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From Waste to Soil Fertility: Comparative Assessment of Anaerobic Digestion and Aerobic Composting in Agricultural Sustainability

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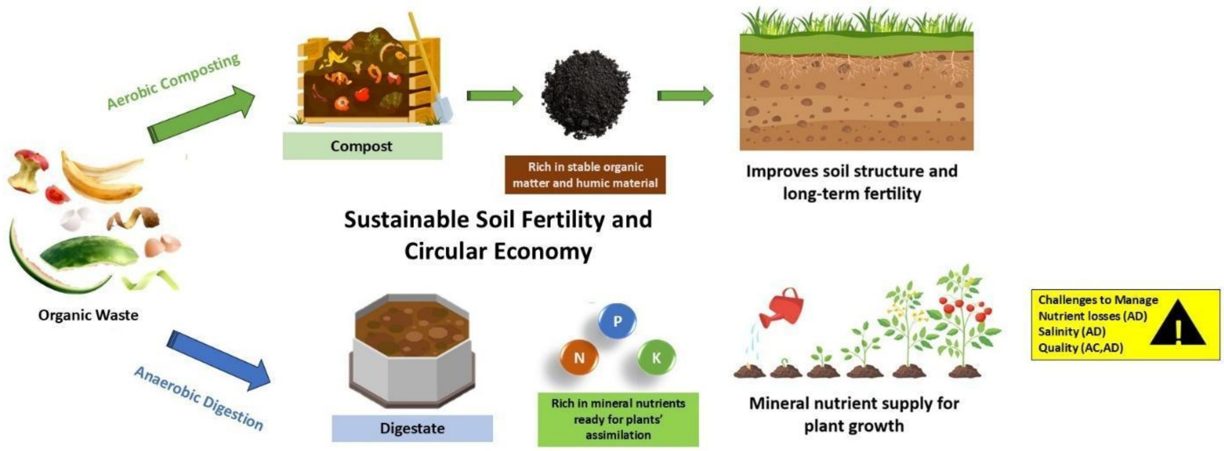
Graphical Abstract

Organic waste management is necessary. Digestates and compost are very valuable products. Compost, which is the output of the aerobic composting process, gives a final material rich in stable organic matter and humic compounds. Digestate, a byproduct of anaerobic digestion, offers a mineral-rich substance that is ready for plant absorption. Over time, the stable organic matter in the compost helps to increase soil fertility and structure. The digestate content supplies a significant source of plants' rapid nutritional support. This quick release of nutrients might result in many environmental challenges, and so the application must be well managed.



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Abstract: The increase in organic waste production, demographic growth, urbanization, and the intensification of agricultural activities have increased the need for sustainable nutrient recycling. Biological treatment of organic waste, represented by composting and anaerobic digestion, is one of the most effective solutions. Compost and digestate are the main products of these processes. These materials meet circular economy principles, though their chemical characteristics and agricultural functions differ. Digestate is rich in minerals readily assimilated by plants, providing rapid nutrient supply. Compost releases nutrients more slowly and contains stable organic matter that improves soil fertility and structure over time. If appropriate agricultural practices are not applied, rapid nutrient availability may lead to risks such as nutrient loss, salinity, or plant phytotoxicity. Compost and digestate are complementary. Their combined use can balance rapid plant nutrition with long-term improvements in soil's physical and chemical properties and reduce reliance on mineral fertilizers.

Keywords: *Organic waste, Anaerobic digestion, Sustainable soil fertility.*

Introduction

Global population growth and economic development have led to an increase in the production of organic waste. In developing countries, solid waste has increased through rapid urbanization [1]. Because of this, it is predicted that by 2050, the production of this solid waste will outpace population growth, particularly in low-income areas where organic waste volumes are rising very fast [2].

Organic waste does not only represent an environmental challenge, but also a rich source of nutrients that can be used in agricultural systems to minimize nutrient losses and enhance fertilization potential, which is in line with the principle of the circular economy [3].

Modern agriculture relies on chemical fertilizers to meet the needs of farmland, especially for nitrogen, phosphorus, and potassium. This intensive fertilizer production is linked to high energy consumption and harmful environmental effects, such as groundwater pollution and greenhouse gas emissions. But, recycling organic waste or recycling nutrients from organic waste can enhance the sustainability of agricultural production and minimize the use of non-renewable resources [4].

The biological treatment of organic waste is one of the most important strategies for transforming biomass into products with high agricultural value; notably, aerobic composting and anaerobic digestion. *The first* is based on the bioconversion of organic matter in the presence of oxygen, which leads to the production of a more stable organic product known as compost. *The second* contributes to improving soil characteristics, the physical and chemical properties of the soil, and increasing its organic content. Anaerobic digestion takes place in the absence of oxygen and produces what is known as digestate, a material rich in mineral nutrients, specifically nitrogen in an assimilable form, which has a relatively rapid fertilizing effect [5].

Compost and digestate are now recognized as supplements or substitutes for traditional fertilizers. Still, they differ greatly in their physical, chemical, and biological properties, which affect how nutrients are released into the soil and how agricultural land interacts with them. Compost significantly improves long-term soil fertility by increasing the percentage of stable organic matter; digestate is a rapid source of plant-available nutrients, leading to accelerated growth in the early stages [3,6].

Nevertheless, there is a lack of comparative studies on compost and digestate, particularly regarding agricultural yield and their effects on soil characteristics and the various ecological features of their use. This review aims to compare compost and digestate as soil-improving biofertilizers and organic fertilizers, focusing on their chemical properties and nutrient-release mechanisms, and on their influence on crop growth and soil quality, alongside ecological and practical considerations related to their use in sustainable agriculture.

Characteristics of Compost and Digestate

The properties of organic matter resulting from biological treatment are considered an essential factor in determining the agricultural effectiveness and its effect on soil and plants. Digestate and compost have varied composition, physicochemical, and biological characteristics, making them behave differently when introduced into the soil. Compost is the result of aerobic biotransformation of organic matter, which is characterized by organic stabilization. Digestate is a by-product of the anaerobic digestion mechanism and contains a high percentage of nutrients in a form that plants can assimilate. These differences directly influence the availability of nutrients, the level of decomposition of organic matter, and the behaviour of each product, whether in improving the soil or as a fast source of fertilization. For this reason, understanding the essential characteristics of compost and digestate is a necessary step before evaluating agricultural yields and environmental benefits.

Compost: production and properties

Compost results from the biological aerobic decomposition of organic residues, whereby microorganisms break down organic matter in the presence of oxygen under controlled conditions of humidity, temperature, and aeration. This process leads to the aerobic fixation of organic matter. Easily decomposable organic compounds are transformed into more stable materials that are less susceptible to further decomposition, which helps minimize undesired biological activity and odours resulting from incomplete degradation [7].

During composting, organic matter goes through several biological and thermal stages. It begins with concentrated microbial activity, which raises the temperature through microbial metabolism. This is followed by the maturation stage, which is characterized by the humification process. In this stage, organic compounds are transformed into complex humic matter with a relatively higher molecular weight. This process is essential to the composition of stable organic matter capable of remaining in the soil for long periods and improving its physicochemical properties [8].

Compost is characterized by a high level of organic matter stability compared to raw organic residues, as reflected by low carbon degradation after adding this product to the soil.

Digestate: origin and properties

Digestate is the residue of anaerobic digestion of organic waste. In this process, microorganisms break down organic matter and transform it into nutrient-rich, semi-liquid or solid matter, while another part is converted into biogas, which is composed of CH_4 plus CO_2. The formation of digestate is mainly based on the type of initial substrate used and also on the operational factors chosen during the process, namely temperature, process duration, and treatment system [5].

Digestate is characterized by a high percentage of mineral nitrogen resulting from the conversion of organic compounds during digestion into more assimilable forms. This contributes to increased nutrient availability for plants after it is added to the soil.

Digestate is characterized by moderate acidity and a high percentage of mineral salts, which can influence the dynamics of nutrients and their behaviour in the soil depending on the circumstances of agricultural application. Digestate comes in two different forms: liquid or solid. Liquid digestate contains more dissolved nutrients, and solid digestate contains a higher percentage of remaining organic matter, which can allow for different agricultural applications depending on the need [5].

Key physicochemical differences

A comparison between digestate and compost reveals significant differences in the biological processes responsible for their production. Compost undergoes aerobic biotransformation, which leads to the creation of stable, mature organic matter. Digestate is the result of anaerobic digestion, which retains the maximum amount of nutrients in a form that plants can assimilate. These differences are reflected in their chemical and agricultural properties. Compost, for example, is characterized by stable organic matter and a balanced C/N ratio. Digestate contains a high concentration of mineral nitrogen, especially ammonium, which gives it a rapid fertilizing effect. These differences directly influence the mechanisms of nutrient release and carbon sequestration in the soil, as well as the nature of the agricultural use of each product, whether as a long-term soil optimizer or an immediate source of nutrients [5,7,9].

The data presented in Table 1 show the marked difference between compost and digestate in terms of their characteristics across different studies, reflecting the direct effect of several factors such as the nature of the initial substrate, the biological treatment conditions, and the duration of stability and maturity before agricultural application. The physicochemical characteristics of these two materials do not represent stable and precise values, but rather margins varying with the production system and soil conditions. These results also show that the evaluation of the effectiveness of compost or digestate cannot be based solely on the initial chemical composition, but must take into account the role and behaviour of nutrients after being added to the soil, specifically the levels of decomposition and nutrient release. The dynamics and behaviour of nutrients in the soil help to explain the differences in agricultural yield between these two products

Table 1. Comparative table of physico-chemical properties of compost and digestate

Property	Compost (examples from studies)	Digestate (examples from studies)	References
pH	8.66 (1:5, v/v); final 7.18 ± 0.02	8.1–8.6	[10-12]
Electrical conductivity (EC)	2.37 mS/cm; final 7.64 ± 0.02 dS/m	26–46 mS/cm	[10-12]
C/N ratio	9.93; final 21.82	(Often low; varies with feedstock/processing—use N fractions instead for robust comparison)	[10,11]
Total nitrogen	11.77 g/kg DM; TKN 1.92% (final)	1.63–13.22 g/kg FM (N_tot); example TN 12 ± 0.35 g/kg FM (solid fraction in one case)	[10-13]
Ammonium (NH4-N)	7.4 mg/kg DM (NH4-N) and NH4/NO3 0.044 (maturity indicator)	0.75–4.75 g/kg FM (NH4-N); NH4-N/TN = 61% (one installation example)	[10,12,13]
Maturity/phytotoxicity indicator	GI reported 57.56 ± 9.43% (example compost not fully mature)	(Usually assessed differently; focus on N mineral forms + EC/pH management)	[11]

Nutrient Dynamics and Fertilization Mechanisms

A comparison between digestate and compost reveals significant differences in the biological processes responsible for their production. Compost undergoes aerobic biotransformation, to become stable, mature organic matter. Digestate is the result of anaerobic digestion, which retains the maximum amount of nutrients in a form that plants can assimilate. These differences are reflected in the chemical and agricultural properties. Compost, for example, is characterized by stable organic matter and a balanced C/N ratio. Digestate contains a high concentration of mineral nitrogen, especially ammonium, which gives it a rapid fertilizing effect. Several studies have shown that these differences directly influence the mechanisms of nutrient release and carbon sequestration in the soil, as well as the nature of the agricultural use of each product, whether as a long-term soil optimizer or an immediate source of nutrients.

Nitrogen is the element that is most influenced by the type of organic substrate added to the soil, given its high sensitivity to microbial and chemical changes. In the case of compost, most of the nitrogen is bound to other stable organic compounds, resulting in a slow release of this element through microbial mineralization. In contrast, digestate contains a significant amount of mineral nitrogen, particularly ammonium, as a result of the anaerobic digestion of organic matter, which leads to rapid nitrogen availability after the agricultural application of the biofertilizer. This rapid availability may be linked to an increased risk of nitrogen losses through leaching or release into the atmosphere if the application period is not appropriate or adequate for the plant's needs at that time [14,15].

Phosphorus and potassium are essential elements for plant nutrition. Their solubility in the soil depends not only on their presence and quantity in organic substrates, but also on the chemical elements present in the soil and the chemical reactions that occur after being added. Phosphorus in organic fertilizers can be present in mineral or organic form with variable solubility levels, leading to a clear change in its levels of absorption by the plant, depending on soil characteristics and application circumstances [16].

Nutrient spread analyses show that in digestates, potassium is often found in higher levels in the liquid fraction because of its high solubility, but phosphorus is found in much higher concentrations in the solid fraction because it is often bound to other mineral and organic compounds. This dispersion influences the characteristics of digestates as biofertilizers. The liquid fraction is often used as a rapid source of potassium; the solid fraction is a rich source of phosphorus [17].

Studies evaluating the biofertilization potential of digestate have shown that the presence of phosphorus and potassium in the soil is largely based on the characteristics of the soil itself. This is particularly true of pH levels and organic matter content. The efficiency of phosphorus use in digestate can be similar or close to that of mineral fertilizers in certain agricultural conditions, with differences related to leaching or nutrient losses [18].

Although compost contains relatively lower percentages of dissolved nutrients than digestate, it improves phosphorus availability indirectly by increasing microbial activity and optimizing the physicochemical characteristics of the soil. This enhances the solubility of phosphorus relative to the soil over time. Compost, when added to the soil, can improve phosphorus use efficiency by balancing the C/N ratio and nutrient balance in the soil [19].

The levels of phosphorus and potassium in compost and digestate are not stable but vary with the substrate's nature and composition before treatment. For this reason, in addition to the comparison between compost and digestate as different materials, the values show that differences in phosphorus and potassium content exist even within each material (Figure 1). This explains the differences in agricultural results across studies regarding the presence of P or K and the risk of nutrient loss during the process. Therefore, when explaining the dynamics of phosphorus and potassium, and also when suggesting the agricultural use of compost or digestate, it is necessary to mention the source of the initial substrate, as this factor determines the nutrient footprint much more than the nature of the treatment alone.

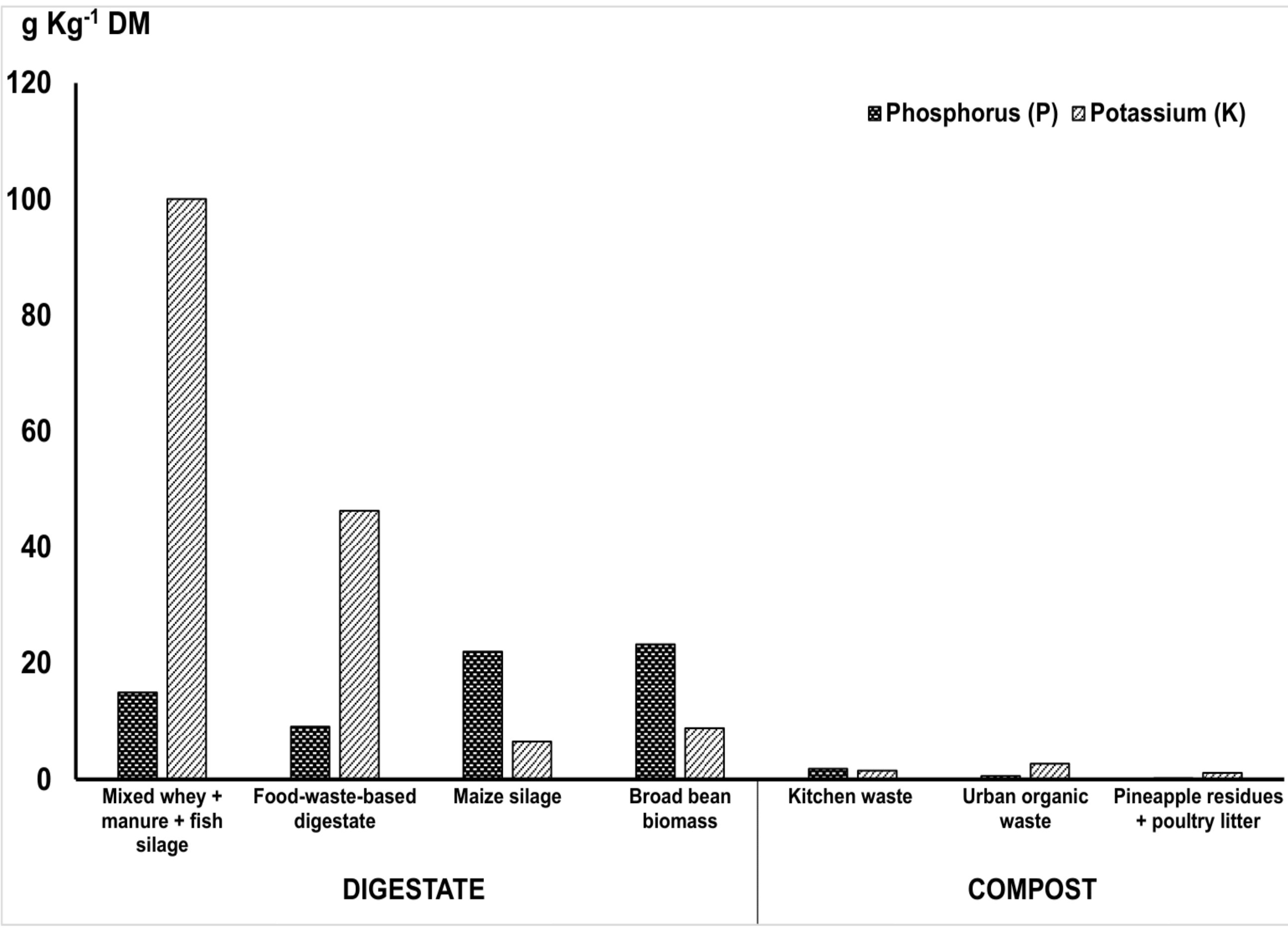

Figure 1. P and K Content in Digestate and Compost from Different Initial Substrates [18,20-22]

One of the key elements influencing the long-term impact of organic matter in biofertilization is organic carbon soil amendment. The addition of compost or digestate immediately affects the soil's carbon balance and the dynamism of organic matter. The type of carbon added, rather than just its amount, determines how stable it is in the soil, how it contributes to the creation of humic matter, and how the soil's physical and biological qualities are improved [23,24]

Because of aerobic biotransformation and humification, compost contains more complex and stable organic molecules. This procedure helps to improve the long-term integrity of the soil structure and raise its amount of organic carbon. Compared to other organic materials that are thought to be less stable, long-term studies have demonstrated that compost greatly increases the organic carbon load and decreases its loss through microbial respiration [25,26].

In contrast, digestate contains a larger fraction of carbon readily biodegradable through the consumption of easily biodegradable organic compounds during anaerobic digestion to produce biogas. This often leads to a simulation of microbial activity and increased respiration levels in the early stages after application, without reaching the same level of long-term carbon accumulation that characterizes compost [27,28].

Therefore, the difference between compost and digestate lies not only in their varying nutrient content but also in the carbon they contain and its behaviour in the agricultural soil system. This explains the difference in their short- and long-term effects on soil fertility.

The rate at which nutrients are released after the addition of organic fertilizers to the soil is an essential factor in determining agricultural efficiency. The impact of these fertilizers is linked to both the quantity of their nutrients and their rate of release, as well as the duration of their availability during the growing season. Compost and digestate release nutrients in remarkably distinct manners because of differences in organic matter and the chemical and biological processes that take place during biological treatment.

Given the significant portion of mineral components that become available following anaerobic digestion, the digestate is characterized by the quick release of nutrients. Digestate is an effective source of immediate plant nutrition because it quickly increases the concentration of nutrients available in the soil within the first few weeks [6,29].

Compost, on the other hand, is characterized by a slow release of nutrients, as it contains more stable organic matter. The slow, continuous microbial mineralization reduces the risk of losing the nutrients. The fertilizing effect of compost on the soil can last for several years after application [30,31].

Table 2 summarizes the main characteristics of compost and digestate, based on nutrient dynamics and their interactions in the soil. This provides a simple comparison to understand the operational differences between the two fertilizers.

Table 2. Comparison of Nutritional Properties of Compost and Digestate

Characteristic	Compost	Digestate	Main Implication for Soil/Fertilization
Processing pathway	Aerobic decomposition	Anaerobic digestion	Determines organic matter stability
Organic carbon stability	High	Moderate to low	Long-term SOM vs rapid turnover
Nitrogen form	Mostly organic N	High mineral N (NH_4^+)	Slow vs rapid plant availability
Nutrient release pattern	Gradual	Rapid	Residual vs immediate fertilization
Phosphorus behaviour	Slowly available	More soluble fractions	Different mobility in soil
Potassium availability	Moderate	Often high and soluble	Fast plant uptake
Microbial response	Progressive stimulation	Immediate stimulation	Short vs long biological activation
Soil structure impact	Strong improvement	Moderate improvement	Aggregation and water retention
Risk of nutrient loss	Low	Higher if mismanaged	Timing of application important
Main agronomic role	Soil amendment	Biofertilizer	Complementary functions

Agronomic Performance

Assessing the agricultural performance of compost and digestate is an essential step in understanding their operational value as sustainable fertilizers, because their definitive effect can be gauged through crop response and changes in soil properties.

Crop Yield and Biomass Response

Digestate tends to show a rapid response in yield and biomass immediately after application, particularly when this coincides with the plants' high nitrogen demand, since a significant portion of the nutrients is in readily available forms.

Agricultural tests on winter wheat have shown that digestate can achieve similar or even better yields than certain mineral alternatives when managed properly [32]. More recent experiments also show that the yield response to digestate can be very strong and repeatable in different agricultural systems, with differences in results depending on soil type, digestate quantity, and how it is introduced into the soil

[33]. Compost has a slower but more stable effect, linked to a gradual improvement in soil fertility and structure, resulting in stable production in the medium and long term. Digestate offers immediate nutrition; compost builds more sustainable soil fertility [33].

Crop Quality Parameters

The effect of compost and digestate is not limited to yield alone, but can also influence product quality and plant nutrition indicators. In leafy crops such as lettuce, digestate, which is rich in nitrogen in rapidly assimilable forms, can increase nitrate concentration in leaves compared to other mineral nutrition systems. But, these values may remain within regulatory limits, depending on the dosage and environmental conditions [34]. In other contexts, comparisons show that quality responses (e.g., physiological and antioxidant indicators) can be influenced by the interaction between digestate and the medium's salinity, highlighting the need to control both dose and timing of application, especially with sensitive crops [35].

With compost, quality indicators, often linked to improved soil condition and gradual nutrient availability, tend to reduce the risk of a sharp increase in nitrates compared to fast-release sources. The final result remains linked to yield and fertilization management.

Environmental Safety and Considerations

Nitrogen Losses and Emissions

The high amount of mineral nitrogen contained in digestate can lead to increasing risks of ammonia volatilization, nitrate leaching, and N_2O emission when timing, dosage, and method of application are not adapted to plant demands and climatic conditions. A multi-site field study in England and Wales measured NH_3 and N_2O emissions and NO_3 leaching after the application of digestate and compost. These losses had different profiles for the materials, and there was a strong influence from field management practices at the site [15].

Pathogens and microbiological safety

The type of input and the conditions of treatment determine the risk to microbiological safety. The monitoring of the anaerobic digestion process has shown that it can efficiently eliminate pathogens (specifically, detectable Salmonella in the final product) [36]. Some literature sources indicate that pathogens may exist in some nutritional products or can stay alive in certain circumstances, which makes hygiene control and standards a necessity, especially when using substrates with high pathogenic risk [37].

Conversely, thermophilic composting is the method of choice as a disinfection technique, as long as rigorous specifications on temperature, time, and aeration are followed. The effectiveness of in-container composting has been recently demonstrated by experimental evidence [38].

Salinity and Phytotoxicity Risks

Salinity and phytotoxicity are among the most significant challenges when using anaerobic digestion products, particularly the liquid fraction. The problem does not arise from the nature of the initial substrate used, but rather from the composition of the final product and its properties, such as the level of conductivity, which is an important indicator of salinity, the concentration of ammonium ions, and the presence of organic compounds that can inhibit seed growth. The influence also depends on the sensitivity of the crops and their stage of growth.

Digestate, and more specifically liquid digestate, can contain dissolved salts and certain forms of mineral nitrogen (especially ammonium) in high concentrations. In sensitive crops, when applied in large doses and during an inappropriate timing, several symptoms may appear, such as reduced plant growth, poor root development, or plant “burn”. This is why several studies rely on the Germination Index (GI) test, as reduced growth is often linked to increased salinity or other specific chemical indicators. Practical studies confirm the need to control the application doses or reduce the use of the material, or apply it only on less sensitive crops, to avoid its negative effects [39,40].

Compost is considered safer if it is mature and stable, as substrate maturity allows components that can inhibit plant growth to be broken down. But, it can become harmful under certain conditions:

- Incompletely mature: i.e., still containing organic acids and extractable harmful compounds.
- High in EC (Salinity): resulting from the use of saline raw materials or poor management during the composting process.

Germination tests are important indicators and essential criteria for confirming the product’s safety before it is applied to the soil [41,42].

Practical Application and Integrated Use of Compost and Digestate

Compost and digestate are distinct alternatives, and their effectiveness is based on several factors, including the objectives of the agricultural application, the physical and chemical characteristics of the soil, and the needs of the plant according to its growth stage.

The quantity of compost or digestate added is just as important as the timing of the application, which takes into account the growth stages of the crop. In agricultural systems, for example, it is often suggested to apply compost for a period of a few weeks to a few months before planting, especially for field crops and cereals. This is to allow sufficient time for the organic matter in the compost to integrate and mix into the soil, as well as to stabilize microbial activity before the beginning of plant growth. Several studies on cereal and vegetable systems have shown that applying compost during autumn or spring or before the main spring planting gives promising results, because it allows gradual mineralization at the beginning of the growing season without creating nitrogen competition in the early stages of plant growth [43].

For short-cycle vegetable crops like lettuce, spinach, or tomatoes, it is typically preferable to add compost to the soil during the seedbed preparation phase rather than after planting. This is because the planting stage necessitates a quick supply of nutrients (digestate), not a gradual release (compost). Doses of 10 to 30 tonnes of dry matter per hectare can offer a long-term balance between enhancing soil qualities and lowering salt and phosphorus accumulation [44].

Digestate, on the other hand, can be used very effectively when applied during the active growth period of crops, but not too long before. In the case of winter cereal systems, it is often advisable to apply digestate during the tillering period or the early elongation stage, as nitrogen assimilation is at its highest at this time, which helps to reduce the risk of nitrate leaching. Field studies on winter wheat have shown that a relatively delayed application time compared to conventional organic fertilizers has led to optimized nitrogen use efficiency and reduced environmental losses [32].

Subsurface soil injection or fast soil incorporation of digestates are among the most efficient applications of digestate, as this significantly reduces the risk of ammonia losses and optimizes the nutrient assimilation potential of the plants. Compared to other conventional applications, the subsurface injection can actually contribute to an important decrease of ammonia release levels, while maintaining the same levels of production as the other methods of application [45]. The application time also varies depending on the type of crop. For example, in nitrate-sensitive crops such as leafy vegetables, it is preferable to divide the doses of digestate applied into small successive doses rather than apply a single large dose. This method aims to control the accumulation of nitrates in lettuce plants. This has been proven by experiments on lettuce, which concluded that the dose and timing directly influence the concentration of nitrates in the leaves, but without any negative impact on biomass production [45].

The different nature of compost and digestate in terms of their chemical properties and their distinct effects on the soil makes them suitable for use in integrated agricultural systems. Compost can be applied a good period before planting, which helps to improve soil properties, and digestate can then be applied during the crop growth period, when plants need a quick source of nutrients. This complementary approach is effective as part of an integrated nutrient management system in modern European agriculture [46,47,15].

For agricultural systems that require a single application before planting instead of applying fertilizers several times during the year, co-composting of digestate is a very useful approach, as it can produce a more stable product that is less complex in terms of application, reducing the need for other more specialized techniques [48].

The chemical composition of the organic matter in compost and digestate is therefore not the only factor to consider before applying the organic fertilizers to agricultural fields. The user must consider all of the following: the timing of application, i.e., the period of high nutrient demand, the agricultural system used, and the adaptation of the strategy to crop sensitivity and field management conditions.

Conclusion

A comprehensive comparison of digestate and compost shows that the difference between these two materials is not limited to resources or their way of production, but also encompasses the nature of their nutrients and the dynamics of their release into the soil, as well as their short- and long-term agricultural and environmental effects. The studies mentioned in this review have shown that digestate is a product capable of providing nutrients very quickly, making it suitable for supporting plant growth during periods of high nutrient demand, particularly in intensive agricultural systems. Other studies have shown that compost contributes more to improving the physical and chemical properties of the soil in the medium term, through the support of stable organic matter and the increase of microbiological activity, which is reflected in long-term sustainable agricultural fertility.

The studies mentioned also showed that crop response is not only based on the chemical composition of the added material, but also on the timing and method of application, as well as the nature of the crop and soil, and environmental conditions. Nitrate accumulation in sensitive crops can lead to significant environmental risks.

From an ecological point of view, the use of digestate and compost allows for useful recycling of nutrients and contributes to reducing the use of mineral fertilizers. This requires implementing appropriate measures to limit nitrogen losses and gas emissions, as well as the risks of salinity and phytotoxicity. The combined use of compost and digestate through co-composting is an ideal solution. It permits rapid nutrient release and improves soil fertility within the framework of sustainable nutrient management.

Overall, compost and digestate are two complementary components of circular agriculture strategies. The ultimate choice between the two depends on the agricultural objective, the nature of the production system, and the crop's growth stage and sensitivity. Future research should include developing universal criteria to assess the quality of organic products and to improve understanding of their long-term interactions with the soil. These should be supported by field studies that link application management, agricultural yield, and ecological sustainability across different circumstances.

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Disclosure of potential conflicts of interest

No potential conflict of interest was reported by the authors.

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