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Anaerobic digestate management for carbon neutrality and fertilizer use: A review of current practices and future opportunities

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ABSTRACT

Biogas production, a low-carbon energy source, has led to heightened focus on sustainable management of its by-product, anaerobic digestate. The unprocessed digestate poses environmental and safety risks, including greenhouse gas emissions and potential soil contamination. Thus, the development of comprehensive, globally applicable guidelines for sustainable digestate management is crucial. The unique aspect of this review lies in the proposed guidelines, addressing micropollutant presence, prioritizing nutrient conservation, and aligning with carbon neutrality and Sustainable Development Goals. The review methodology involves an exhaustive study of existing literature and innovative valorization methods for anaerobic digestate, including biological, chemical, thermal, and mechanical processes. The review emphasizes the importance of enhancing digestate quality before soil application, thus reducing environmental contamination and improving fertilization properties. This review notably contributes to the understanding of sustainable anaerobic digestate management in the context of carbon neutrality and process circularity, offering valuable insights for future research and practical applications.

1. Introduction

As the global energy crisis intensifies and non-renewable resources, particularly fossil fuels, approach depletion, sustainable alternatives are gaining global prominence. The attention is increasingly focused on renewable energy and waste management, especially the effective treatment and valorization of waste. The use of digestate - a biogas production byproduct - for creating organic mineral fertilizers is a promising and sustainable choice. There is a significant gap in formulating marketable, full-value digestate-based fertilizers [1]. This paper proposes a new digestate management approach addressing this gap. It considers the economic factors affecting digestate use, such as cost-effectiveness and market demand, in addition to sustainability needs.

The ongoing energy crisis and resource depletion globally demand a shift to sustainable resources, highlighting the importance of waste management. Digestate, a biogas by-product, is a potential source for organic mineral fertilizers. Valorizing digestate into value-added organic mineral fertilizers presents an attractive option due to its sustainability, economic feasibility, and local availability. The application of anaerobic digestate as a fertilizer can help reduce synthetic fertilizer usage and contribute to the circular economy.

Geopolitical concerns, particularly in the European Union, have spurred the growth of biogas plants as a means to mitigate reliance on natural gas imports from geopolitically unstable regions like Russia [2]. Biogas, produced from locally available renewable raw materials such as biological waste, serves as a viable alternative [3]. The EU's Circular Economy Action Plan and the Renewable Energy Directive II support both the sustainable use of bio-waste and the transition to renewable energy sources like biogas.

Doubts over natural gas supplies have heightened the demand for alternatives like biogas, prompting a focus on sustainable, local sources [1,2,4]. Therefore, there is a pressing need to develop and implement sustainable waste management strategies that include the proper treatment and valorization of biological waste streams. In addition to the production of biogas, digestate technology can provide nutrient-rich fertilizers that can be used to improve soil fertility. This aligns with current regulations that govern the use of organic waste as fertilizers, thereby reducing dependence on synthetic fertilizers. According to the latest Intergovernmental Panel on Climate Change (IPCC) report, global greenhouse gas (GHG) emissions reached 59.1 gigatonnes of CO_2 equivalent in 2022 [5]. Proper treatment and valorization of waste streams have the potential to significantly contribute to the reduction of

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Abbreviations

AD	Anaerobic Digestion
C:N	Carbon-to-Nitrogen Ratio
CMC	Component Material Categories
COD	Chemical Oxygen Demand
DM	Dry Matter
E	Electrical Conductivity
EC50	Half Maximal Effective Concentration
GHG	Greenhouse Gas
GI	Germination Index
N_{tot}, P_{tot}, K_{tot}	total Nitrogen, total Phosphorus, total Potassium
PAH	Polycyclic Aromatic Hydrocarbons
REACH	Registration, Evaluation, Authorization, and Restriction of Chemicals
SDGs	Sustainable Development Goals
TKN	Total Kjeldahl Nitrogen
TS	Total Solids
VS	Volatile Solids
VFA	Volatile Fatty Acids

these emissions and the conservation of resources.

The paper explores the roles of biogas and anaerobic digestate in renewable energy and waste management while emphasizing the circular economy approach. It recognizes the crucial contribution of Anaerobic Digestion (AD) to the energy sector. Additionally, it covers nutrient recovery and valorization strategies, recent policy shifts impacting biogas production, industry status, and the challenges and prospects in digestate management. This research presents an in-depth overview of digestate potential, its part in fostering sustainable, renewable energy, and the prospects for its effective management and valorization.

Optimizing biogas usage requires comprehensive waste management strategies, focusing on waste treatment and valorization. Such strategies aim to reduce environmental impact and harness waste as a resource, aligning with the principles of the circular economy.

Although existing studies address various aspects of anaerobic digestate management, this paper introduces a new method for transforming digestate into value-added organic mineral fertilizers, outlining the basic principles and procedures involved.

Solubilizing nutrients is a crucial step in nutrient recovery because it transforms nutrients into a form that can be readily absorbed by plants. The solubilization process enhances the bioavailability of nutrients and makes nutrient recovery more efficient. Valorizing digestate into organic mineral fertilizers involves recovering nutrients such as nitrogen, phosphorus, and potassium. These nutrients can be combined in different ratios to produce a variety of fertilizers that cater to the specific nutritional needs of different crops. The process includes several steps, like pretreatment, separation, stabilization, and conditioning, ensuring that the final product meets quality standards for fertilizer use [6,7].

To increase the value of the fertilizer obtained from digestate, gentle solubilization of the nutrients trapped in organic matter is necessary. For this purpose, chemical conditioning with small doses of concentrated acids and/or bases can be used. Acid or alkaline solubilization involves adjusting the pH of the digestate to extreme levels. Acids or bases break down the complex structures, releasing the nutrients into a soluble form that can be more easily processed and absorbed. For example, the addition of 10 % concentrated sulfuric and/or phosphoric acid or potassium hydroxide has been shown to be effective in solubilizing the nutrients [8]. However, it is important to consider both the feasibility and the cost of acid consumption.

The acid and alkaline solubilizates obtained from the conditioning process can then be combined for neutralization and subjected to granulation and composition correction, including the introduction of micronutrient salts. This process results in the production of an organic-mineral fertilizer that is tailored to specific plant crops and has commercial value [9].

The article aims to provide a comprehensive review, supported by an exhaustive list of references, of the current state of knowledge and technology in waste management for biogas production. It particularly focuses on digestate derived from various feedstocks. It evaluates and compares composting and additional post-anaerobic digestion processes through a comparative analysis, providing detailed metrics and case studies as alternative methods for managing digestate. It delves into different digestate management strategies, explores how input feedstocks influence digestate characteristics, examines the typical chemical composition of digestate in relation to its potential agronomic use, and discusses the legal and marketing issues associated with these factors [10,11].

2. Comparison of AD with other biobased methods of waste management

Biobased wastes can be managed through various methods: landfill, incineration, gasification, composting, or anaerobic digestion (AD). The process of anaerobic digestion with biogas production enables the simultaneous achievement of two goals: the valorization of biological waste and the production of renewable energy [12]. Biogas production can effectively reduce pathogens, and single-reactor methods allow for co-fermentation of digestate [13,14]. Biogas, the product of anaerobic digestion (AD), can be processed and integrated into a natural gas distribution network or used on-site for electricity generation.

2.1. Biogas and anaerobic digestate

In the context of renewable energy and waste management, the term "AD" is crucial and stands for "Anaerobic Digestion" not to be confused with "Anaerobic Digestate" Anaerobic Digestion is a process wherein microorganisms decompose organic matter without oxygen, leading to the production of biogas and a nutrient-rich by-product named Digestate. This by-product, abundant in vital nutrients like nitrogen, phosphorous, and potassium, can serve as a soil conditioner or fertilizer. Proper management of Digestate is essential for efficient nutrient use and environmental protection. Therefore, it is necessary to differentiate between AD, which denotes the process of organic waste breakdown, and digestate, which refers to the resultant product.

This paper offers insights into the valorization of digestate into fertilizers, considering the context of the EU Green Deal and the United Nations Sustainable Development Goals (UNSDGs). The focus is on the application of a circular economy approach in digestate management, with a particular emphasis on nutrient recovery. This valorization process not only transforms waste into valuable resources but also contributes significantly to promoting a circular economy, reducing waste, and lowering greenhouse gas emissions, thus aligning with the EU Green Deal. Simultaneously, it supports key UNSDGs such as responsible consumption and production (Goal 12), and climate action (Goal 13).

Biogas utilization addresses energy security concerns while offering environmental benefits. Biogas production reduces GHG emissions, particularly methane, and aids in waste management. Anaerobic digestate, a byproduct of biogas production, can serve as an organic fertilizer [15], contributing to the circular economy and reducing dependence on synthetic fertilizers. Investment in biogas infrastructure can drive technological advancements and foster collaboration between industry, academia, and policymakers, leading to a more resilient and sustainable energy future.

Biological materials can be valorized in two ways: composting and anaerobic digestion. The composting method requires careful management of inputs, including maintaining an optimal carbon to nitrogen ratio, ensuring appropriate humidity levels, and using a textureloosening agent to facilitate the process [16]. This process produces compost that can be applied directly to the soil and is a commercial product. On the other hand, the anaerobic digestion process has less stringent requirements for the feedstock, allowing for a less restrictive value of the carbon-to-nitrogen ratio and a non-loose texture [17]. This process produces biogas, which is a useful renewable fuel. However, the suitability of the digestate, generated during the process and constituting approximately 50 % of the biobased waste input, for direct application to the soil can vary. This is largely dependent on the feedstock used and process conditions, as these factors influence the presence of microflora and anaerobic metabolites that may cause phytotoxicity effects [18]. Phytotoxicity studies have been carried out by measuring the Germination Index of various crops, such as cress and lettuce, with the application of unprocessed digestate. Phytotoxicity has been shown to be negatively correlated with electrical conductivity, indicating the salinity of the material has a phytotoxic effect [19–21].

The direct application of unprocessed digestate is possible, but to avoid phytotoxicity effects, residual CH_4, H_2S, and NH_3 should be collected and short-chain fatty acids should be neutralized. It important to note that in several countries, regulations require ponding or storage of digestate before it can be spread on agricultural soil [19–24]. The material, rich in fertilizer nutrients, can be used as a feedstock for fertilizer production. However, to obtain an effective organic mineral fertilizer from digestate, sanitization is required to neutralize microflora, including pathogenic microflora. Sanitization is essential to ensure that digestate does not contain pathogens or other harmful biological agents that may cause nutrient loss through volatilization or leakage. Anaerobic fermentation typically neutralizes 90 % of pathogens, and the T90 decimation time is used to measure the destruction time of 90 % of pathogens, such as *Salmonella typhimurium, S. dublin, Escherichia coli, Staphylococcus aureus, Mycobacterium paratuberculosis, Coliform bacteria,* and *Streptococci,* including *Streptococcus faecalis*. The efficiency of sanitization is influenced by various factors, most notably the duration and temperature of the anaerobic digestion process. Specifically, longer durations and higher temperatures are generally more effective at reducing the presence of most pathogens, including various types of bacteria and parasites [25–27].

Digestate can be successfully utilized as a raw material to obtain organic-mineral fertilizers through physical, chemical, and biological methods. There is a knowledge gap regarding marketable, full-value AD-based fertilizer formulations, which this paper aims to address [28].

2.2. *The process of anaerobic digestion*

This section delineates the anaerobic digestion process with an emphasis on the characteristics of the resultant digestate that are pertinent for formulating fertilizers. AD is a complex process influenced by several factors including the type of feedstock, temperature, and fermentation time. These factors affect the properties of the resulting digestate [29].

The resulting digestate, a byproduct rich in nutrients, can be used as a raw material for creating fertilizers, but it is essential to understand its properties to create value-added and commercially useful fertilizers. The production of fertilizer from anaerobic digestate frequently necessitates supplementary technologies to enhance Class B digestate. Further treatment processes are necessary to upgrade the digestate to a higher class of sludge suitable for use as fertilizer. Typically, fertilizers are composed by mixing by-products of several processes to obtain multi-component organic-mineral NPK fertilizer. The properties of the digestate are dependent on the type of feedstock used and the process parameters, which determine the degree of maturation of the resulting digestate. To be able to point out specific compounds with potential phytotoxic properties and take advantage of the beneficial properties of anaerobic digestate, it is important to understand the mechanism of anaerobic digestion [30]. The process generates a complete set of macro and micronutrients with a low content of toxic elements, which makes digestate an excellent source of nutrients for plant growth. However, its direct application to the soil causes residual methane, ammonia, and hydrogen sulfide emissions and odorous gases, as well as phytotoxic effects due to the presence of volatile fatty acids (VFAs) [31–33].

Developing processes to mitigate the formation of phytotoxic compounds and eliminate residual emissions such as methane, ammonia, and hydrogen sulfide is crucial for the safe soil application of digestate [34]. Understanding the AD process enables the formulation of effective strategies for digestate management and its use as a valuable fertilizer [35].

The present work reports an innovative methodology for digestate management through the use of advanced molecular techniques. These methods enable the identification of specific microbial strains crucial for the degradation of specialized waste types. This research is among the pioneering efforts to systematically tackle challenges related to the direct application of digestate to soil, such as residual emissions and phytotoxic effects. This not only augments the existing scientific literature but also offers practical solutions for industrial applications. The emphasis on specialized microbial activities and the identification of potential risks differentiate this work, providing a nuanced understanding indispensable for the advancement of future anaerobic digestion technologies.

2.3. *Comprehensive overview of anaerobic digestion: fundamentals, stages, and microbial interactions*

Our study uniquely describes how high moisture conditions influence the two material streams produced: gaseous and liquid/solid. The gaseous stream is primarily composed of biomethane, carbon dioxide, and trace amounts of H_2S, NH_3, and H_2. Concurrently, the liquid/solid digestate, a byproduct with high concentrations of nitrogen and phosphorus, has potential for valorization into useful products like fertilizers or biochar [14].

A biogas plant with a 500 kW capacity can generate an estimated 10,000 tonnes of solid digestate annually. The composition of the biogas can vary based on the feedstock used, as well as specific process parameters, such as temperature and fermentation time [36].

Our study uniquely focuses on how varying feedstock types influence digestate properties, providing new insights for effective digestate valorization. This knowledge can help in identifying specific compounds with phytotoxic properties and developing processes to reduce them. It can aid in addressing the problem of residual methane, ammonia, and hydrogen sulfide emissions that can occur after soil application of the digestate [37].

The quadriphasic anaerobic digestion process refines both biogas production and digestate quality through four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Each stage is facilitated by specialized groups of microorganisms that contribute to the production of specific compounds [33,38].

In the first phase, hydrolysis, hydrolytic bacteria break down biopolymers present in biological waste, including proteins, polysaccharides, and fats, into simpler compounds such as sugars, amino acids, and fatty acid [39]. This biodegradation primarily occurs through the action of extracellularly produced enzymes. The resulting monomers, soluble in the liquid phase of the digestate, serve as substrates for the next stage, acidogenesis.

During acidogenesis, acidogenic bacteria convert these substrates into short-chain organic acids, such as butyric or propionic acid [32]. Following this, in the acetogenesis stage, acetogenic bacteria transform these short-chain organic acids and other intermediates into acetic acid, hydrogen, and carbon dioxide [40].

In the fourth and final stage, methanogenesis, methanogenic archaea utilize these compounds to produce methane and carbon dioxide. This phase results in the generation of biogas and a liquid and/or solid residual known as anaerobic digestate [30,41].

Biogas, an increasingly popular and important alternative energy source, can be produced from locally available raw materials, generating digestate as a byproduct. Proper management of digestate is crucial to fully utilize its agronomic potential, as it contains a complete set of macro and micronutrients with a low content of toxic elements [42]. However, the direct application of digestate to the soil can cause residual methane, ammonia, hydrogen sulfide emissions, and odorous gases, as well as phytotoxic effects due to the presence of volatile fatty acids (VFAs) [43]. Untreated digestate may contain inhibitory substances like heavy metals or excess salts, adversely affecting plant growth and metabolism.

Advanced molecular techniques delve into the unique growth kinetics, equilibrium, and nutritional needs of microorganisms across different phases. Microorganisms in various phases differ in growth kinetics, equilibrium states, and responses to process parameters [36,40]. These microorganisms work together, each playing a specific role in the degradation and conversion of organic matter into biogas. Table 1 provides an overview of the key microorganisms involved in the different stages of anaerobic digestion and their functions. The table highlights the complex microbial interactions and their roles in converting organic matter into biogas during the anaerobic digestion process. An examination of various studies [44–46]. Recent studies [32,39] highlight the complex interplay of diverse microbial groups in the biogas production process, each contributing distinctly to its phases. This understanding is pivotal for optimizing anaerobic digestate management and potentially enhancing biogas production efficiency. Specific microbial strains, for example, could be strategically seeded to enhance the breakdown of particular waste types.

It is important to fill the existing knowledge gaps, particularly in the role of environmental factors on microbial interactions. Future research should further explore the influence of environmental variables on these microorganisms, including the potential role of yet unidentified contributing species. Such investigations could catalyze the development of innovative anaerobic digestate management techniques that leverage these conditions to optimize biogas production.

The complex microbial community in a biogas plant can be influenced by various factors, such as temperature, pH, and substrate composition, which in turn affect the efficiency of the biogas production process [46]. Maintaining optimal conditions and understanding the interactions between these microorganisms is crucial for maximizing biogas production and ensuring the stability of the anaerobic digestion process [38].

Advanced molecular techniques, including metagenomics for gene identification, metatranscriptomics for RNA sequencing, and metaproteomics for protein analysis, elucidate the microbial ecology within anaerobic digestion systems. Specific strains of methanogenic archaea and acetogenic bacteria, identified through these techniques, prove critical for efficient biogas production. Literature data indicate a 15 % increase in methane yield and a 20 % reduction in volatile fatty acid (VFA) concentrations in the digestate when these strains are present. Such granularity in understanding microbial roles and interactions enables the development of targeted interventions, like the strategic seeding of beneficial microbial strains, to enhance both biogas yield and digestate quality. This foundational understanding sets the stage for subsequent research endeavors to tailor microbial communities for enhanced biogas production under distinct environmental conditions, like fluctuating pH levels and diverse feedstock compositions [46].

Various microorganisms involved in each stage of the process, their role, and the examples of genera and strains responsible for carrying out specific tasks. This knowledge can help in optimizing the biogas production process and, consequently, the quality of the digestate generated. The activities of these microorganisms directly influence the composition of the digestate, including its content of macro and micronutrients such as nitrogen, phosphorus, and potassium. Understanding the role of each microbial group in the process allows for better control and management of the process conditions, ensuring that the end product has the desired nutrient profile suitable for its use as a fertilizer.

Table 1
Key microorganisms involved in biogas production and their functions [32,39,44–47].

Stage	Microbial group	Examples of genera	Role	Strain	Effective at breaking down	Favorable Environmental Conditions	Potential Strategies for Biogas Production	Examples
Hydrolysis	Bacteria, fungi	*Bacillus, Pseudomonas, Aminobacterium, Aspergillus*	Break down biopolymers into monomers	Hydrolytic bacteria, cellulolytic fungi	Cellulose, hemicellulose	Neutral pH, moderate temperature	Pre-treatment of feedstock to increase surface area	*Bacillus subtilis, Pseudomonas putida, Aspergillus niger*
Acidogenesis	Bacteria	*Clostridium, Bacteroides, Enterobacter*	Convert monomers into short-chain organic acids	Acidogenic bacteria	Simple sugars, amino acids	Low pH, moderate temperature	Control of pH and temperature	*Clostridium acetobutylicum, Bacteroides fragilis, Enterobacter aerogenes*
Acetogenesis	Bacteria	*Acetobacterium, Syntrophomonas, Moorella*	Convert short-chain organic acids into acetic acid, hydrogen, and carbon dioxide	Homoacetogenic bacteria, Acetogenic microbiota	Organic acids	Neutral pH, moderate temperature	Maintain steady organic loading rate	*Butyribacterium methylotrophicum, Acetobacterium woodii, Syntrophomonas wolfei*
Methanogenesis	Archaea	*Methanobacterium, Methanosarcina, Methanococcus*	Convert acetic acid, hydrogen, and carbon dioxide into methane and carbon dioxide	Methanogens, Hydrogenotrophic methanogens, Acetotrophic methanogens	Acetic acid, CO_2, H_2	Neutral to slightly alkaline pH, moderate temperature	Removal of inhibitory substances	*Methanobrevibacter smithii, Methanosarcina barkeri, Methanobacterium bryantii, Methanogenum thermautotrophicus, Methanosarcina mazei, Methanosarcina thermophila*
Sulfate-reducing bacteria	Bacteria	*Desulfovibrio, Desulfobacter*	Produce CO_2 and H_2S	–	Organic material in the presence of sulfate	Slightly acidic pH, low oxygen levels	Sulfate control and regulation	*Desulfovibrio vulgaris, Desulfobacter postgatei*

Knowledge of the microorganisms involved in the process helps identify any potential issues that might arise from the presence of pathogens or harmful substances in the digestate. Ensuring the safety of the digestate as a fertilizer is essential for its application in agriculture, as it can impact crop growth, yield, and quality.

2.4. Management of digestate

The increasing number of biogas plants in Europe is leading to a growing problem of digestate management [48]. Due to the rising cost of landfilling organic materials and the limited availability of natural gas, biogas plants have become an attractive alternative, and the number of biogas plants in Europe has increased to 28,000 [49]. As the amount of digestate produced is rapidly growing, it is crucial to develop effective processes for its management (Dutta et al., 2021). Proper logistics planning is important, with local biogas plants located in areas where biological waste can be easily collected from local producers, and the resulting digestate can be applied to the soil of local farms to minimize transport costs [15].

Producing organic mineral fertilizers from digestate can help reduce dependence on synthetic fertilizers, which can negatively impact the environment and human health. Organic mineral fertilizer production contributes to the circular economy by reducing waste and increasing resource efficiency [15].

Biogas technology applications extend beyond farm waste. The treatment of other biological waste streams, such as post-harvest residues, animal waste (including animal husbandry waste, manure, and slaughter waste), food waste, and solid residues from food processing, also plays a crucial role in renewable methane production [[2,50]. Consequently, developing effective methods for managing the resulting anaerobic digestate is essential.

Numerous studies have investigated various approaches to anaerobic digestate management. For example Reuland et al. [51] proposed a method for producing organic-mineral fertilizers from digestate, while Uddin and Wright discussed the challenges and opportunities associated with digestate management, emphasizing the need for sustainable solutions that align with circular economy principles [30].

Specific challenges in digestate management include the handling and storage of digestate, the high cost of treatment processes, and the difficulty of managing variable digestate quality. Despite these challenges, opportunities exist in areas such as nutrient recovery, energy production, and the creation of value-added products.

In recent years, the increasing need for sustainable energy and waste management has led to several innovative technologies and approaches in anaerobic digestate management. These advancements enhance the efficiency of digestate utilization and contribute to the broader goals of sustainability and carbon neutrality. This section discusses these developments and their implications.

The development and implementation of sustainable anaerobic digestion (AD) management technologies are crucial for achieving a closed-loop circular economy approach by obtaining nutrient-rich fertilizers. Thermal conversion processes, such as hydrothermal treatment and pyrolysis, can be integrated with digestate to create hydrocarbons or biochar for various applications. These hybrid processes facilitate the full valorization of renewable raw materials. If syngas and biochar from pyrolysis or other thermal processes are used as energy sources, the mechanism for the final reduction of CO_2 and other greenhouse gas (GHG) emissions needs to be clarified and substantiated [52].

Studies have focused on improving anaerobic digester performance by optimizing process conditions and feedstock composition. For instance, Li et al. (2022) investigated the effect of substrate-to-inoculum ratio on anaerobic digestion performance, finding that an optimal ratio can enhance biogas production and process stability [53]. Similarly, Odejobi et al. [54] evaluated the potential of co-digesting animal manure and food waste, demonstrating that combining various feedstocks can improve biogas yield and diversify input materials.

While the number of biogas plants is increasing and interest in biowaste valorization grows, much of the biological waste generated globally still remains unprocessed. Livestock production residues, such as manure, are often discharged into the soil without proper treatment, which not only reduces soil fertility but also poses a risk to human health and leads to the dispersion of nutrients in the environment. Nutrient leaching into ground and surface waters can contribute to eutrophication, while the release of GHGs and odors can negatively impact the environment [55].

Anaerobic digestion, compared to alternative methods of biobased waste management, offers several advantages. It outperforms landfilling in sustainability and incineration due to its lack of GHG and toxic byproducts, while also contributing to renewable energy production, and generating nutrient-rich fertilizer [15,56,57]]. Further benefits include: no requirement for aeration, lower installation space than composting plants, reduced odor emissions, and potential valorization of the digestate into products such as fertilizers, biochar, and substrates for microorganism cultivation.

The management of digestate is a critical issue in the efficient operation of anaerobic digestion plants. The nutrient-rich digestate can be used as a raw material to produce organic-mineral fertilizers using physical, chemical, and biological methods [58]. The resulting fertilizers can be tailored to specific plant crops and have commercial value [59]. To mitigate phytotoxic effects, digestate requires suitable treatment to neutralize volatile fatty acids and emissions of residual gases like methane, ammonia, and hydrogen sulfide [37,58,60,61]. Appropriate digestate management can reduce GHG emissions, odor issues, and nutrient leaching [62].

2.5. Methods of digestate management

2.5.1. Microorganism interaction

Alongside the points on biogas production and usage, it is worth noting that the microorganisms present in the resulting digestate correspond to the different stages of the AD process. For example, during the hydrolysis phase, both bacteria and fungi become prevalent; e.g., *Bacillus, Pseudomonas, Aminobacterium, Aspergillus, Bacillus halodurans*), acetogenesis (bacteria; *Acetobacterium, Clostridium,* e.g., *Halophaga foetid)*, methanogenesis (archaea; *Methanobacterium,* e.g.*, Methanococcus vannielli*) [13,33]. It is worth noting that most anaerobic digestion plants use the produced gas and/or energy for their own needs. This is largely due to the complexities involved in selling the cleaned gas or energy to the grid, a process that involves numerous regulatory and technical challenges.

2.5.2. Pre-treatment of digestate

The treatment of digestate before its application to soil is crucial to ensure its optimal use as a fertilizer. Several methods can be applied to this end, including composting, thermal methods such as incineration and pyrolysis, chemical hydrolysis methods like alkaline hydrolysis, and ozonation. Composting, one of the most common methods used to stabilize the digestate and reduce the concentration of volatile organic compounds, is an effective approach to digestate management. It is an easy and low-cost method that can be used to produce a high-quality organic fertilizer with a low concentration of heavy metals, organic pollutants, and pathogens [63]. Thermal methods require pre-treatment to reduce the moisture content, energy costs, and improve the management of the digestate. The choice of the digestate management method depends on the optimization of costs and energy while ensuring the stability and safety of digestate [64]. Hydrolysis methods like alkaline hydrolysis can be used to increase the solubility of nutrients in the digestate, while ozonation can be used to reduce the concentration of organic compounds and pathogens [65].

2.5.3. Choice of digestate management method

The choice of the digestate management method should be based on the characteristics of the feedstock, as well as the specific conditions of the plant, including the local regulatory requirements and the available resources. The appropriate management of digestate is essential for the sustainable use of biowaste, which is important for the reduction of GHG emissions and the promotion of a circular economy approach [34].

2.5.4. Liquid vs. solid fraction of anaerobic digestate

Partitioning anaerobic digestate into liquid and solid fractions can yield two compositionally distinct components, providing added benefits. Various studies have investigated the division into solid and liquid fractions, with regards to dry matter, nitrogen, phosphorus, and heavy metals. The solid fraction of digestate was found to contain the majority (87 %) of nitrogen and (71 %) of phosphorus, while the liquid fraction of digestate contained most of the organic nitrogen and potassium in the form of ammonium and potassium ions [66]. Phosphorus is mainly present in the solid fraction of digestate. The phosphate ions are released from organic matter and then precipitated as phosphates of Ca(II), Mg (II), and Fe(III) [67]. In contrast, most of the organic nitrogen and potassium can be found in the liquid part of AD. While the liquid fraction of anaerobic digestate may contain a greater proportion of macro and micronutrients, it is not recommended to apply digestate directly to the soil due to the presence of pathogens (such as *Salmonella, Campylobacter, Yersinia enterocolitica*, and *Cryptosporidium*), odors, GHG emissions (minimization of N losses during composting), phytotoxic volatile fatty acids (mainly acetic acid), viscosity (approximately 1000 cP), and high humidity (70–80 %) which makes application to the soil difficult [22, 68].

Studies have confirmed the toxic effects of volatile fatty acids, including formic, acetic, propionic, isobutyric, butyric, iso-valeric, valeric, and caproic acids, on plants such as Lepidium sativum or *Lolium multiflorum*. These effects have been proven in germination tests by determining the Germination Index (GI) in the dose-response system. The EC50 values have also been reported in the context of seedling emergence and shoot dry weight, calculated from the dose-response model. There is a positive correlation between carbon chain length and toxicity. Another relationship exists between individual plant species and their response to VFA [60,69].

The literature suggests that the toxicity of volatile fatty acids (VFAs) (especially propionic and butyric) in digestate on plants, remains partially unidentified. It may be related to their contribution to the acidity and conductivity of digestate and their lipophilicity. A relationship has been found between the antimicrobial activity of non-dissociated molecules and the adverse effect of VFAs on abscisic acid metabolism [31,63].

Several measures can be taken to reduce the phytotoxicity of AD. One approach is to fractionate the digestate into liquid and solid parts, as VFAs are mainly present in the liquid part. Composting of the solid fraction can reduce odor emissions and lower phytotoxicity by minimizing the concentration of volatile compounds. Composting can also inhibit some phytopathogens, such as Fusarium sp., and promote favorable yield-forming effects by adjusting the pH, C:N ratio, and organic matter quality [63].

Caution is necessary when employing digestate in agriculture, owing to the presence of pathogens (such as *Salmonella, Campylobacter, Yersinia enterocolitica,* and *Cryptosporidium*), odors, greenhouse gas emissions, and a high VFA content. The presence of VFA in digestate, such as acetic, propionic, and butyric acids, can be toxic to plants, affecting seed germination, plant growth, and yield. The mechanism of toxicity may be related to an imbalance of pH and ionic strength or to the carbon chain length of VFA. The effect of VFA on different plant species may vary [60, 69].

3. Feedstocks for biogas plants

The quality of the feedstock is a crucial factor in biogas production, as it can determine the efficiency of the AD process and the properties of the digestate produced. The agricultural value of the digestate is influenced by its chemical composition, which can greatly vary depending on the feedstock [36].

Common feedstocks include manure, crop residues, sewage sludge, fruit and vegetable waste (FVW), the organic fraction of municipal solid waste (OFMSW), and energy crops [12].

3.1. Comparative analysis of animal waste and high-energy waste

Animal waste, food waste, and sewage sludge are widely used as feedstocks for AD, but their potential for energy generation differs [56]. Among the various materials suitable for the AD process, waste feed, slaughterhouse waste, and manure are frequently mentioned. While manure is a beneficial feedstock for fermentation, it yields lower quantities of biogas compared to other feedstocks. However, it contains microflora that support the AD process, and the fermentation residue has a well-balanced macro and micronutrient composition [2]. To enhance fermentation effectiveness, manure should be mixed with high-energy waste.

Energy crops, such as corn, sorghum, and grasses, are also common in biogas production. These crops provide high biogas yields and can be specifically cultivated for this purpose. However, their use can raise concerns about land use competition with food crops and potential environmental impacts [70,71].

The selection of feedstock for biogas production should consider factors such as the efficiency of the AD process, the chemical composition and agronomic value of the digestate, and the environmental and social impacts of feedstock production [63].

3.2. Digestate from food waste

It is estimated that a third of the world's food is wasted, consisting of biodegradable matter like proteins, carbohydrates, lipids, and inorganic substances [72,73]. Anaerobic digestion is currently the most favorable direction for food waste management, as it allows for the recovery of both energy (biogas) and materials (anaerobic digestate as a resource for fertilizer production) [73]. The digestate carries high concentrations of organic matter, suspended solids, N, and P, making it important to recover agriculturally useful components [74]. Biogas generated from food waste also contains hydrogen and hydrogen sulphide [75].

Decentralized biogas plants serving individual institutions, such as a restaurant or canteen generating around 20–30 tons of food waste annually, could present a practical solution. For such small, local biogas plants, production becomes more profitable because there is no problem with transport, which can be a costly operation. Erraji et al. (2021) demonstrated the operation of such a small biogas plant to obtain biogas and to check the effect of soil application of liquid digestate [62]. Promising results were obtained in tests on lettuce, corn, and potatoes, using raw and diluted digestate.

Implementing small-scale biogas plants can reduce the environmental impact of food waste while providing a valuable source of renewable energy and nutrient-rich digestate for agricultural use. The development of these decentralized systems could contribute to sustainable waste management practices, reducing GHG emissions and promoting a circular economy approach [1,5,8 37].

The process of separating solid and liquid fractions in anaerobic digestion can be challenging due to the presence of gelling substances such as proteins and polysaccharides, which can make it difficult to filter or centrifuge the digestate [11,76]. Food waste, in particular, can be problematic because microorganisms in anaerobic digestion generate extracellular polymeric substances (EPS), which further deteriorate the specific resistance to filtration, the normalized capillary suction time, and the bound water content. Such issues are especially observed when the fermentation time is too long or too short [13,76].

Despite the challenges in separating the solid and liquid fraction, anaerobic digestion from food waste generates a digestate rich in ammonium, phosphate, and potassium ions. These nutrients make the digestate valuable for agricultural applications such as fertilizers, as well as potential feedstocks for the production of biofuels and biochar [77,78]. Researchers have developed methods to utilize food and dairy digestate using hydrothermal liquefaction and membrane distillation. By doing so, they were able to obtain biocrude oil and a fertilizer-rich stream that was concentrated using the residual heat from hydrothermal liquefaction. However, the permeate obtained from membrane distillation contained high levels of volatile organic compounds that show a phytotoxic effect on cultivated plants [79].

The environmentally friendly method of anaerobic digestion allows for the extraction of energy and agricultural fertilizer from biowaste. Biowaste, which includes food waste, plant waste, and other organic waste, is considered to be a good source of nutrients such as nitrogen, phosphorus, and potassium. When considering the use efficiency of nitrogen, studies have shown that liquid compost has a higher value compared to mineral N fertilizer. The co-fermentation product from slurry and food waste had an even higher value, while the waste from vegetable processing and brewery had a lower result [28].

One of the major components of anaerobic digestate is ammonium N. Anaerobic digestate food effluent (ADFE) contains high concentrations of ammonium N (3 g/L N–NH_3), making it a useful source of nitrogen for various applications. ADFE can be used as a substrate for microalgae cultivation, which can convert ammonium N into protein-rich biomass. The biomass can then be used for animal feed, biofuels, or bioplastics [14].

There are also other potential uses of anaerobic digestate, such as soil amendment, biogas production, and production of value-added products. For example, anaerobic digestate can be used as a soil amendment to provide nutrients to plants and improve soil quality. Anaerobic digestate can be processed to produce value-added products such as biochar, which can be used as a soil amendment, and bioplastics, which can be used as a substitute for petroleum-based plastics [36].

3.3. Digestate from the wastewater treatment plant

The generation and management of digestate from biological wastewater treatment plants with separate fermentation chambers pose significant challenges. Approximately 10 million tonnes of digestate, accounting for about 50 % of the operating costs, are produced yearly in wastewater treatment plants across the EU [12,37]. The quality of the digestate produced from wastewater treatment plants depends on the nature of the incoming feedstock and the processing conditions used in the anaerobic digestion process [7,40]. To improve the quality and agricultural usefulness of digestate, co-digestion of mixed waste sludge, as well as fruit and vegetable waste, has been proposed. The co-digestion of waste sludge and organic waste such as fruit and vegetable waste (FVW) has been shown to increase methane production, improve the quality of the digestate, and reduce its phytotoxicity, making it more suitable for use as an agricultural fertilizer [37].

Pre-treatment methods such as thermal, mechanical, or chemical methods can enhance the anaerobic digestion process and improve the quality of digestate [74]. Pre-treatment can increase the solubilization of organic matter and the biodegradability of the substrate, leading to higher biogas yields and a more stable anaerobic digestion process [80].

In the post-digestion stage, composting serves to reduce the volume and weight of the digestate, stabilize the organic matter, and eliminate pathogens and weed seeds [81]. Nutrient recovery processes can extract valuable nutrients such as nitrogen, phosphorus, and potassium from the digestate, allowing for the production of tailored fertilizers that can be adapted to specific crop requirements [82].

4. The chemical composition of digestate

4.1. Factors influencing anaerobic digestion efficiency and stability

Apart from the parameters mentioned previously, both temperature and organic loading rate (OLR) play crucial roles in determining the efficiency and stability of the anaerobic digestion process [37,38]. The optimal temperature range for mesophilic anaerobic digestion (AD) lies between 35 and 40 °C, while for thermophilic AD, it is between 50 and 55 °C. The choice of temperature relies on the feedstock characteristics and specific quality requirements of biogas [40].

The organic loading rate represents the amount of organic matter added to the system per unit time and reactor volume. High OLRs can result in process instability, substrate inhibition, and reduced methane yield. To counteract this, the hydraulic retention time (HRT) must be carefully regulated to ensure adequate time for substrate breakdown, thereby creating a balanced and efficient anaerobic digestion process [42].

4.2. Digestate treatment

Digestate treatment can enhance its quality and agricultural value. One such method is solid-liquid separation, which separates the solid fraction from the liquid fraction of the digestate [43]. This procedure significantly reduces the volume of liquid digestate, facilitating its management, transport, and soil application. An alternative treatment is composting, involving aerobic degradation of the digestate's organic matter. Composting can stabilize the digestate and decrease its phytotoxicity, making it a beneficial soil amendment [11,83].

The following parameters of the AD process significantly influence digestate quality: temperature, retention time, pH, volatile fatty acids (VFA) concentration, and electrical conductivity [84]. Standardization of digestate parameters is essential for successful digestate management, and compliance with regulations ensures the safe and efficient use of produced digestate [14].

4.3. Standardization parameters and regulations

Numerous regulatory bodies have set standardization parameters for AD, including the European Union [85], which defines limits for heavy metals, pathogens, and nutrient content (NPK). Researchers, including Lavergne et al. (2018) and Reuland et al. (2021), have proposed standardization parameters for the physical and chemical properties of digestate, such as pH, dry matter, nitrogen, phosphorus, potassium, and electrical conductivity [51,86].

Table 2 consolidates essential standardization parameters for organic-mineral fertilizers, as well as their significance in anaerobic digestion (AD) management, for the assurance of the fertilizer's quality, safety, and effectiveness. The parameters are classified not only by the conventional categorization of measurement methods, acceptable ranges or limits, importance for fertilizer management, and sources of organic and mineral components, but also in terms of their applicability to waste types and potential influence on biogas yield.

Parameters such as moisture content, total solids, COD, BOD, and ammonia (NH_3), are determined using methods like gravimetric, spectrophotometric, and colorimetric analyses. Regulatory bodies designate the acceptable range for each parameter to assure that these fertilizers remain safe for the ecosystem. Conformity to these standardization parameters enables manufacturers to produce organic-mineral fertilizers that bolster sustainable agriculture and soil fertility.

Table 2 outlines parameters including total nitrogen (N), phosphorus (P), potassium (K), pH, electrical conductivity (E), carbon-to-nitrogen ratio (C:N), and heavy metals, highlighting their significance in fertilizer management. This information covers aspects such as setting the NPK ratio, fostering root growth, and enhancing plant resistance, as well as the implications for nutrient availability. Different measurement

Table 2
Standardization parameters for organic-mineral fertilizers and digestate management [8,87–90].

Parameter	Method	Acceptable Range/ Limits	Importance for Fertilizer Management	Sources of Organic and Mineral Components	Most Applicable to Waste Type	Potential Effects on Biogas Yield
Total Nitrogen (N)	Kjeldahl method	1–5% (w/w)	Determines the fertilizer's NPK ratio	Livestock manure, crop residues, rock phosphate	Livestock manure	High nitrogen content can increase biogas yield
Phosphorus (P)	Colorimetric method	0.1–3% (w/w)	Promotes root growth and seedling development	Rock phosphate, bone meal, manure	Manure	Phosphorus content does not directly influence biogas yield
Potassium (K)	Flame photometry	0.5–3% (w/w)	Improves plant resistance and quality	Wood ash, compost, manure	Wood ash	Potassium content does not directly influence biogas yield
pH	pH meter	6.0–7.5	Affects nutrient availability and plant uptake	Lime, dolomite, gypsum	Organic waste	pH imbalance can inhibit microbial activity, affecting biogas yield
Electrical conductivity (E)	Conductivity meter	0.2–2.5 mS/cm	Indicates the presence of excess salts in the soil	Rock dust, kelp meal, manure	Manure	Excessive salts can inhibit microbial activity, reducing biogas yield
Carbon/Nitrogen ratio (C:N)	Calculation using total organic carbon and total nitrogen	10–20	Affects decomposition rate and nutrient availability	Straw, sawdust, leaves, manure	Crop residues	Optimal C:N ratio can improve biogas yield
Heavy metals (e.g., Pb, Cd, Hg)	Atomic absorption spectroscopy	Pb: <100 mg/kg, Cd: <3 mg/kg, Hg: <1 mg/kg (based on EU standards)	Ensures safety for plants and the environment	Compost, manure	Compost	High heavy metal concentration can inhibit microbial activity, reducing biogas yield
Soluble nutrients (N total, P total, K total)	Standard SFS-EN 13652	1:5 water extraction, g/kg FM	Ensure nutrient availability to plants	Specific organic and mineral fertilizers	Organic waste	Nutrient content does not directly influence biogas yield
P availability	Sequential extraction	H_2O, 0.5 $NaHCO_3$, 0.1 M NaOH, 1 M HCl	Determines the portion of total P available to plants	Specific organic and mineral fertilizers	Organic waste	P availability does not directly influence biogas yield
Volatile Fatty Acids	Gas chromatography	Acetic, propionic, n-butyric, iso-butyric, caproic, iso-valeric	Ensure the proper digestion of organic matter and methane production	Organic waste and manure	Organic waste	High levels can decrease pH and inhibit microbial activity, affecting biogas yield
N–P–K Ratio (e.g., 2-2-2%)	ICP-OES, CN elemental analyzer	As specified by regulatory bodies	Ensures balanced fertilization of crops and improves soil fertility	Specific organic and mineral fertilizers	Mixed organic and mineral waste	NPK ratio does not directly influence biogas yield
Moisture content	Gravimetric analysis	40–60 % (w/w)	Affects the stability and storage of the organic-mineral fertilizer	Specific organic and mineral fertilizers	Mixed organic and mineral waste	Excessive moisture can inhibit biogas production
Total solids	Gravimetric analysis	40–60 % (w/w)	Determines the organic and mineral matter content	Specific organic and mineral fertilizers	Mixed organic and mineral waste	Higher total solids can increase biogas yield
Chemical oxygen demand (COD)	Oxidation using strong chemicals	As specified by regulatory bodies	Determines the amount of organic matter in the fertilizer	Specific organic and mineral fertilizers	Organic waste	Higher COD can increase biogas yield
Biochemical oxygen demand (BOD)	Oxygen consumption by bacteria	As specified by regulatory bodies	Measures the amount of oxygen consumed by microorganisms	Specific organic and mineral fertilizers	Organic waste	Higher BOD can suggest more biodegradable matter, potentially increasing biogas yield
Ammonia (NH_3)	Spectrophotometric analysis after distillation	As specified by regulatory bodies	Determines the amount of ammonia in the fertilizer	Specific organic and mineral fertilizers	Livestock manure	High ammonia concentrations can inhibit microbial activity, reducing biogas yield

methods for these parameters ensure their accuracy, safeguarding plant and environmental health. For example, atomic absorption spectroscopy measures heavy metals, while volatile fatty acids are quantified using gas chromatography. The table provides insight into the best type of waste each parameter applies to and its potential effects on biogas yield, demonstrating how each parameter influences both the fertilizer's quality and its energy production potential.

Table 2 also discusses the consequences of exceeding acceptable limits for parameters such as heavy metals and how variations in parameters, like the C:N ratio, can impact fertilizer effectiveness. It points out gaps in current knowledge and potential areas for future research, addressing discrepancies between various regulations or studies on these parameters. It lists common sources for organic and mineral components for fertilizers, such as livestock manure, crop residues, rock phosphate, wood ash, compost, and organic waste, underscoring the diverse materials that can be used in fertilizer production, and indicates the potential for process improvements based on these findings.

4.4. Agricultural application of digestate

If properly managed, digestate serves as a valuable resource in agriculture, functioning as a fertilizer to enhance soil quality and reduce reliance on mineral fertilizers. To avoid any negative impacts on soil, crops, or the environment, maintaining high digestate quality is vital [36]. The nutrient composition of digestate can be improved through the co-digestion of diverse feedstocks, which increases its suitability for agricultural application [40]. It is crucial that the anaerobic digestion (AD) process is optimized, with operators adjusting necessary parameters as needed to ensure ideal results [84].

Table 3 presents a range of compositions for digestate as reported in various scientific studies. The composition of digestate is contingent on the type of feedstock used in the biogas plant. Feedstock may consist of

Table 3
Digestate composition: a comparative study and its implication.

Parameter	Study 1	Study 2	Study 3	Study 4	Study 5	Interpretation	Implications
	[27]	[91]	[87]	[92]	[93]		
As (mg/kg DM)	29	–	–	–	–	Study 1 reported the highest concentration of As.	High As may lead to toxicity concerns in certain applications.
C total (g/kg DM)	–	6.8–26.9	0.2–17.7	365–460	–	Studies 2 and 4 reported similar ranges for C total.	C is a key nutrient and affects nutrient ratios in the soil.
C:N	–	1.5–6.1	1.3–29.8	4–20	–	Study 3 reported the widest range for C:N ratio.	The C:N ratio is crucial for microbial activity in soil.
Ca total (g/kg DM)	1.4–2.5	–	–	0.0036–2.56	–	Study 1 reported the highest concentration of Ca total.	Ca is crucial for plant cell wall structure.
Cd (mg/kg DM)	<0.43	–	0.1–10	<1	–	Study 3 reported the widest range for Cd.	High Cd can be toxic to plants and animals.
Cr (mg/kg DM)	<0.43	6–188	2–103	–	–	Study 2 reported the highest concentration of Cr.	High Cr may pose environmental and health risks.
Cu (mg/kg DM)	2.7–12.8	0.43	1–681	61–270	–	Study 3 reported the widest range for Cu.	Cu is a necessary micronutrient but can be toxic at high levels.
DM (%)	5.6–6.4	–	1.4–45.7	15–30	–	Study 3 reported the widest range for DM.	High DM affects the moisture content and manageability of digestate.
Fe (mg/kg DM)	–	70.7	–	10,800–47000	–	Study 4 reported the highest concentration of Fe.	Fe is a necessary micronutrient for many biological functions.
K total (g/kg DM)	2.9–4.1	–	–	0.001–4	–	Study 1 reported the highest concentration of K total.	K is essential for plant growth and development.
Mg total (g/kg DM)	0.5–0.8	–	–	0.001–0.512	–	Study 1 reported the highest concentration of Mg total.	Mg is an essential part of chlorophyll in plants.
Mn (mg/kg DM)	–	2.20	0–1100	133–780	–	Study 3 reported the widest range for Mn.	Mn is necessary for several biological functions but can be toxic at high levels.
N NH_3 (g/kg FM)	3.1–3.4	–	1.7–4.5	0.05–2.75	1.7–4.5	Studies 3 and 5 reported similar ranges for N NH_3.	Ammonia-N can affect the smell and toxicity of digestate.
N total (g/kg DM)	4.6–5.2	–	–	0.005–7.8	22–46	Study 5 reported the highest concentration of N total.	Total N is important for plant growth and soil fertility.
Ni (mg/kg DM)	–	<0.43	–	20–57	–	Study 4 reported the highest concentration of Ni.	Ni is a necessary micronutrient but can be toxic at high levels.
P total (g/kg DM)	0.9–1.1	–	–	0.002–2.4	–	Study 1 reported the highest concentration of P total.	P is crucial for energy transfer in plants.
Pb (mg/kg DM)	–	<0.43	–	<25	–	Study 4 reported the highest concentration of Pb.	Pb is a potential pollutant and may pose health risks.
pH	–	7.6–8.3	5.6–9	7–8.5	–	Study 3 reported the widest range for pH.	pH affects the availability of nutrients and biological activity in soil.
TKN (g/kg FM)	–	2.2–8.7	–	–	–	Study 2 reported the highest concentration of TKN.	TKN is a measure of total nitrogen in a sample.
Total solids (g/kg FM) (TS)	–	19.9–78.8	–	–	–	Study 2 reported the highest concentration of total solids.	Total solids impact the physical properties of digestate.
Volatile Solids (g/kg FM) (VS)	–	12.3–63.7	–	–	–	Study 2 reported the highest concentration of volatile solids.	Volatile solids are indicative of the organic matter content.
Zn (mg/kg DM)	–	2.01	–	–	–	Study 2 reported the highest concentration of Zn.	Zn is a necessary micronutrient for many biological functions.

manure, agricultural feedstock, food waste, organic fraction of municipal solid waste (OFMSW), and industrial waste. In some cases, co-digestion of different raw materials is performed, leading to further variations in digestate composition.

The standardization of digestate is essential to correct the composition and should take into consideration agronomic properties: nitrogen, phosphorus, and potassium content, as well as trace elements like zinc, copper, and iron. As demonstrated in Table 3, even within the same parameter, the composition of digestate exhibits significant variations. For instance, the concentration of As in digestate ranges from 29 mg/kg DM to not detected, depending on the study. This highlights the need for more consistent measurement and reporting methods across studies.

The application of digestate as a fertilizer should be carefully planned to match the specific nutrient requirements of the crops and avoid excessive nutrient loading. The wide range of C:N ratios reported in Table 3, for example, indicates varying levels of nitrogen availability for crops. Determination of the optimal application rates and timing for different crops and soil types is needed in the future.

Heavy metals and other potentially toxic substances in digestate pose a significant concern. Regular monitoring of these elements is necessary as their concentration can vary depending on the feedstock used. For instance, the concentration of Cr in digestate reported in study by Koszel and Lorencowicz (2015) [91] is significantly higher than that reported by Al Seadi et al. (2013) [27]. This suggests that the feedstock used in the paper by Koszel and Lorencowicz (2015) [91] may have contained higher levels of Cr, highlighting the importance of careful feedstock selection and monitoring.

Though digestate has noteworthy potential as a fertilizer, challenges arise in its management and use due to its variable composition. To better understand these variations and develop strategies for optimizing the use of digestate as a fertilizer, further research is required. This could include the development of new measurement and standardization methods, as well as studies investigating the interactions between different parameters and their impact on fertilizer effectiveness.

5. Available digestate processing technologies

The use of acid and alkaline solubilization techniques can increase the solubility of nutrients and improve the agronomic quality of digestate, as corroborated by a comprehensive review from Izydorczyk et al. (2021) [94]. Acid solubilization works by using an acid to lower the pH, breaking down nutrient compounds and making them soluble. On the other hand, alkaline solubilization raises the pH to extreme levels using a base, resulting in similar breakdown and solubility. These techniques work because many nutrients are more soluble at high or low pH levels. Several studies have reported the successful application of these techniques for nutrient recovery from digestate [8,9]. The use of organic-mineral fertilizers produced from digestate has been shown to improve plant growth and reduce environmental impacts compared to traditional chemical fertilizers [8]. These fertilizers help reduce environmental impacts by utilizing waste material and decreasing the reliance on synthetic fertilizers, thus reducing the carbon footprint of agricultural practices.

Processing technologies such as thermal processes, combustion, co-composting, drying, integrated biorefinery, and nutrient recovery offer several benefits. These include reducing volatile fatty acids (VFAs), increasing the bioavailability of nutrients, and sanitizing the digestate, which makes it safe to use as a fertilizer. These processes help to increase the efficiency of nutrient recovery from digestate, contributing to the circular economy concept.

The section describes various available technologies for processing anaerobic digestate for fertilizer valorization. Thermal processes such as pyrolysis and hydrothermal carbonization (HT), combustion, co-composting, drying, integrated biorefinery, and nutrient recovery are some of the methods used for processing anaerobic digestate [95]. Processing is necessary to increase the usefulness of anaerobic digestate for fertilization. Conditioning and stabilization are two valuable methods for this purpose. Conditioning with mineral acids such as sulfuric or phosphoric acid can sanitize the digestate and increase the bioavailability of nutrients by hydrolyzing and mineralizing the biomolecules containing nitrogen, phosphorus, and potassium and microelements. In addition, this process reduces volatile fatty acids (VFAs) [19,96].

Lime conditioning is also used in practice. However, liming is a controversial approach because it increases the pH, which causes ammonia volatilization, leading to the loss of nitrogen. Composting or co-composting is the most common method used for stabilization. During the composting process, the degradation of phytotoxic VFAs occurs, increasing the bioavailability of nutrients, sanitizing the digestate due to the high temperature of the process, and contributing to the humus content and soil fertility [20,97].

The literature reports that anaerobic digestate still has potential to produce residual methane yields, with liquid digestate generating around 70 N ml CH_4/g VS, and constant digestate producing around 90 N mL CH_4/g VS. However, several issues are associated with digestate storage and use, such as the loss of biogas, high transport costs, and additional restrictions imposed by the European Nitrates Directive. To address these limitations, various alternative methods of digestate valorization are being explored, including thermal, thermochemical, and enzymatic methods. The enzymatic process has proven to be particularly advantageous for the recovery of methane, as it can increase the methane yield by up to 51 % for solid fraction digestate and 13 % for liquid anaerobic digestate [27]. Recycling of digestate is also shown to increase methane yield [98]. Fig. 1 illustrates the various directions of anaerobic digestate processing and valorization, as described by Barampouti et al. (2020) [92].

In recent studies, attempts have been made to use saline digestate as a feedstock for the production of bioethanol. As a result of the presence of carbohydrates and residual lignin, this digestate can be used as a raw material for alcoholic fermentation. To optimize this process, a combined chemical hydrolysis process (acid and alkaline) was used, followed by an enzymatic process. It was found that a higher level of saccharification (72 %) is obtained in alkaline hydrolysis. Through the valorization of digestate and the production of bioethanol in this hybrid process, it was possible to maximize the energy yield of the process [99].

5.1. Thermal process of digestate treatment

One of the possible approaches for digestate processing is hydrothermal carbonization (HTC), a process that converts digestate into a solid biochar-like material using high temperatures and pressure in the presence of water. HTC is considered an alternative to composting and pyrolysis methods [36,100]. A promising concept not discussed in this paper but warranting consideration is the coupling of anaerobic digestion with the Thermal Hydrolysis Process (THP) [36]. This approach could potentially enhance the benefits derived from the AD process, including increased biogas yield and improved digestate quality. The HTC process converts digestate into a solid biochar-like material by using high temperatures and pressure in the presence of water [95]. The biochar obtained through the HTC process can be used as a soil amendment or as a source of energy [101].

Although the HTC process has several advantages over other methods, it also has some drawbacks. The biochar produced through HTC is acidic and contains polycyclic aromatic hydrocarbons and other organic toxic compounds [102]. It has a low value of the sorption surface, which affects its potential use for water treatment or gas storage [77]. Hence, biochar from HTC should be characterized in terms of its elemental composition, pH, volume, and pore size distribution [77].

The liquid fraction produced during HTC, containing various organic acids, phenolic compounds, and furan derivatives, is also an essential component to consider in the context of HTC overall process and its potential applications [77]. The properties of the liquid fraction are important in determining its potential use as a feedstock for biogas production or as a source of chemicals [6].

One of the significant environmental problems associated with pyrolysis is the aqueous solution generated during the process, which contains several toxic compounds such as phenols and furan derivatives [95]. However, it has been shown that this aqueous solution can be returned to the fermentation chamber and used as part of the feedstock in biogas production, which could enhance the overall yield of biogas production [103]. By integrating pyrolysis and anaerobic digestion, the conversion of digestate by thermochemical methods can be achieved,

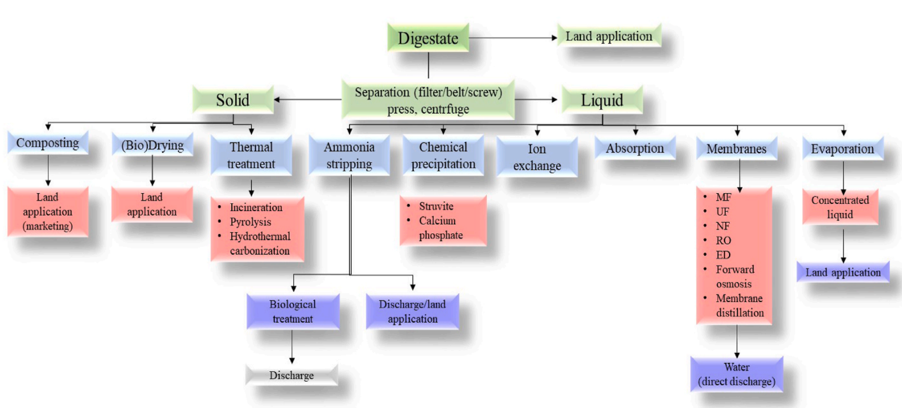

Fig. 1. Digestate processing: recovery of nutrients from anaerobic digestate [27,92].

and the bioconversion of pyrolysis fluids can be done [103].

5.2. Combustion

The combustion of digestate offers a promising alternative solution for its disposal, as it not only reduces waste but also produces renewable energy in the form of heat energy. In this process, the digestate is dried and pelletized together with wood in a 1:1 ratio and used as fuel in an ordinary domestic air furnace. A study by Pedrazzi et al. (2015) found that this method was effective in producing heat energy, demonstrating its potential as a viable option for digestate management [48].

A self-sustaining smoldering combustion method has been proposed for the flameless oxidation of anaerobic digestate. The process is limited by the kinetics of oxygen diffusion to the surface, and its rate is influenced by the moisture content and airflow. Serrano et al. (2020) found that a moisture content of 82 % m/m and a Darcy air flow of 50 cm/s were key parameters affecting the course of the process [35].

Combustion of digestate is a promising alternative solution for its disposal. It not only reduces waste but also produces renewable heat energy. It is important to ensure that the process is performed correctly to avoid negative impacts on the environment and human health. The emissions from the combustion of digestate must be carefully monitored to ensure that they comply with relevant regulations. To optimize the process and ensure that it is performed in an environmentally and socially responsible manner it is necessary to conduct further research.

5.3. Co-composting

Composting, or co-composting, is a controlled process that biologically decomposes and transforms biodegradable material into a humus-like substance known as compost. It involves microbial decomposition, deodorization, and heat production to neutralize pathogenic organisms. Co-composting of digestate with organic waste is an effective method for valorizing digestate, reducing waste volume, and producing a high-quality compost that serves as a valuable soil amendment. It enables the utilization of nutrients in the digestate and organic waste [104]. It has been proven to decrease the phytotoxicity of digestate, thereby improving its agronomic value [60].

The effectiveness of co-composting depends on various factors, such as the ratio of digestate to organic waste, moisture content, temperature, and aeration. Optimal conditions for co-composting vary depending on the type of organic waste and the desired end-product. The monitoring of key parameters during co-composting, such as pH, temperature, and C:N ratio, is crucial for achieving a high-quality compost [104]. Recent studies have focused on enhancing the performance of co-composting through the use of microbial inoculants and biochar amendments [63].

The digestate was mixed with organic waste, and the composting process was carried out. The research involved various percentages of digestate, with the most favorable effects observed when 20–40 % of digestate was incorporated into the compost mass. Two distinct phases were identified: active aeration and maturation. The quality of the compost obtained was assessed using several criteria, including pH, electrical conductivity, total solids, organic matter, respirometry, C:N, NH_3:NO_3^-, and Solvita tests (measuring stability and maturity) [104].

Bustamante et al. conducted a study on digestate co-composting to obtain material suitable for agricultural use. Solid digestate from silage and cattle manure was used, combined with postharvest residues for composting. The compost maturity, in vitro suppression of *Fusarium oxysporum f.* sp. Meloni, and the physical and chemical characteristics were evaluated. A bulking agent was added during composting, and the resulting composts exhibited favorable agricultural properties [63].

Cucina et al. (2017) explored the potential for nutrient and energy recovery through co-fermentation of pharmaceutical plant waste and waste biomass from biotechnological daptomycin production. The fermentation residue was composted, yielding organic fertilizer with a composition of 27.1, 6.2, and 17.8 g/kg of total NPK, respectively. The absence of daptomycin was confirmed in the compost derived from the digestate [105].

The anaerobic co-fermentation of waste fish and strawberries was investigated [35]. Fermentation of fish waste alone was found to be inefficient due to the low organic carbon content compared to other nutrients, particularly the COD:N:P ratio. Strawberry extrudate was used as a source of organic matter and as a factor that reduced the concentration of chlorides, N, and P (factors inhibiting the anaerobic process) during fermentation. The study demonstrated that the addition of strawberry extrudate improved the biodegradation of volatile organic compounds (by 83 %). The resulting digestate contained nutrients in a form that was bioavailable to plants [35].

5.4. Digestate drying: an overview and implications

Digestate drying, a critical step in nutrient recovery, involves reducing the moisture content in the residual material—known as digestate—after anaerobic digestion. This process not only aids in managing digestate but also has implications for nutrient content and emissions. Awiszus et al. delved into the investigation of the digestate drying process and its impact on nutrient content and emissions. They examined the effect of temperature on nutrient retention and explored the possibility of recovering nitrogen from the exhaust gas. The objective of the study was to achieve both minimal environmental impact from the drying process and maintain the digestate nutritional value [34].

The researchers discovered low concentrations of CH_4 and CO_2 in the exhaust stream. The ammonia concentration was considerably higher, at 183 mg/m^3. To address this issue, an ammonia scrubber was employed to capture and recover ammonia emissions. The scrubber successfully reduced ammonia concentrations by 94 %, reaching a level of 11 mg/m^3 NH_3 [34]. A significant challenge faced by many facilities worldwide is the high ammonia content in the AD liquid centrate. This issue needs to be addressed, possibly through the implementation of ammonia recovery technologies or the development of methods to reduce ammonia concentrations. The findings of this study suggest that the digestate drying process can be optimized to minimize emissions while preserving nutrient content. Further research could explore different drying techniques, operating conditions, and emission control technologies to enhance the sustainability and efficiency of digestate drying processes. The potential applications of recovered ammonia in agriculture or other industries could be investigated to promote resource recovery and circular economy principles.

5.5. Integrated biorefinery

An integrated biorefinery is a holistic system that involves the conversion of biomass into a spectrum of value-added products. An integrated biorefinery is a holistic system that involves the conversion of biomass into a spectrum of value-added products, supported by the application of green solvents in biorefineries utilizing lignocellulosic biomass as feedstock [106]. By treating digestate as feedstock for the production of various value-added products, such as hydrolytic enzymes (cellulases, proteases), biosurfactants (sophorolipids), and biopesticides (*Bacillus thuringiensis*), this process can be incorporated into a sustainable biorefinery (Cerda et al., 2019) [107]. Barampouti et al. explored alternative methods for nutrient recovery from digestate, highlighting the significant variability in the composition of digestate: N ranging from 1.6 to 21 % (in dry matter), and P ranging from 0.1 to 3.5 % (in dry matter). The authors proposed a concept for an integrated biorefinery that would produce bio-based products for the supply chain [1].

The concept of an integrated biorefinery could be effective when combining digestate with other processing steps. This valorizes the entire waste stream and reduces environmental impact. It could generate additional revenue streams. This approach not only supports the circular economy principles but also enhances the sustainability of waste management practices.

It is needed to develop and optimize integrated biorefinery concepts that maximize the recovery of nutrients and the production of value-added products. These efforts should include the evaluation of different feedstocks, process conditions, and innovative technologies. It is essential to consider the economic and environmental implications of the biorefinery to ensure its long-term viability and sustainability.

5.6. Recovery of nutrients: techniques and challenges

The recovery of nutrients from digestate incorporates a variety of technical processes, such as vacuum evaporation, stripping, and reverse osmosis. Vacuum evaporation is a method that separates volatile components from a solution by lowering the boiling point of the solvent through pressure reduction. Stripping is another process used to extract volatile components, specifically ammonia, from the liquid phase. Reverse osmosis, a water purification technology, utilizes a semi-permeable membrane to filter contaminants.

The effectiveness of nutrient recovery techniques is not uniform, varying depending on the waste type, processing conditions, and the specific recovery technology employed. Thus, an evaluation from technical, economic, and environmental perspectives is crucial for a comprehensive understanding.

Various studies have looked into the possibility of nutrient recovery through the evaporation of digestate from biogas plants. These evaporation systems employ a combination of techniques, including vacuum evaporation, ammonia scrubbers, stripping, and reverse osmosis, utilizing waste heat from cogeneration units for operation [108].

The fermentation process, particularly acidogenesis and methanogenesis, influence the stability and availability of nutrients in digestate. Nutrient loss can pose challenges in the storage, processing, and application of digestate to arable soil, despite its agronomic value. While dewatering and drying are conventional digestate management methods, other techniques like struvite precipitation, enhanced phosphorus recovery, and absorption have been explored for nutrient recovery and digestate concentration [38].

Yet, these techniques have not found wide adoption due to profitability concerns and their limitation to only partial nutrient recovery. Even though organic matter plays a crucial role in soil fertility, essential components such as potassium, trace elements, and organic carbon are often not recovered. Therefore, it's pivotal to work towards methods that enable comprehensive nutrient recovery, including the enhancement of phosphorus availability in digestate and the retention of ammoniacal nitrogen.

Bolzonella et al. (2018) investigated nutrient recovery from digestate of agricultural residues, conducting technical and economic assessments on a pilot scale. They tested various technologies, including stripping/drying with acidic recovery and membrane separation. Nutrient content in the feedstock varied depending on the type of waste, with N and P concentrations ranging from 1 kg N/ton and 0.25 kg P/ton in food waste to 15 kg N/ton and 1 kg P/ton in chicken manure [56]. These nutrients can be recovered in a condensed form from digestate and transported for direct field application after stabilization.

Post-fermentation digestate is characterized by high levels of CO_2 and NH_3. Ammonia removal can be achieved through stripping by raising the pH to above 10.8. Due to the presence of CO_2 and its associated buffering and acidifying properties through carbonate ions and bicarbonates, raising the pH can be difficult. Thus, CO_2 removal is required prior to ammonia stripping [109].

A method for removing ammonia from food waste digestate has been developed using biogas as a stripping agent. Effective ammonia removal required an increased temperature of 70 °C and an alkaline pH of 10 [110].

Microbial electrochemical technologies (METs) combined with crystallization processes have been employed to recover nutrients (phosphorus) and energy from digestate. Electricity and H_2 generation occurred in Microbial Fuel Cells and Microbial Electrolysis Cells, while phosphorus was removed as struvite ($MgNH_4PO_4{\cdot}6H_2O$) by increasing the pH at the cathode [111]. Crystallization was induced by adding $MgCl_2$ or seawater.

Digestate has been used as a component of algae culture medium. Undiluted digestate inhibits algae growth, but dilution by 10–30 times makes it a useful growth medium. Factors that can inhibit algae growth after fermentation include turbidity, ammonium ions, anaerobic bacteria metabolites, and toxic metal ions. Pretreatment of digestate with activated sludge has proven to be an effective method of conditioning digestate for valorization into a suitable medium for algae cultivation [74].

Algae grown in such a medium can assimilate nutrients from the digestate, resulting in the production of algal biomass that can be harvested and processed for various applications, such as biofuel production, animal feed, or even as a source of high-value compounds like antioxidants and omega-3 fatty acids [40]. The utilization of digestate in algae cultivation not only provides a sustainable source of nutrients for algae growth but also contributes to the circular economy by recycling waste materials and minimizing environmental impacts.

5.7. Microbial Electrochemical Technologies and nutrient recovery

Microbial Electrochemical Technologies (METs), encompassing techniques like Microbial Fuel Cells (MFCs) and Microbial Electrolysis Cells (MECs), utilize bacteria to convert chemical energy into electrical energy, or vice versa. These technologies show potential for various applications, including energy generation, waste treatment, and nutrient recovery from waste streams such as digestate.

When coupled with crystallization processes, METs can recover nutrients and energy from digestate. MFCs generate electricity, while MECs produce hydrogen, both harnessing the metabolic activities of microorganisms [112]. An effective method for phosphorus recovery from digestate is to increase the pH at the cathode and precipitate struvite ($MgNH_4PO_4{\cdot}6H_2O$), a valuable slow-release fertilizer [111]. This crystallization process can be facilitated by adding $MgCl_2$ or seawater, supplying the necessary magnesium ions for struvite formation [113].

5.8. Digestate for algae cultivation: opportunities and challenges

The use of anaerobic digestate in algae cultivation presents a sustainable nutrient source, contributing to a circular economy. However, certain challenges exist. Undiluted digestate may inhibit algae growth due to high turbidity, ammonium ions, metabolites of anaerobic bacteria, and toxic metal ions. Thus, applying suitable pretreatment processes, like dilution or conditioning with activated sludge, is essential to effectively utilize digestate [74].

Algae grown in appropriately treated digestate can assimilate nutrients, yielding algal biomass that can be processed for diverse applications, such as biofuel production, animal feed, or as a source of high-value compounds like antioxidants and omega-3 fatty acids [40,114]. The integration of digestate in algae cultivation not only offers a sustainable nutrient source but also promotes waste recycling and minimizes environmental impacts.

6. Soil fertility: the impacts and management of anaerobic digestate in agriculture

Soil fertility is influenced by various factors including the content of organic matter, nitrogen mineralization, microbial activity, pH, texture, temperature, humidity, and oxygen concentration [115]. It is well-documented that farmers frequently struggle with nutrient balance when utilizing organic, raw fertilizers. This imbalance often results in nitrogen losses to the environment. Consequently, it is essential to develop appropriate doses of various types of biowastes applied to the soil, considering the plants' nutrient needs, in order to maximize yields and minimize nutrient losses to the environment [115].

Researchers conducted a brief study to ascertain the presence of various nitrogen forms in the soil post-digestate addition. The parameters of N mineralization in the post-fermentation mixture were assessed, and its availability to plants was determined. The fermentation process utilized feedstock comprising cattle slurry, silage maize, and hay, leading to the confirmed presence of organic and ammonium nitrogen. The following digestate doses were applied in terms of N: 0, 38, 75, and 150 mg N/kg of soil (equivalent to 0, 90, 180, and 360 kg total N/h) [116].

The fertilization potential of digestate is associated with the presence of organic carbon, phosphorus, and potassium. After applying solid and liquid digestate to the top soil layer (0–40 cm), the fertility category increased from high (200–300) to very high (>300 mg/kg) P_2O_5, using nitrogen doses in digestate form: 170 kg/ha N, which increased the N content five-fold. Digestate has been demonstrated to positively impact soil quality, fertility, mobile humic acid content, soil durability, and sustainability [117].

These findings suggest that the appropriate use of digestate as an organic fertilizer can enhance soil fertility, improve crop yields, and contribute to sustainable agricultural practices. Careful consideration of application rates and digestate forms is crucial to prevent over-fertilization, which might result in adverse environmental consequences like nitrogen leaching and greenhouse gas emissions. Implementing best management practices and incorporating scientific knowledge can help maximize the benefits of digestate use in agriculture while minimizing potential environmental risks [118].

6.1. Why should unprocessed digestate not be applied directly to the soil?

Anaerobic digestate is composed of semi-degradable organic matter, microorganism biomass, and inorganic compounds. While direct application of digestate to the soil is practiced, it can lead to soil degradation and secondary environmental contamination [58]. When using digestate for agricultural fertilization, it is necessary to monitor the risk of nutrient leaching, particularly at the beginning of the growing season [6].

Studies have revealed that untreated digestate can cause severe phytotoxicity. Research by Cucina et al. (2018) found no negative effects on soil microflora. Comparative studies with compost obtained from similar feedstock showed that compost (unlike AD) had a beneficial effect on germination and plant growth [119].

It is essential to determine the agrochemical properties of digestate from agricultural and agroindustrial raw materials to preliminarily assess its fertilizer value. Although digestate has fertilizing potential due to its concentration of ammonium nitrogen, it also contains components that exhibit phytotoxic properties, such as the presence of microorganisms, salinity, toxic element content, and low bioavailability of fertilizer nutrients, as they are trapped in organic matter [58].

Two primary strategies have been developed for digestate management: 1) Conditioning, which involves obtaining standardized solid and liquid fertilizers, and 2) Removal of fertilizer and organic components, allowing the liquid residue to be discharged into the sewage system. This results in a purified liquid, composted solids used as fertilizer, and a concentrated mineral fertilizer. To facilitate phase separation, additives, flocculants, and precipitants are used. The process must be economically viable (energy and chemical inputs). Fertilizer nutrients can be recovered by membrane techniques such as nanofiltration (NF), ultrafiltration (UF), and reverse osmosis (RO). This produces a concentrate of fertilizer nutrients and water. Waste heat from the biogas plant can be used for evaporation. Reduction of nitrogen from digestate can be achieved by ion exchange, ammonia stripping, or struvite precipitation [84].

Digestate is applied to the soil using the same machinery as for slurry or manure. Farmers should be aware of the nutrient content of the digestate to successfully include it as part of a comprehensive fertilization plan. Compared to slurry, digestate has greater soil penetration ability due to its homogeneity and improved flow properties. To minimize nutrient losses, certain rules have been developed: application at the beginning of the growing season or during heavy rainfall (as drought increases nitrogen losses); digestate should not be spilled or splashed, and it should be applied by pipes or injection into the soil [84,120,121].

To prevent environmental contamination, digestate should be used in the spring and applied to farmland near the biogas plant to reduce transport costs. Separation of digestate into different fractions should also be considered, as these fractions possess distinct properties. The liquid fraction contains potassium (K) and nitrogen (N), while the solid fraction contains phosphorus (P) and fiber. The solid part can undergo composting and can then be used as a soil amendment [120].

The quality of digestate should be evaluated based on pH, dry matter content, organic matter and nutrient content, homogeneity of the composition, health and safety issues, cleanliness (absence of physical contamination like glass or plastics), sanitation (absence of undesirable and pathogenic microflora), and the absence of chemical contamination (organic and inorganic). The quality of digestate is closely related to the quality of the raw material. This highlights the need for technology adaptation to meet fertilizer requirements and the implementation of digestate certification systems in practice [60,71].

Some studies confirm that digestate is biologically unstable, and excessive application leads to water contamination, resulting in eutrophication. Excessive doses of digestate can cause pollution of ground and surface water (nutrient leakage), changes in soil structure and microflora, changes in vegetation populations, increased ammonia, methane, and odorous gas emissions, the presence of insects (e.g., flies), and risk of pathogen penetration into the environment [122]. Due to its high water content and low stability, digestate is challenging to transport and store, reducing energy recovery in thermal processes [77].

The effect of digestate on the soil, as well as its fertilization value, is influenced by factors such as its varying chemical properties, biochemical stability, nutrient content, the type of raw material used, and the specific process undertaken. For example, feedstocks like manure or food waste and processes like thermophilic or mesophilic digestion significantly affect the biochemical characteristics of the resulting digestate. This variability in composition is the primary obstacle in the commercialization of digestate-based fertilizers. Typical parameters of fertilizer value include total nitrogen (N), phosphorus (P), and potassium (K), dry matter, and ratios such as C:N, total ammoniacal nitrogen (TAN), TAN:TN, C:Organic-N, and volatile solids. Studies have shown that none of the raw digestates meet European fertilization standards. It is essential to implement digestate quality standards for fertilization applications, which is crucial for effective digestate management [123]. Direct application of digestate into the soil also leads to the transfer of micropollutants and pathogens [123].

The digestate may contain organic pollutants (phenols, pesticides), pathogenic bacteria (*Escherichia coli, Listeria* spp., *Salmonella* spp.), or antibiotics. These components have an ecotoxicological effect on soil microbial communities and, consequently, soil health [124].

Only a few field trial studies on digestate-based fertilizers are available in the literature. A four-year study with mineral fertilizers as a reference fertilizer was conducted. It is crucial to prevent the accumulation of phosphorus in the soil, as this will cause leaching of phosphorus and nitrogen into groundwater. This problem is addressed by the EU Nitrates Directive, the implementation of which has led to limitations in the doses of fertilizers used, especially organic ones such as manure and unprocessed digestate [125].

The application of digestate has been shown to support soil fertility without reducing crop yield, and research has shown that mineral fertilizers can be successfully substituted with digestate-derived fertilizers [126]. This substitution leads to an increase in phosphorus availability, and consequently, a higher risk of leaching without providing a beneficial effect on crop yields or phosphorus uptake by plants [125]. Therefore, careful management of digestate application is necessary to minimize the environmental risks while maximizing its potential as a valuable fertilizer.

6.2. Ecotoxicological consequences of digestate application

Due to digestate use in soil, its ecotoxicity is primarily studied using earthworm bioassays. Ecotoxicity studies on other organisms are also carried out, including plants (*Lepidium sativum*), aquatic species (*Daphnia magna* and *Artemia* sp.), and luminescent bacteria (*Vibrio fischeri*) [69,127,128].

The impact of digestate on earthworm populations has been studied in both short-term (6 months) and long-term (>2 years) contexts, although most reported works are short-term. The use of higher doses of digestate has been found to be unfavorable for earthworm populations, reducing their numbers by 32–60 % compared to other organic materials. This may be attributed to the high ammonium content and low organic matter charge in the digestate [62].

In the majority of digestates derived from various materials, the nitrogen (N) content is similar to that of the raw material, although the ratio of ammonium N to total N content is higher. This is related to protein degradation, which increases the proportion of ammonium N by 15–30 %. Total ammonium N consists of nonionized NH_3 and ionized NH_4^+, which are in equilibrium as a function of pH and temperature. NH_3 is more toxic to earthworms than NH_4^+. Therefore, it has been suggested that digestate from food sources exhibits higher earthworm ecotoxicity than livestock slurry due to its higher pH [129].

To better understand the ecotoxicological consequences of digestate application and minimize potential negative impacts on the environment and soil biota, more long-term studies are needed to evaluate the cumulative effects on various organisms in the soil ecosystem. It is crucial to optimize the application rates and methods for different types of digestates [58,117]]. By doing so, it will be possible to harness the fertilization potential of digestate while minimizing its ecotoxicological consequences.

6.3. GHG emissions after digestate application

Another environmental concern associated with applying raw digestate directly to farmland is the loss of nitrogen, contributing to greenhouse gas emissions. Nitrogen losses occur from digestate obtained from food waste, amounting to 40 % of total nitrogen, and digestate from animal slurry, accounting for 30 % of total nitrogen (with a higher share of ammonium N than in untreated slurry). Most of the nitrogen losses occur within 6 h after application. In comparison to compost obtained from the same feedstock, the emission of nitrogen from digestate is significantly higher [130].

When designing global digestate management strategies, the environmental burden of direct soil application should be considered to determine the environmental fate of pollutants and GHGs, such as NO_2, NH_3, CH_4, and N_2O. To accurately assess these emissions, the following parameters need to be measured: 1) emissions from surface application of digestate quantified for business-*as*-usual (BAU) scenarios, and 2) environmental burden minimization potentials for three mitigation measures, including digestate from) mixed waste) soil-incorporated, and) post-methane. The use of processed digestate has shown significant potential to reduce ammonia, methane, and nitrous oxide emissions [131]. This finding has important implications for addressing climate issues and mitigating environmental pollution.

To maximize nitrogen utilization by plants, minimize environmental losses, and further reduce GHG emissions, it is crucial to develop best management practices for digestate application, explore additional research and innovative approaches such as optimizing the timing and method of digestate application, utilizing advanced processing techniques, and tailoring application rates to specific crop requirements [58,117]. By doing so, it will be possible to harness the benefits of digestate as a fertilizer while reducing its environmental impact.

6.4. Agronomic properties of raw AD

There are various studies, such as [132–134], that provide concrete examples of how digestate can improve soil fertility. It also has a beneficial effect on how plants deal with biotic and abiotic stress, thus improving plant resistance and health. As a result, it can have a beneficial effect on the yield-generating capacity of plants and the quality of agricultural crops. The content of macro and micronutrients in plant tissues has been shown to increase after digestate application [91].

Raw digestate, depending on the type of raw material used, can sometimes be utilized unprocessed as a natural fertilizer, each having different efficiencies. Natural fertilizer - comes from farm animals (slurry, manure); it must be mixed with the soil; prohibition of soil application with no vegetation cover when the terrain slope >10 %. Organic fertilizer is made from organic materials; it does not have to be mixed with the soil. The method of digestate soil application, which is most commonly managed with the R10 rule that includes treatments beneficial to agriculture and the environment carried out on the soil surface. It is influenced by several factors: 1) the method of digestate processing, 2) the species of cultivated plants, 3) the date of application, and 4) the impact of different treatment methods on the nutrient content of the digestate [91]. On the surface of the field, sprinkling equipment and spreaders of liquid manure. Sprinkling machines can be employed if digestate contains <5 % dry matter. Alternative digestate applications include energy materials, and biofertilizers [91].

The effect of fertilizing fodder plants with digestate was investigated, taking into account the yield, utilitarian properties of plants, and soil properties: ryegrass, pea, and clover. The effect of increasing organic carbon in soil was obtained by 14 % as compared with mineral fertilizer and 8 % in relation to the negative control.

The European Nitrates Directive and other regional legal regulations impose restrictions on the annual maximum dose of soil nitrogen in the amount of 170 kg of nitrogen per hectare of soil, affecting the practical use of digestate [135]. For effective global digestate management and planning the production of digestate-based fertilizers, Life Cycle Assessment (LCA), Ecological Risk Assessment (ERA), and economic analysis are necessary to compare the environmental effect of the application of unprocessed digestate with the digestate processed into fertilizers using different valorization methods [136]. This can be done using ecotoxicological tests using the matrix-based approach. Such tests can be performed using the direct and indirect approach by various living organisms: aquatic organisms, *Lepidium sativum*, earthworms (e.g., *Eisenia fetid)*, luminescent bacteria (*Vibrio fischeri*), and plant bioassays (*Artemia* sp. and *Daphnia magn)*. Most of these tests showed a clear dose-effect relation. The application of 15 % m/m of digestate was found to be the least toxic for individual species of living organisms [137].

In the development of all new technologies, including those based on secondary raw materials, an environmental assessment is essential to make the best use of the LCA methodology. It is necessary to develop a field trial program to quantify the agronomic value of the digestate, considering possible limitations in its application, such as specific periods or crops where its use is not recommended. It is proposed to use 5 doses of digestate tested for the calculation of uptake of N from perennial ryegrass and yield, which is a measure of bioavailable nitrogen [138].

Five municipal waste digestates (feedstock for AD, the following waste: food, organic solid, a mixture of activated sludge, and vegetable) were agronomically tested. After using all fertilizers, a 5–30 % higher growth of ryegrass was observed, compared to the reference mineral fertilizer (dose converted to N). The highest agronomic value was found in digestate from organic fraction and food waste, calculated as the availability of fertilizer nutrients and the low content of toxic elements. Digestate from fermentation of activated sludge had a higher level of heavy metals and was characterized by a lower nitrogen availability to plants, so digestate based on excess sludge had a low fertilizing value

[139]. The quality of digestate, as per European quality criteria, is evaluated by parameters such as pH, organic matter, and heavy metal content, and quality tests of digestate fertilizers were conducted using the germination index (GI) as a measure of the agricultural use of the digestate [21]. Tables 4 and 5 report agronomic properties and characteristics, along with a list of the negative consequences of digestate soil application. Fig. 2 characterizes feedstock and fertilizer products in terms of agronomic characteristics and value.

Table 4 explores anaerobic digestate derived from organic waste, its characteristics, benefits for plants, environmental impact, and use cases. Key to understanding its potential as an organic-mineral fertilizer are the interactions between parameters such as the carbon to nitrogen ratio (C:N) and moisture content. A high C:N ratio slows decomposition and nutrient release, which can be further hindered by low moisture content that suppresses microbial activity. This balance impacts the digestate efficacy as a fertilizer. These parameters also pose implications in digestate management. For example, excessive heavy metals could lead to environmental risks, including soil contamination and bioaccumulation in plants, affecting food safety. Variations in the C:N ratio, influenced by feedstock type and operational conditions, can alter nutrient release, thus impacting fertilizer effectiveness.

While our understanding of digestate management has improved, gaps remain. For instance, detailed correlations between feedstock type, operating conditions, and digestate quality need further exploration. Inconsistencies between regulations and studies concerning acceptable parameters such as heavy metal content also require additional investigation. The synthesis of this information prompts new ideas and improvements. Refining measurement methods for parameters like the C:N ratio and heavy metals could enhance data accuracy. Developing techniques to manage and adjust these parameters could optimize digestate's utility as a fertilizer. Exploring how parameter adjustments might improve digestate applications in areas like pest management, reforestation, and bioenergy production could also be beneficial.

Table 5 outlines the risks, challenges, and management considerations inherent in the utilization of digestate, a by-product of anaerobic digestion. The information presented indicates a multifaceted relationship between the digestate's source, treatment, and application, and the subsequent effects on plant growth and environmental impact. For instance, variability in the feedstock and anaerobic digestion conditions can result in inconsistent nutrient content in the digestate, and these variations can interact with the presence of contaminants such as heavy metals and pathogens. These factors pose significant challenges to the safe and effective use of digestate as a soil amendment. The data suggest that exceeding the acceptable limits of contaminants, like heavy metals, may lead to soil pollution and potential food chain contamination. Variability in the nutrient content, particularly the carbon to nitrogen ratio, could also influence the effectiveness of digestate as a fertilizer. These observations underscore the need for careful monitoring and strict adherence to regulatory frameworks in digestate management.

Despite extensive research, several knowledge gaps remain. While many studies highlight the potential risks of heavy metals and pathogens, a consensus on the acceptable limits for these contaminants in different contexts is still lacking. There is also scant information on how non-biodegradable and hard-to-degrade compounds in the digestate could affect its usability and environmental impact. Future research should aim to fill these gaps to ensure the safe and effective use of digestate.

Considering the challenges associated with contaminants and nutrient content variability, there is a clear need for innovative solutions in digestate management. Techniques for more accurate measurement of contaminants and nutrient content could improve safety and effectiveness. New strategies to manage or adjust these parameters, such as

Table 4
Overview of digestate properties, characteristics, and agronomic applications: a summary of key studies.

Subsections	Digestate Properties & Characteristics	References
Source and Characteristics of Digestate	Derived from various types of organic waste, including kitchen waste and animal manure. The feedstock selection is flexible.	[35,140]
	The digestate is characterized by its pH, organic matter, and heavy metal content. These properties can be controlled and modified. The dewaterability of the digestate can be improved by understanding its relationship with extracellular polymeric substances (EPS).	[26,54]
	The composition of the digestate is influenced by the types of feed and the operating conditions of the digestion process. The feedstock type significantly impacts the quality of the digestate. There is potential for nutrient recovery from digestate through microbial electrochemical technologies (METs).	[2]
Nutrient Content and Benefits for Plants	Digestate provides nutrients beneficial to plant growth, including elements like Nitrogen, Phosphorous, and Potassium.	[4,35]
	Digestate offers readily available fertilizer nutrients which can be efficiently absorbed by plants. It also enhances nitrogen cycling processes in the soil.	[58,123]
	Digestate enhances nutrient availability in bio-based fertilizers and improves nutrient release profiles. Process simulation and modeling can enhance understanding of the digestion of complex organic matter.	[79,85]
	Digestate assists in nitrogen removal from digested slurries and aids in nutrient cycling and management. Technologies for nutrient recovery from waste streams hold promise.	[69,131]
Impact on Soil and Environment	Digestate influences soil properties through its chemical composition. It can improve soil structure and water holding capacity and aids in nutrient cycling.	[1], 36]
	Digestate influences nutrient availability and crop growth. Crop performance often improved with digestate application. Digestate has a significant impact on total and active prokaryotic communities in soils.	[71,112]
	Digestate enhances soil quality and productivity when co-composted with poultry litter biochar. Synergistic benefits are observed with co-composting.	[28]
	Digestate has potential use in phytoremediation to immobilize heavy metals in contaminated soils.	[30,35]
Experimental Applications and Use Cases	The value of digestate as a fertilizer has been tested through chemical analyses and growth experiments. It has been found to be an effective alternative to traditional fertilizers. There is a possibility of utilizing digestate as a slow-releasing fertilizer for sustained nutrient release.	[141,142]
	Digestate has been used in growth experiments to demonstrate its efficacy. It results in increased crop yield and demonstrates potential for synergistic benefits with co-composting.	[75,143]
	Digestate has been utilized in soil mineralization tests to understand nutrient cycles. It helps in improved understanding of nutrient dynamics in soil and aids in recovery of ammonia nitrogen from industrial wastewater treatment.	[4,49]
	Experimental applications show digestate's ability to support reforestation efforts.	[35,40]
	Digestate could act as a substitute for peat in horticultural substrates.	[56,57]
	Digestate aids in pest management by acting as an effective component in the production of biopesticides.	[11,51]
	There are opportunities for biochar and digestate combinations to improve soil conditions and crop yields.	[35,144]
	Digestate can be used for algae growth in biofuel production. Integrated systems for waste treatment and bioenergy production show promise.	[6,104]

Table 5
Digestate risks, challenges, and management considerations: Insights from key studies.

Subsections	Digestate Risks & Challenges	References
Variability and Management of Digestate	Variability in residual materials due to different waste sources could lead to inconsistent nutrient content.	[35,123]
	Strict regulatory frameworks necessitate careful digestate management. These regulations pertain to the handling, storage, and application of digestate.	[85,142]
	Careful monitoring and control of feedstock and digestion conditions is required to maintain consistent nutrient content.	[30,71,112,145]
Risks of Contaminants	Raw digestate may contain harmful biological and chemical pollutants, including pathogens and heavy metals.	[71,112]
	There is a risk of ammonia, heavy metals, phytotoxic compounds, and pathogens in digestate.	[69,86]
	Some pathogens may survive the anaerobic digestion process. Therefore, safety regulations need to be strictly followed.	[33,115]
	Careful monitoring of heavy metal content is required to prevent soil pollution and potential food chain contamination.	[6,104]
Impacts on Plant Growth	Unstable digestate could impede seed germination and plant growth.	[1,140]
	High doses of digestate may inhibit seed germination and plant growth. Therefore, application rates need to be carefully managed.	[2,56]
	Specific treatment may be needed to reduce pathogen content in digestate. There is a risk of plant disease transmission.	[30,111]
	The ability of digestate to support reforestation could be dependent on the tree species. The type of vegetation can influence mineralization patterns and needs to be considered.	[11,51]
Challenges and Solutions	The presence of non-biodegradable and hard-to-degrade compounds in digestate can be problematic.	[77,124]
	The type of vegetation can influence mineralization patterns. This needs to be considered while applying digestate.	[15,130]
	Simplified ammonia stripping technique is required. Technology improvements are needed for efficient nitrogen recovery. Roadmaps for setting up an optimal treatment train can aid in overcoming this challenge.	[82]
	The effects of digestate can vary under different irrigation regimes. Irrigation practices impact digestate efficacy. Therefore, optimizing irrigation practices is essential to maximize the benefits of digestate application.	[131]
Emission and Odor Concerns	There is potential for greenhouse gas (GHG) emissions due to undigested organic matter in digestate.	[13,146]
	There is potential for odorous emissions from digestate. Strict regulatory frameworks necessitate careful digestate management to control these emissions.	[113,141,143]

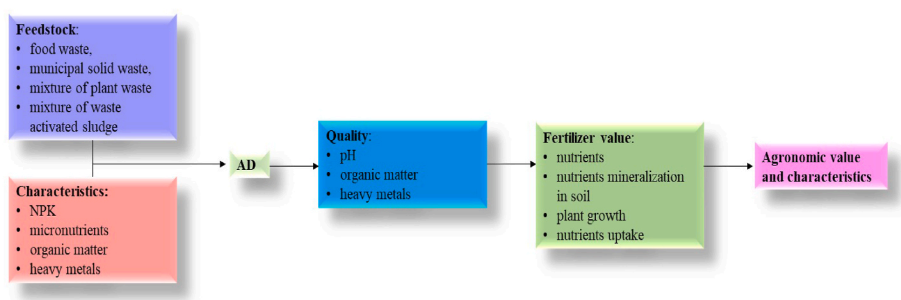

Fig. 2. Characteristics of the value of feedstock and fertilizers in the context of agronomic value and characteristics.

advanced treatment methods or digestate refinement techniques, could enhance its viability as a sustainable fertilizer alternative. Understanding and optimizing irrigation practices, as well as developing efficient techniques for nitrogen recovery, could also maximize the benefits of digestate application.

Based on the studies by Serrano et al. (2020), Jin et al. (2022), and Kataki et al. (2017) [7,35,71], anaerobic digestion digestate holds potential for soil amendment due to its agronomic properties and characteristics. These involve aspects such as plant growth promotion, influence on soil chemical properties, availability of fertilizer nutrients, findings from growth experiments, and soil mineralization tests. The fertilizer value of the digestate is analyzed through chemical analysis of nutrients, soil nitrogen mineralization tests, and short-term ryegrass growth experiments.

There are several adverse effects linked to the direct application of raw digestate to the soil. The digestate may carry biological and chemical pollutants that can negatively impact soil health and productivity. Organic matter that remains unprocessed within the digestate could potentially contribute to the release of greenhouse gases, generating approximately 125 g of CO_2 equivalent for each kg of digestate. The digestate might house compounds that resist degradation or are impossible to break down, which comprise substances like lipids, lignins, residues from farming activities such as lignocellulose, and constituents of municipal waste including sand, plastic, glass, metallic elements, rubber, and ceramics.

The application of digestate to soil also carries certain chemical risks. These include the presence of ammonia, heavy metals, phytotoxic compounds, and pathogens, particularly when the raw material includes manure and sewage. Unstable digestate can adversely impact seed germination and plant growth, highlighting the need for appropriate management and treatment of digestate before its application as a soil amendment.

6.5. Agronomic guidelines

The development of guidelines for the agronomic management of digestate is critical and should include details on how local and broader regulatory frameworks impact its practical use, more information on potential soil contamination consequences from heavy metals and other harmful compounds. Sould take into account the optimization criteria necessary for digestate nutrient recovery strategies [82]. The quality of digestate-based fertilizers can be determined through various indicators, including extractable nutrients, crop yield, and nutrient balances, which help to evaluate the fertilizing value of digestate [125].

The agronomic properties of digestate obtained from animal waste may differ from those obtained from food waste [70]. The method used to process the digestate can affect its quality and agronomic properties. For example, processed digestate has been shown to reduce ammonia, methane, and nitrous oxide emissions [131].

Therefore, the development of agronomic guidelines for digestate should take into account various factors related to the source of the digestate and the method of its processing. These guidelines will help promote the sustainable use of digestate as a valuable agricultural resource while minimizing its potential negative environmental impacts.

7. Legal aspects

The European Union's Green Deal establishes a roadmap for making the EU's economy sustainable. Aiming to reduce GHG emissions and promote circular economy, the Green Deal aligns well with digestate valorization, as it helps reduce waste and promote renewable resources usage. Recognizing digestate valorization's potential, the EU has developed policies to encourage its use, including nutrient recovery promotion and AD-based fertilizer standards development [7,107].

According to Stürmer et al. (2020), there are currently 28,000 biogas plants in operation in Europe, and this number is expected to increase significantly in the coming years, highlighting the growing interest in biogas as a renewable energy source [147]. Approximately 80 % of these biogas plants use farm waste as their primary input material [67].

The legal complexities of using digestate as a fertilizer require consideration of various factors, including digestate safety, compliance with organic fertilizer criteria, and the regulatory framework for nutrient recovery products. The development of standardized testing methods, quality assurance procedures, and regulations is paramount. The EU's Fertilizing Products Regulation (FPR) is a crucial aspect of the legal framework governing the use of digestate. It defines minimum requirements for CE-marked products and includes provisions for testing methods, product labeling, and quality assurance. This regulation is intended to facilitate the development of a competitive market for nutrient recovery products, including digestate, which in turn will contribute to the transition towards a circular bioeconomy. The potential for valorizing digestate and construction of new technological lines for acquiring fertilizers are both largely influenced by legal limitations and require a unified legal framework for processed biological waste. While 125 kWh per metric ton (Mg) of energy and 100 kg per metric ton (Mg) of fertilizer can be recovered from the feedstock, not all types of digestate can be used for agricultural applications [12]. The processing of digestate causes it to no longer be considered as waste under European law, and its practical agronomic use becomes possible [123]. Digestate obtained in agricultural biogas plants is classified as hazardous waste, making its management difficult. This is due to the high probability of increased content of toxic elements and pathogenic bacteria [15].

Matching legislative requirements for digestate with actual technical parameters is crucial. The digestate should be safe in terms of hygiene and should contain a required level of nutrients. The digestate does not meet the criteria for organic fertilizer due to its noncompliance with organic carbon content and macronutrient levels. The content of heavy metals usually does not exceed the limits, unlike the hygienic parameters. The digestate can be commercialized according to the European fertilizer product categories, such as PFC 3 (organic soil improver), PFC 4 (growing medium), and PFC 6 (organic, non-microbial plant biostimulant). At present, international trade of digestate is not possible due to the lack of standardized quality and traceability of the digestate [49,112]. The circular economy model emphasizes the efficient use of resources and waste reduction. This necessitates a shift in the current legal framework towards a more sustainable approach [85].

A review of the U.S. legal framework for digestate suggests that current federal and state regulations inadequately promote its reuse as a fertilizer. A lack of standardized testing procedures and quality control methods results in the limited use of digestate as a fertilizer in the US. Therefore, there is a need for uniform guidelines and regulations for the safe and beneficial use of digestate in agriculture [141].

Fig. 3 provides an overview of the quality standards for solid and liquid fertilizers produced from anaerobic digestate according to European legislation. The new Fertilizer Product Regulation has classified digestate-based fertilizers under Component Material Categories (CM) 4, 5, and possibly 3. CMC 4 refers to biogas digestate based on plant raw materials, while CMC 5 refers to biological waste from the segregation of waste, animal origin, categories 2 and 3, fragments of living organisms, or living organisms. This category excludes mixed municipal waste, industrial sludge, sewage sludge. The input of raw material for CMC 4 and 5 is subject to Regulation (EU) 142/2011, which specifies temperature and fermentation/composting time requirements that should be at least 20 days [141]. The digestate derived from CMC 5 should contain <6 mg/kg PAH16, <5 g/kg DM macroscopic impurities of DM (glass, plastics, metal >2 mm), 3 mg/kg each, and a maximum residual methane potential of <0.25 l/g VS for CMC 4 and 5 [85,123].

Authorities have exempted digestate from registration under REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) to improve the product marketability [49]. The quality tests of digestate-based fertilizers should comply with the European fertilizing product standards. These tests include the evaluation of total nitrogen,

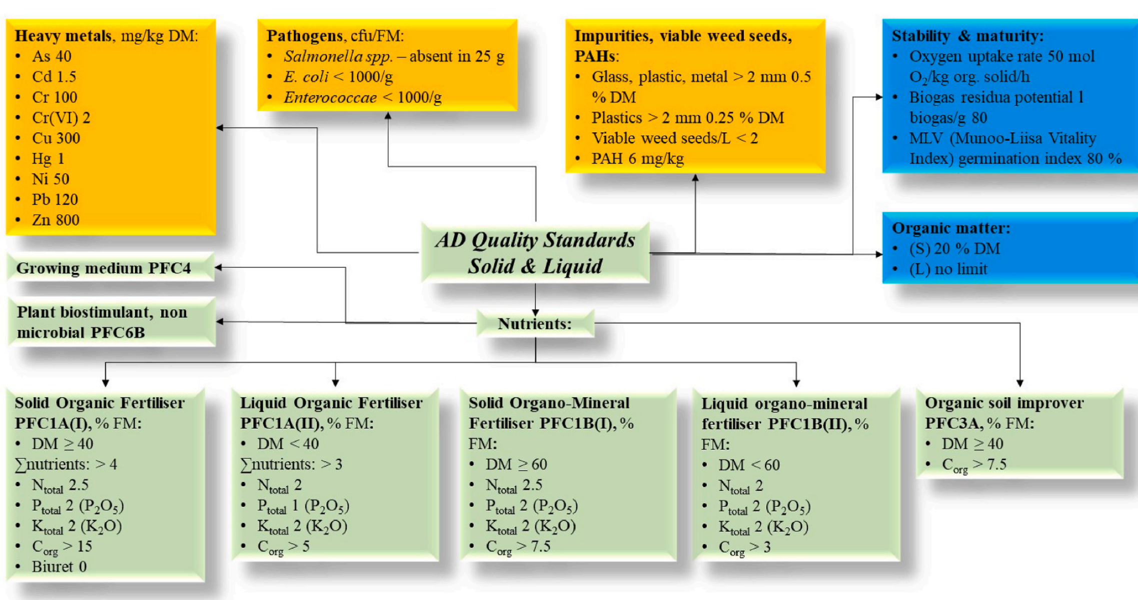

Fig. 3. Quality standards for solid and liquid fertilizers based on anaerobic digestate [88,147–151].

phosphorus pentoxide, and potassium oxide, heavy metal content, and organic pollutants, among others [143]. The compost and digestate used for agricultural purposes must comply with the quality standards and legislation defined by each country [142]. In Ireland, for instance, the quality of compost and digestate is regulated by the National Standard of Composting and the European fertilizer standards (EN 13,933–1) [85].

8. Commercialization of organo-mineral fertilizers based on digestate

An analysis of the marketing strategies involved in introducing digestate to the market was conducted. They highlighted the need to establish effective management methods for digestate, a form of biogas waste, which holds importance for the advancement of biogas production. The authors identified a considerable commercialization potential for digestate-enriched and dehydrated products, despite persisting negative perceptions of digestate as a fertilizer ingredient among customers. Consequently, they emphasized the necessity of educating farmers, the potential recipients of these products, to enhance market acceptance. Their market research underscored the need for careful investigation of digestate marketing strategies to successfully position this category of products within the market [152].

Organic and mineral fertilizers produced from digestate have commercial potential. The market for digestate-enriched and dehydrated products is promising, as there is a niche in the market for products that are more concentrated in nutrients than raw digestate [152]. Market research shows that customers continue to perceive the feedstock for the fertilizer to be the digestate in a negative way. Thus, there is a need to educate farmers, as potential recipients of digestate-based organic fertilizers, to increase their acceptance of this type of product. It is also essential to investigate the marketing possibilities of digestate to successfully position this class of products on the market [122,146,153].

9. Future research and challenges

In the future, it is essential to introduce legislative changes. These changes would make the commercialization of organic-mineral fertilizers based on digestate more economically feasible. Clear specifications should be established regarding the feedstocks that can be used to obtain digestate valorized to fertilizers, as well as the parameters of the digestate process maturation stage, process temperature), as these factors determine the suitability of the digestate for fertilizing purposes. Another crucial direction is the standardization of nutrient composition in these fertilizers and the development of standard procedures to test agronomic utility. Standardizing research methods will facilitate the comparison of results from different authors and allow for drawing reliable and meaningful conclusions.

Considering recent research, it is necessary to investigate the impact of digestate and digestate-based fertilizers on the bioavailability of nutrients for plants, soil microorganisms, and soil health in general. Challenges related to the comprehensive chemical quantitative analysis of various pollutant indicators in the digestate should also be addressed. The digestate is a complex organic matrix containing microplastics, brominated hydrocarbons, flame retardants, and others.

Digestate can be a component in the formulation of organic-mineral fertilizers. digestate processed through various methods, such as stabilization, conditioning, or thermal processes, can be incorporated into fertilizers. Organic-mineral fertilizers exhibit optimal agronomic properties when composed of materials generated through different processes. For instance, digestate may be conditioned with a mixture of sulfuric and phosphoric acid. The resulting digestate requires neutralization and composition correction, preferably by adding ashes, such as those from digestate thermal processing (e.g., fly ash) containing oxides of Ca, K, Mg, Zn, Mn, etc. Additional formulants can then be introduced to ensure the product meets the legal requirements for organic-mineral fertilizers (NPK 2-2-2% and Cu, Mn, Zn, Fe 1000 mg/kg). It is advantageous to incorporate granulation additives, such as clutan, Zn, or Cu lignosulfonates, to achieve granules with high mechanical strength, which is essential for transportation and application of granular fertilizers.

Anaerobic digestate, the byproduct of anaerobic digestion processes, presents both challenges and opportunities for waste management, carbon neutrality, and agricultural applications. Current research highlights various strategies for its management and valorization. For instance, Bai et al. (2023) examined alkaline pre-treatment techniques to enhance hydrolysis and methane production, thus contributing to carbon-neutral energy production [154]. Subbarao et al. (2023) emphasized the role of anaerobic digestion as a sustainable technology aligning with circular economy principles [155]. The agronomic value of digestate has also been explored, with Tian et al. (2023) studying the impact of *Myrothecium verrucaria* and MnO_2 on the fertilizer quality of the digestate. Shen et al. (2023) evaluated activated pyrochar to enhance anaerobic digestion performance and microbial communities [156]. Concerns over soil health impact have also been addressed, by van Midden et al. (2023) reviewing the effects of anaerobic digestate on soil ecology [157]. These studies signify the multidimensional potential of anaerobic digestate, opening avenues for its integration into carbon-neutral strategies and its application as a valuable agricultural input.

9.1. Regulatory standardization

The lack of standardized regulations is a significant barrier to the commercialization of digestate-based organic-mineral fertilizers. Policymakers should focus on defining acceptable feedstock types and setting stringent parameters for digestate maturation, including process temperature and pH levels. These guidelines are crucial for ensuring the digestate's suitability for agricultural use and for facilitating market entry [81].

9.2. Pollutant identification and management

The diverse composition of digestate makes the identification of pollutants challenging. A comprehensive chemical analysis is essential for detecting a wide array of potential contaminants, such as heavy metals and microplastics. These contaminants can adversely affect soil health and compromise food safety. Therefore, the development of advanced analytical methods is imperative for ensuring the safe application of digestate in agriculture [158].

9.3. Soil microbiome and nutrient uptake

The impact of digestate-based fertilizers on soil health extends beyond nutrient availability. Future research should delve into how these fertilizers influence the soil microbiome and plant nutrient uptake. Such studies will contribute to a more nuanced understanding of the long-term sustainability and agronomic efficacy of digestate-based fertilizers.

9.4. Public perception and policy impact

Public perceptions of digestate use in agriculture are shaped by multiple factors, such as prevailing policies and awareness initiatives. For instance, in Germany and the Netherlands, favorable policies and educational efforts have resulted in greater acceptance of fertilizers derived from digestate [159]. However, in regions where such support is lacking, public skepticism remains a significant hurdle.

9.5. Advanced treatment techniques

Advancements in technology present novel methods for digestate treatment, including acid conditioning and thermal processing. For instance, conditioning with sulfuric and phosphoric acids can enhance the digestate nutrient profile. Subsequent neutralization and composition adjustment, often involving the addition of thermally processed ashes, are necessary steps to meet legal nutrient composition requirements [160]. Numerous studies, including a research paper by Reuland et al. (2021), have investigated various approaches to anaerobic digestate management [51].

10. Conclusions

Limited attention has been devoted to transforming digestate into a fertilizing product with proven agronomic effectiveness. This paper presents an overview of digestate processing methods, including thermal processes, stabilization, and conditioning. The resulting materials can be integrated into multicomponent organic-mineral fertilizers with compositions tailored to specific cultivated plant species requirements. Practical guidelines are provided from a fertilizer formulation perspective, considering other biowastes in light of applicable laws and waste management principles, prioritizing soil health and increased crop yields.

The geopolitical landscape has forced the European Commission to reconsider its stance on biowaste as secondary raw materials. The increasing production of biogas from diverse sources such as manure and energy crops necessitates legislative changes. These changes aim to facilitate the commercialization of digestate-based organic-mineral fertilizers, ensuring economic viability. An equilibrium must be maintained between the volume of digestate generated and the amount of fertilizer required, aligning with the availability of local arable land. Proper planning for integrated crop and livestock systems at the local level is therefore essential.

Digestate can be used to produce organic fertilizers for marketing purposes. This requires adjustments to their composition and standardization. Digestate possesses promising agronomic properties due to the presence of nitrogen, phosphorus, potassium, and potentially beneficial microflora, such as plant growth-promoting rhizobacteria. Digestate valorization methods should aim to reduce odor emissions, pathogens, and weed seeds. Developing standard guidelines for digestate use is crucial for maintaining biomaterial processing in accordance with closed-economy rules.

Legal provisions allowing the direct soil application of digestate are inconsistent across regions. In some areas, the direct application of untreated digestate to the soil is permitted. The work presented in this review is expected to be information for policy-makers and stakeholders, and enable the implementation of technologies for converting digestate into fertilizers. The results discussed in this paper may help address the commercialization challenges of anaerobic digestate-based fertilizers. Future research should focus on confirming agronomic properties through plant studies, preferably conducted under actual field conditions.

Author contribution

Katarzyna Chojnacka: conceptualization and writing. Konstantinos Moustakas: investigation, supervision.

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No data was used for the research described in the article.

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