulates growth and increases nutrient uptake due to the growing season. N_2O emission measurement related to the study by Rodhe et al. (Rodhe et al., 2015) resulted in low emission with negative values during spring application of digestate cattle slurry and cattle slurry.

Application rate is a crucial variable determined by factors such as type of fertilizer (liquid or granular) and nutrient source (organic or synthetic). The fertilizer application rate is determined based on plant and soil demand to minimize nutrient losses. Liquid digestate contained high N, which is fundamental in determining the application dose (Czekała et al., 2020). However, managing nitrogen dosage is slightly tricky because of the feedstock variability (Paolini et al., 2018). In this work, different variant doses of liquid digestate applied to winter wheat showed no significant difference in nutrient volatilization into the atmosphere. Nevertheless, there was a slight difference in crop grain yield between variants with the regenerative N and control.

Injection of the liquid fertilizer directly into the soil can avoid nutrient evaporation instead of spreading on the soil surface (Riva et al., 2016). An investigation of digestate injected up to 15 cm in depth proved in minor odor release

(Zilio et al., 2021). Injection by trailing-shoe methods is the most proper method for land application of liquid digestate was suggested (Nkoa, 2014). In this study, a shallow injection method in the depth of 5 cm revealed reduced emission to the environment. This work is in line with a study by Nicholson et al. (2018) that precision application for spreading liquid digestate and slurry uses shallow injection, promoting the very low emission. This result is related to the method application, which used the deep placement of N fertilizers to reduce NH_3 volatilization and increase nitrogen use efficiency (T. Q. Liu et al., 2015). The liquid fertilizer injected into the soil at a 50–100 mm depth is appropriate for decreasing N fertilizer losses and providing nutrients near plant roots (da Silva & Magalhães, 2019).

5.2.Emissions

Digestate is seen as a sustainable way to reduce the environmental pollution of fertilization due to its high nitrogen content, which is readily available to plants (Verdi et al., 2019). The main critical issue in digestate is the release of nitrogen into the environment that can be reduced by applying best soil quality conservation practices (Paolini et al., 2018). Digestate has been recognized as good practice for an appropriate way to reduce odor emissions (Zilio et al., 2021). Digestate from the liquid separation was reported that released low emission after application (Lu & Xu, 2021).

Figure 10 shows that NH_3 is significantly different between control and variants. Rich in mineral nitrogen, formed as ammonium (NH_4^+) in digestate, prone to losses via NH_3 (Nkoa, 2014). Variant 4 resulted in a low NH_3 flux pattern compared to other variants in our study. The shallow injection has been shown to be effective in reducing NH_3 emissions and nitrate leaching losses from digestate and food slurry in spring crop production (Nicholson et al., 2018). The NH_3 emissions applied to winter wheat were related to atmospheric conditions (Yang et al., 2014). NH_3 emission increases at a peak at 108 h when the wind increase (see figure 9). Nevertheless, the temperature pattern is not compatible with NH3 emission, whereby the temperature rises with declining NH_3 emission. Similar to the study by Yang et al. (2014), the dynamic of ammonia flux was synchronized with the fluctuating wind speed, while the dynamic of ammonia emission differed considerably from the soil temperature.

N_2O emission showed a negative emission value (very low emission) for all variant doses after the application and subsequent measurement. This result is not similar to the study by Severin et al. (2016) that N_2O emission flux has positive values corresponding to a different depth in the application. N_2O emission is strongly correlated to the initial ammonium (NH_4^+) content (Dietrich et al., 2020). Nitrifying bacteria required oxygen residing in soil for oxidation NH_4^+ to NH_3- (Oertel et al., 2016). Soil moisture content might be another factor influencing N_2O emission. In this work, soil moisture was measured on average of 29 % that can inhibit the microbe activities. The soil moisture content influences soil microbial activities, particularly for nitrification of NH_4^+-N contained in digestate. N_2O emission decreased with the increase of soil moisture content because wet soil indicated poor soil O_2, which is used for the aerobic process by nitrifying bacteria. Thus, the available NH_4^+ - N rich-contained in liquid digestate (Drosg et al., 2015) was maximally utilized for crop growth, not converted to nitrate form due to the potential impact of increasing soil moisture content (Moredi, et al., 2021).

Measurement of CO_2 emission showed the highest release compared to other emissions. Different dose applications slightly affected the CO_2 emission release. However, emission differed significantly among variants. Our study related to GHG investigation by Dietrich et al. (2020) resulted in the highest CO_2 emission compared to other emissions. First monitoring resulted slightly significant between variants and control. However, the average concentration values of CO_2 declined in the second measurement. Soil respiration may have been the primary factor that affects CO_2 emission. Soil microbe produced energy from decomposed organic matter, resulting in CO_2 emission (Czubaszek & Wysocka-Czubaszek, 2018; Severin et al., 2016). A study by Maucieri et al. (2016) resulted a significant decrease in CO_2 emission by increasing the depth application. Therefore, increasing injection depth might promote lower emission of CO_2 is suggested for mitigating CO_2.

CH_4 production is required by an anaerobic condition (Oertel et al., 2016). One study investigated that deeper injection depths result in a lower oxygen supply, consistent with slightly higher methane emissions after deeper injections (Severin et al., 2016). CH_4 emissions increase markedly with seasonal increases in temperature. Decreasing soil moisture content incorporated with reducing CH_4 emission due to aerobic conditions (Doyeni et al., 2021). In this study, CH_4 emission was indicated by low emission. Nevertheless, CH_4 emission was measured with no significant difference between variants. In addition, it seemed the flux was declining for the following measurement.

5.3.Soil Physical Properties

Bulk density (BD) is strongly correlated to organic matter content. Soil organic carbon (SOC) enhances soil fertility by improving soil structure (Stockmann et al. 2013). Typical sandy soil has more prominent particle grain, and thereby the structure is rich in soil porosity. The percentage of carbon that is not degraded in digestate stabilizes the organic material in the soil where this digestate is applied (Lamolinara et al., 2022). Thus, the infiltration in sandy soil is higher than in other types of soil corresponding to the soil structure. The optimum bulk density range for plant growth in sandy soil is less than 1.6 g/cm3, and the restriction for root growth is more than 1.8 g/cm^3 (USDA, 2008). In this study, bulk density values showed in the maximum range of 1.43 g/cm3, which is under the limit of the optimum BD range of sandy. Assessment of bulk density of this study shows in figure 8 that values differ insignificantly. Nevertheless, the BD values among variants revealed higher compared to the control.

Penetration resistance (PR) of the variants with N regeneration showed slightly lower values than variants without regeneration (see figure 14). Nevertheless, there was no significant difference in penetration resistance values among the variants. Penetration resistance, however, is related to the bulk density in influencing soil properties. Soil penetration resistance increased with raising the bulk density. Increased BD was reported with increased soil compaction (Nagy et al., 2018). This study revealed that BD values align with PR values, defined as slightly different for each variant. One of the most affected soil characteristics is the compaction of the soil. Thereby, the water ability to penetrate soil is not inhibited for expanding nutrient uptake. Soil compaction, which is affected by BD, decreases soil hydraulic conductivity. Soil compaction, as affected by BD regulates the hydraulic conductivity of the soil, an indicator for determining soil health (Shah et al., 2017)

Altered in saturated hydraulic conductivity (Kfs) referred to bulk density, which increased dynamically (Kool et al., 2019). Low BD values can indirectly influence water retention ability, promoting larger soil pores. This condition decreases the soil capacity for water storage and may induce nutrient loss flow vertically to the groundwater. On the contrary, surface runoff can be regulated by increasing soil water capacity, primarily by increasing the SHC value. Infiltration capacity represents the maximum amount of water that can penetrate and retain in the soil. Another major factor influencing the infiltration rate is soil structure, wherein the water flow depends on soil porosity. Therefore, infiltration measurement on saturated soil was conducted to evaluate the ability of soil to retain water. Table 3 shows the average SHC and soil water content values, indicating the ability of soil to permeate water into the soil. Variant 5 with a low value of BD subject to an increase of SHC value, indicating low soil porosity. The SHC values were undoubtedly affected by the infiltration rate influenced by BD values, which indicate the soil compaction. The compaction resulted in reduced pore space, poor air and water movement through the soil (Aranyos et al., 2016).

Analysis of SHC values using Tukey's HSD test showed a homogenous value in variants 5 and 1 (control). Nevertheless, both variants 5 and 1 significantly differed from other variants. In this work, all variants showed slightly differing soil moisture content, resulting in a high SHC value in variants 1 and 5. Soil moisture did not contribute as much as organic matter influencing water infiltration rate and capacity (Sun et al., 2018).

Soil structure is an indicator of soil quality, and its alteration is slowly evolving after crop and fertilizer management. Thus, digestate application slightly affected the alteration of soil structure. Nkoa (2014) reported that short-term digestate application has positive effects on reducing bulk density, increasing saturated hydraulic conductivity, and enhancing moisture retention capacity. Aranyos et al. investigated a long-term study of organic fertilizer (compost) application in sandy soil improved soil structure by increasing bulk density. However, this study suggested the long-term application of digestate that will alter soil properties such as bulk density, penetration resistance, and hydraulic conductivity.

5.4.Crop Yields

A comparative study of digestate, cattle slurry, and NPK applied to winter wheat resulted in no significant difference in grain and straw yields (Šimon et al., 2015). In addition, a study by Verdi et al. (2019) resulted in crop yields under two fertilizations (digestate and urea) was not significantly different (digestate and urea) in terms of dry matter content. In this work, grain yields increased in each variant with increasing doses application, particularly with additional N regeneration. Nevertheless, there was only a slightly significant difference between variants (4, 5, 6, and 7) with the control. Similar to the study by Nabel (Nabel et al., 2014), an increase of digestate dose between 5 t ha^{-1} - 80 t ha^{-1} also increases the total dry mass of the crops and exceeds dose of 160 t ha affected harmful risk for the crop growth.

This study contrasts with the study by Kostić et al. (2021) that grain and biomass yields were significantly higher with fall application than spring application of N fertilizer to winter wheat in chernozem soil. The different soil types may cause different results. That Kostić's had chernozem soil, whereby soil structure consists of a high percentage of humus, differed from our experiment field with sandy soil.

The high mineral N content of the liquid digestates promoted a higher yield of crop production. Valentinuzzi et al (2020) found a positive N mineralization release in the soil due to high NH_4^+ in liquid digestate. Similar to the study by Makdi et al. (2012), wheat obtained significantly high biomass yields due to available nutrient content. Thus, liquid digestate triggered crop production correlated to digestate composition. Moreover, the efficiency of fertilizer use is likely to be high, where the organic matter content of the soil is also high (Singh & Ryan, 2015). Therefore, the advantage of liquid digestate to increase crop production and improve soil fertility was reported.

6. CONCLUSION

Emission release to the atmosphere was insignificantly different among variants with different application doses. However, NH_3 and CO_2 emissions significantly differed between variants and control. Different doses application had no meaningful effects on emission release but only affected crop production. Therefore, the digestate application with shallow injection (5 cm in depth) was confirmed as an appropriate technique for applying liquid fertilizer into the soil. In this study, all gas emissions resulted in low concentration and declined gradually over time. Thus, NH_3 emissions declined about 40 % from the measurements immediately after application and the next day.

In this study, winter wheat crop production significantly increases under digestate application and additional N fertilizer. Additionally, application with a dose (25 t ha^{-1}) produced the highest grain yield. Proper fertilizer application needs to be considered with the type of fertilizer, dose, time, and application technique. Thus, the purpose of the fertilization process can be achieved to increase both the quality and quantity of agricultural production, reduce environmental pollution, and improve soil quality.

Regarding soil physical properties, digestate did not impact significantly for PR and BD but only slightly differed on SHC. Therefore, this study suggested a long-term experiment of liquid digestate application to improve soil structure and fertility.

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