


Review

Sludge Composting—Is This a Viable Solution for Wastewater Sludge Management?

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Abstract: Wastewater treatment plants generate significant amounts of sludge, a residual product that is rich in nutrients, usually considered waste, and traditionally eliminated by storage or incineration, methods that are expensive, environmentally damaging, and often unsustainable. Composting is increasingly recognized as an ecological and durable solution for managing biodegradable waste, including sludge resulting from wastewater treatment. The composting of residual sludge usually requires mixing with bulking agents, such as green waste or agricultural residues, to ensure a well-balanced carbon–nitrogen ratio. This mixture undergoes a controlled aerobic decomposition, sometimes followed by post-treatment, resulting in a stabilized final product that is nutrient-rich and pathogen-free and can be used as soil amendment or fertilizer in different agricultural or landscaping applications. By using composting, communities can reduce elimination costs, reduce greenhouse gas emissions, and minimize the environmental impact of sludge management. This paper reviews recent reported experiences in the laboratory regarding full-scale sludge composting, highlighting the particularities of the processes, the influence factors, the quality of the final product, and the environmental and regulatory constraints. Composting is a sustainable and ecological solution for managing wastewater sludge, contributing to nutrient circularity, and minimizing the environmental impact.

Keywords: sludge composting; wastewater sludge management; sustainability



Citation: Manea, E.E.; Bumbac, C. Sludge Composting—Is This a Viable Solution for Wastewater Sludge Management? *Water* **2024**, *16*, 2241. <https://doi.org/10.3390/w16162241>

Academic Editors: Le Fang and Siqi Tang

Received: 10 June 2024

Revised: 27 July 2024

Accepted: 6 August 2024

Published: 8 August 2024



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1. Introduction

The importance of municipal sludge management is broad-based and involves several interconnected concerns, notably environmental, health, and economic. The activated sludge process, one of the most widely used wastewater treatment processes, relies on microorganisms to mitigate environmental problems [1]. Municipal sewage sludge (MSS), a by-product of wastewater treatment, is a complex and potentially polluting material constituted of various components, which are hard to handle and dispose of “as is” without polluting and endangering the environment. The traditional approaches to MSS management have been landfilling, incineration, and agricultural use. However, landfilling or incineration of MSS is increasingly seen as unsustainable due to environmental and health risks [2]. Moreover, the accumulation of contaminants of emerging concern (CECs) in sludge points to the risk to human and ecosystem health [1]. Thus, considerations on the potential environmental, economic, and health impact have translated into regulations that limit the possibilities of landfilling and set thresholds for maximum concentrations of contaminants, thus urging the need for advanced treatment before reuse or disposal [3]. Conventional MSS treatment mainly involves biological processes such as anaerobic digestion and aerobic (endogenous) stabilization to stabilize sludge and reduce pathogens and pollutants [4]. Additionally, anaerobic co-digestion has been shown to increase the production of biogas compared to single-substrate anaerobic digestion, which contributes to the recovery of energy from waste and ensures the principles of a circular economy [5]. However, these processes do not completely eliminate all contaminants, necessitating further treatment to ensure the safe use of the resulting biosolids [6].

The management approach of MSS has shifted from conventional waste disposal toward resource recovery, considering that sewage sludge could be both a reliable resource for energy and nutrients recovery [2]. Moreover, advanced treatment processes, for example, chemical coagulation, have been applied to improve the dewaterability of sludge, aiming to reduce sludge volume and to enhance handling and disposal process [7]. Wastewater and sludge processes are energy-intensive operations; therefore, significant environmental challenges are expected, which have raised the need for life cycle assessments (LCAs) to indicate their environmental improvement potential [8].

In recent years, alternative methods such as pyrolysis, anaerobic digestion, and co-combustion with coal have gained attention. Pyrolysis, for instance, converts sludge into biochar, gas, and oil, significantly reducing its volume and immobilizing hazardous compounds, making it a promising option for both waste reduction and resource recovery [9–11]. The drying and bio-drying of municipal waste to increase the calorific value by reducing the humidity of the waste to approximately 15% is another alternative for sustainable municipal wastewater sludge management, as it offers minimal environmental impacts relative to other waste management technologies [2,12]. Figure 1 presents a schematic diagram to illustrate the various methods of sludge treatment, including landfilling, incineration, anaerobic digestion, and composting.

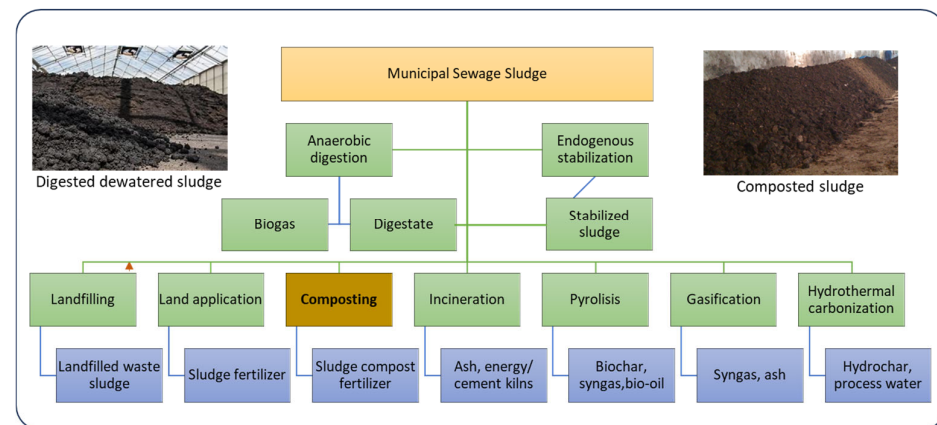


Figure 1. Sewage sludge treatment/disposal/reuse.

The composting of MSS is a prominent process for dealing with the growing amounts of sludge originating from municipal wastewater treatment. The co-composting of MSS with bulking agents such as pumice and expanded perlite has been investigated to improve composting parameters and nutrient bioavailability, creating biosolids that could be successfully used as a soil amendment for ornamental plant production [13]. Composting, in particular with lignocellulosic amendments, can produce stable and mature compost. The stability of the compost and its maturity are influenced by feedstock composition [14,15]. Following wastewater treatment, sewage sludge treatment is required by statutes such as the U.S. Clean Water Act, 503 Biosolids Rule and the European Union's Sludge Directive and Urban Waste Water Treatment Directive to reach a certain quality. This can be a significant expense for wastewater treatment plants (WWTPs) as investments and additional technological efforts are usually required to comply with the minimum quality requirements. The implementation of stricter European Union regulations, for instance, has posed new challenges for European countries, necessitating investments into infrastructure to manage sewage sludge effectively while adhering to the principles of circular economy [16].

The environmental and economic investigation of the sludge treatment processes have proven the benefits of composting, especially when microbial inoculums were added and semi-anaerobic conditions were controlled to improve the nutrient content and reduce the emissions [17]. Moreover, the role of the anammox bacteria in the composting process provides a potential method for nitrogen management and reducing greenhouse gas (GHG) emissions [18]. Anammox bacteria play a crucial role in the composting of sewage sludge

by facilitating the removal of nitrogen, which is essential for maintaining the balance of nutrients and minimizing environmental pollution. These bacteria, which have been primarily studied in wastewater treatment processes, have shown potential in composting due to their ability to oxidize ammonia in anaerobic conditions, thus with the potential of reducing the emission of greenhouse gases like ammonia (NH₃) and nitrous oxide (N₂O) [13]. The presence of anammox bacteria in composting environments, despite the aerobic nature of the process, suggests that they can thrive in microenvironments within the compost where oxygen levels are low, working in conjunction with other microorganisms to enhance nitrogen removal efficiency [13]. This is particularly beneficial as it allows composting at a low carbon-to-nitrogen ratio (C:N ratio) without additional energy input through aeration, as is typically required to maintain aerobic conditions [13].

Bridging the gap to more efficient and environmentally committed WWTP management is possible also due to integrated management approaches that are consistent with International Standards like ISO 14001 [14]. ISO 14001 provides a comprehensive framework for managing environmental impacts, optimizing resource efficiency, and ensuring regulatory compliance. Thus, composting facilities can identify and mitigate environmental risks, such as pollutants and GHG emissions, while promoting sustainable practices and continuous process improvement by adapting advanced technologies and innovative strategies to enhance compost quality and environmental performance. The environmental impact assessment of waste management practices, including sludge treatment, is essential for these practices to achieve a good environmental performance and reach the goals of the circular economy [19]. In sum, to ensure public health safety, environmental preservation, and sustainable development, it is critical to know the state of the practice of MSS management.

This study aims to comprehensively analyze and understand wastewater sludge composting by evaluating current knowledge on sludge management, with a focus on composting. It reviews the environmental, economic, and social advantages and disadvantages of using composting as a sludge management practice. Additionally, the study seeks to identify recent advancements from laboratory to full-scale studies, outline the challenges and limitations of sludge composting, and highlight research gaps that need to be addressed through innovative research to establish composting as a viable, widespread method for sludge management.

2. Composting as a Sustainable Solution

2.1. Common Residual Sludge Management Approaches

Due to environmental, economic, and societal pressures, the methods employed for managing MSS have evolved over the years. The primary traditional approaches to MSS management have been landfilling, incineration, and agricultural use. Table 1 provides an overview of these typical techniques for sludge projects, emphasizing their advantages and drawbacks.

Table 1. Overview of traditional wastewater sludge disposal methods.

Method	Description	Advantages	Disadvantages	References
Landfilling	Disposing of dewatered sludge in a sanitary landfill to protect waste from the environment	Isolates contaminants Well-known solution	<ul style="list-style-type: none"> Landfill volume/Lifetime Potential for groundwater contamination. Leachate generation 	[20,21]
Land Application	Treated sludge that meets specific regulations can be applied to land as a soil conditioner or fertilizer.	Nutrient source for plants Enhances soil structure Reduces disposal expenses	<ul style="list-style-type: none"> Requires close monitoring for contaminants such as heavy metals and pathogens Concerns of public perception Controlled application rates and land types appropriate for sludge utilization 	[22–24]

Table 1. Cont.

Method	Description	Advantages	Disadvantages	References
Incineration	High-temperature burning results in reduced volume and organic destruction	Significant volume reduction (up to 95%) Potential for energy production	<ul style="list-style-type: none"> • High costs • Air pollution control systems required to minimize emissions • Ash residue needs disposal 	[25–27]

Landfilling was a common practice to dispose of sludge by dumping it in certain locations, but it is less and less used because it takes up a lot of space and can contaminate groundwater. Incineration is another traditional approach that reduces the volume of sludge and removes organic pollutants, but it requires preliminary advanced drying to evaporate water content that would otherwise lower combustion efficiency, and if the process is not managed correctly, it can become a source of contamination with gaseous pollutants [25]. The use of sludge in agriculture was the most used method, being preferred for its nutrient recovery potential; however, concerns about potentially high concentrations of contaminants such as heavy metals, pathogens, and emerging pollutants have led to stricter use regulations and, in some cases, even a complete ban on this practice [27]. Despite these challenges, the use of properly treated sludge in agriculture remains a viable option under specific controlled conditions. The changing perspective on sludge, now seen as a resource rather than a simple waste, has led to the exploration of energy recovery methods such as anaerobic digestion and gasification, offering a more sustainable approach to sludge management and resource recovery [28]. In addition, the integration of modern wastewater treatment technologies, such as the use of microalgae and bacteria for nutrient removal and biosorption, presents innovative ways to reduce the environmental footprint of sludge disposal while recovering valuable resources [29].

Composting organic waste transforms it into a value-added product suitable for enhancing soil quality and supporting plant growth. This process involves the aerobic decomposition of organic materials, such as agricultural waste, municipal solid waste, and sewage sludge, under controlled conditions [30]. The fundamental principles of composting revolve around managing factors such as temperature, moisture, oxygen, and the carbon-to-nitrogen (C:N) ratio to optimize the activity of microorganisms that break down organic matter [31]. The composting process is characterized by several phases, starting with the mesophilic phase, where moderate temperatures facilitate the rapid multiplication of microorganisms. This is followed by the thermophilic phase, where temperatures can rise significantly, leading to the breakdown of more complex organic compounds. The process eventually cools and matures, resulting in the stabilization of organic matter and the formation of humic substances, which are crucial for soil health [32,33]. Microbial activity is central to composting, with bacteria and fungi playing dominant roles in decomposing organic matter and suppressing soil-borne pathogens through the production of metabolites such as siderophores and antibiotics [34]. Moreover, composting can significantly reduce the presence of antibiotic resistance genes and other potential health hazards, making the final compost safer for land application [35,36]. The addition of specific inoculants or bulking agents can influence the efficiency and outcome of the composting process, affecting factors like gas emissions, nutrient content, and the mobility of heavy metals in the final product [37,38]. Furthermore, composting not only recycles waste but also contributes to the circular economy by producing a nutrient-rich amendment that can improve soil structure, fertility, and microbial diversity, thereby supporting sustainable agricultural systems.

Composting is a sustainable biological process due to its multifaceted environmental, economic, and agricultural benefits. Composting MSS is a sustainable solution due to its environmental, economic, and agricultural advantages. Composting MSS contributes to the recycling of nutrients, supporting sustainable development and closing the loop in nutrient cycles [6,39]. The resulting product—sewage sludge compost—can be used as a soil

amendment, reducing the demand for chemical fertilizers and enhancing soil quality [39,40]. Recent studies focusing on methods for improving nutrient bioavailability and the slow-release properties of nutrients show promising results when composting SS with bulking agents like pumice and expanded perlite [6]. The use of microbial inoculants and the maintenance of semi-anaerobic conditions during composting further enhance compost quality by increasing humic acids and total nitrogen concentrations while minimizing emissions like NH_3 [3]. Compared to incineration, composting MSS has significantly lower GHG emissions, thus supporting climate change mitigation efforts [41,42]. The integration of composting with other waste management technologies, such as anaerobic digestion, can further optimize the environmental benefits by complementing each other and enhancing overall sustainability [42]. Composting MSS is cost-effective, with lower treatment costs compared to other methods like incineration, and it can generate commercial products like gardening substrates, adding economic value [3,41] (Table 2).

Table 2. Different MSS treatment/disposal methods costs.

Country, Year	Germany, 2016 [43]	Italy, 2015 [44]	Italy, 2020 [44]	EU, 2019 [45]	Different EU Countries [46]	Germany, 2017 [46]	Poland, 2017 [46]	Sweden, 2017 [46]
Composting	230–290 EUR/t			150–310 EUR/t	310 EUR/t		150 EUR/t	
Incineration	280–480 EUR/t	80–90 EUR/t	120 EUR/t	80–438 EUR/t	315 EUR/t	80–120 EUR/t	438 EUR/t	
Agriculture	94–180 EUR/t	50–70 EUR/t	103 EUR/t	25–210 EUR/t	160 EUR/t	8–45 EUR/t	75 EUR/t	100 EUR/t
Landfilling		70–250 EUR/t	202 EUR/t	125–255 EUR/t	255 EUR/t		125 EUR/t	215 EUR/t

The process also aligns with the principles of circular economy and bioeconomy by recovering valuable materials and energy from waste, thus reducing the reliance on non-renewable resources and minimizing the waste sent to landfills [47,48]. Furthermore, composting MSS can improve soil organic matter (SOM) and microbial activity, which are crucial for maintaining soil fertility and productivity in agricultural systems [40,49]. Overall, composting MSS is a sustainable solution that addresses waste management challenges, enhances soil health, reduces environmental impacts, and provides economic benefits, making it a viable strategy for sustainable land management and resource recovery.

Table 3 presents a comparative analysis of composting against established wastewater sludge disposal techniques, with a particular focus on the merits associated with composting.

Table 3. Advantages of composting over traditional wastewater sludge disposal methods [7,12,44,48].

Feature	Composting	Landfilling	Incineration
Volume reduction	Moderate (30–50%).	Up to 90% (through dewatering and drying).	Significant (up to 95%).
Resource recovery	Nutrients in obtained compost.	No resource recovery.	Potential for heat production (recovered during the process).
Environmental Impact	Low risk of groundwater contamination. Low risk of soil contamination.	Potential impact (air, water, and soil).	Air pollution concerns from emissions.
Cost	Variable depending on existing infrastructure and sludge characteristics.	Lower than incineration.	High costs.

Composting effectiveness hinges upon appropriate management practices for efficient degradation and minimizing odor production, and ongoing research efforts are aimed at optimizing composting techniques for wastewater sludge treatment. Although composting

offers advantages, it is important to recognize its limitations and the ongoing research endeavors toward this approach.

2.2. Role of Composting in the Circular Economy

Sewage sludge composting is crucial for the circular economy, as waste is transformed into valuable resources and the waste management and resource recovery cycle is completed. By combining the sludge digestate of municipal wastewater treatment plants with composting, the agronomic properties and biological stability of the final product are enhanced. This final product then complies with the regulations established by the EU for fertilizers, contributes to mitigating environmental hazards, and valorizes the nutrients present in the sludge (total N 5–9%, available P 0.8–1.3%, organic C 32–33%) [50]. The transition toward a circular economy has already been noticed through the shift from less sustainable sewage sludge management practices, such as incineration, toward more eco-friendly wastewater sludge management methods, including anaerobic digestion followed by composting, driven by recent legislative restrictions and the necessity of recovering both energy and nutrients [38]. By its very nature, the composting process is exothermic. Heat can be retrieved and used for low-temperature applications like residential water heating; this may cover a considerable part of the annual hot water demand in countries such as Greece and Switzerland [51]. Wastewater treatment plants are increasingly viewed as key components of the circular economy, with the potential to recover valuable products from sewage sludge, including nutrients and, more recently, polyhydroxyalkanoates [6,52]. Using inorganic material in the composting of sewage sludge has been shown to enhance the compost parameters and nutrient bioaccessibility [53]. The environmental and economic analysis of sludge treatment processes shows that composting, with specific microbial inoculants and semi-anaerobic conditions, increases nutrient concentrations (>20% TN, >30% TP, >50% TK and >60% in humic acids) and reduces costs by approx. 13% compared to open composting [3]. The model structure of “Wastewater Treatment Planet of the Future” highlights the necessity of circular approaches (including for MSS) in waste management, allowing the recycling of water, energy, and raw material [54].

Rich in nutrients, biosolids from sewage treatment offer a nexus for accelerating a circular economy that promotes cleaner agricultural production and landfill reduction [16]. Table 4 summarizes specific characteristics of the composted sludge, including details on nutrient concentrations, particle size, organic matter content, moisture content, C:N ratio, pH level, and pathogen levels. The application of compost made from municipal sewage sludge in land reclamation reveals that soil-forming processes can be initiated to reach a permanent reclamation and fit in with the principles of circular economy [55].

Table 4. Characteristics of composted sludge.

Characteristic	Description	Range	Citation
Nutrient concentration	Source of macro- and micro-nutrients for plant growth	Nitrogen: 2–6% Phosphorus: 1–3% Potassium: 0.5–2%	[3,56]
Particle Size	Influences handling, application, and nutrient release	Can vary widely depending on pre-treatment processes and the bulking agents used. Usually are in the sand-silt fraction (1 μm –5 mm)	[57]
Organic Matter Content	Provides a source of energy for soil microbes	25–60% depending on the initial sludge composition, composting method, additives, and bulking agents used	[16,58]
Moisture Content	Affects storage, transportation, and use	30–60%	[49,59]
C:N Ratio	Indicates potential for nitrogen immobilization or release	10–30:1	[60,61]

Table 4. Cont.

Characteristic	Description	Range	Citation
pH Level	Affects nutrient availability and microbial activity	6.2–8.5	[17,58]
Pathogen Levels	Crucial for safe land application	Stringent regulations to minimize pathogens (e.g., <i>E. coli</i>) The composting process can significantly reduce pathogens	[62,63]

The potential environmental and health risks need to be managed within the appropriate regulatory framework, which stipulates limits on the concentration of heavy metals, microorganisms' quantity, and the compost's level of maturity. For instance, in Europe, compost must satisfy certain conditions of biological stability and nutrient content before being sold as a fertilizer in accordance with the European Union's fertilizer directive [64]. In addition to that, safety measures provided by the WHO (World Health Organization) and FAO (Food and Agricultural Organization) should be applied to prevent soil pollution caused by sewage sludge used in agriculture [65].

3. Process of Sludge Composting

3.1. Feedstock Selection and Characteristics

Choosing the right inputs is the first step in the composting of municipal wastewater treatment sludges to produce composts. Such a choice should ensure the production of compost with desirable agronomic characteristics and long-term stability. The input selection is critical for the success of composting since it influences the compost's nutrient content, biological stability, and agronomic value. Municipal sewage sludge (MSS) as a source of organic matter and nutrients is one of the primary inputs in composting processes focused on obtaining valuable fertilizers for agricultural applications [3]. MSS is characterized by a complex multi-component material composition that is known to be difficult to handle but contains substantial resources for energy and fertilizer production [66] (Table 5).

Table 5. MSS characteristic parameters.

Parameter	Units	Municipal Sludge (Typical Range)	US EPA 503 Biosolids Rule [65]	Sludge Directive [66]
Total Solids (TS)	% dry weight	30–90 depending on the drying method and climate conditions [37,67,68]	Minimum 75%	-
Moisture Content	%	65–95 [60,69]	≤25% sewage sludge that does not contain unstabilized solids for direct soil application ≤10% sewage sludge that contains unstabilized solids for direct soil application	-
pH	-	5–8 [70,71]	12 or higher	-
Total Nitrogen (TN)	mg/kg dry solids	4200–7000 [72]	-	-
Total Phosphorus (TP)	mg/kg dry solids	2400–4700 [73]	-	-
Organic Matter	% dry weight	45–67 [72]	-	-

Table 5. Cont.

Parameter	Units	Municipal Sludge (Typical Range)	US EPA 503 Biosolids Rule [65]	Sludge Directive [66]
Heavy Metals				
Cd	mg/kg dry solids	0.2–2.8 [73] 4.35 [74]	85	20–40
Ni	mg/kg dry solids	9–129 [73] 151 [74]	420	300–400
Pb	mg/kg dry solids	0–80 [73] 67 [74]	840	750–1200
Zn	mg/kg dry solids	150–3000 [73] 1027 [74]	7500	2500–4000
Hg	mg/kg dry solids	0.7–15 [73] 2.5 [74]	57	16–25
Organic Contaminants				
polyaromatic hydrocarbons (PAHs)	µg/kg dry solids	9700 [75]	9212	6866
polychlorinated biphenyls (PCBs)	µg/kg dry solids	-	10–1000	-
Pathogens				
Coliforms	MPN/g	0.1–107 × 10 ⁴ [76]	≤1000	-
Salmonella	MPN/g		≤3	-

To improve the quality of the final product and to enhance the composting process, sludge is often mixed with organic fractions of municipal solid waste (OFMSW) and mature compost (MC) as bulking agents. These mixtures make it possible to adjust the C:N ratio, which is critical for the composting operation and the quality of the resulting compost [14]. To obtain a stable and mature product, composting time has been reduced by using mature compost as inoculum and lignocellulosic amendment materials and bulking agents like wheat straw, wood chips, energy willow, conifer sawdust, and pine bark [77]. Hence, the selection and characteristics of feedstock are very important in the composting process. Using green waste to compost thermally hydrolyzed anaerobically treated dewatered sludge has shown environmental and economic benefits, as total nitrogen concentrations and humic acids in final composts are increased by 21.8% and 63.4%, respectively [3]. Choosing a proper feedstock combination for composting municipal wastewater treatment sludge is a significant determinant, which mainly involves incorporating sludge with different organic materials to maximize the composting process and improve the ultimate compost quality for agricultural uses (Table 6).

An approach for obtaining a more balanced C:N ratio of feedstock and moisture content is using different types of sludge (primary and secondary) in combination. Sludge treatment techniques such as dewatering, thickening, and lime stabilization can contribute to improved composting substrate properties (moisture content, reducing pathogens, or addressing potential concerns over heavy metals). Primary sludge is typically richer in organic matter, while secondary sludge often contains higher nitrogen levels [78].

Careful feedstock combination can increase the decomposition rate and decrease processing time, keep the composting process manageable, develop a nutrient-rich compost for application, minimize odor generation in composting, reduce the need for additional amendments, and ensure a successful and sustainable sludge composting operation by selecting feedstock materials [16].

Table 6. Feedstock selection and characteristics [16,18,55,58].

Feature	Description	Importance for Composting
Sludge Characteristics	<ul style="list-style-type: none"> • Dry solids content • Organic matter content • Nutrient content • Heavy metal content • Pathogen levels 	<ul style="list-style-type: none"> • Dry solids content impacts aeration and moisture balance; levels below 20% can lead to anaerobic conditions and odors. • Nutrients are essential for plant growth in the final compost. • Heavy metals can limit compost use and require monitoring. • Pathogens need to be reduced to meet safety regulations.
Bulking Agents	Various materials with high carbon content and good structure	<ul style="list-style-type: none"> • Enhances aeration and porosity. • Create physical structure.
C:N Ratio	<ul style="list-style-type: none"> • Ideal ratio: 25–30:1 	<ul style="list-style-type: none"> • Optimal conditions for microbial activity. Excess N can lead to ammonia emissions. • C:N ratio can be adjusted by selecting bulking agents that are complementary to the sludge.
Moisture Content	<ul style="list-style-type: none"> • Ideally between 40–60% 	<ul style="list-style-type: none"> • Supports microbial activity. • Higher values lead to anaerobic conditions and odors. • Microbial activity is inhibited in low humidity conditions.
Particle Size	<ul style="list-style-type: none"> • Size distribution of sludge and bulking agent particles 	<ul style="list-style-type: none"> • Influences aeration, pile humidity, and the decomposition rate.

3.2. Mixing and Bulking Agents

The choice of mixing and bulking agents in composting municipal wastewater treatment sludge strongly affects the properties and quality of the final compost. It has been found that the addition of lignocellulosic amendments and structuring agents (e.g., wood chips, wheat straw, energy willow, pine bark, and conifer sawdust) exert some changes in stability and maturity of the resulted compost with regard to the duration of the thermophilic phase, respiration activity, and carbon ratio in humic acids to total organic carbon in the achieved compost [58]. Similarly, recycled wood as a novel bulking agent can improve soil amendment quality by enhancing microbial activity and reducing the C:N ratio, thereby facilitating seed germination and reducing the toxicity of industrial sewage sludge [35]. The choice of bulking agents also impacts the physicochemical and microbiological properties of the compost. For instance, a study showed that when sawdust is used as a bulking agent in the in-vessel composting of sewage sludge, it can cause a significant reduction in the levels of pathogens, rendering the treated sludge suitable for agricultural application [16]. Furthermore, the addition of cellulolytic bacteria and manure into the composting of municipal solid waste was found to hasten humification, resulting in the premature maturation of the compost [49]. However, the initial contamination of sewage sludge and the ratio of bulking agents can govern the heavy metal content of the final compost, with some composts failing to meet the most stringent heavy metal standards despite achieving a high degree of stabilization and sanitization [79]. Moreover, the nature of sludge sources and bulking agent selection can potentially influence the environmental impact of composting, as different properties of stocks and composting conditions can lead to the outcomes of GHG and emissions of air pollutants [80]. During sludge composting, bulking agents are one of the most significant impact factors. The characteristics of bulking agents and considerations are shown in Table 7, along with their benefits in composting.

While bulking agents primarily influence the issues of aeration and drainage, amendments may be employed to optimize the sludge composting process further by improving compost stability, maturity, and nutrient content, thus decreasing the environmental risks. The addition of lignocellulosic amendments such as wood chips, wheat straw, energy willow, pine bark, and conifer sawdust has been demonstrated to generate stable and mature compost; this addition will shorten the composting time to stability and maturity while increasing humic substances (HS) and humic acids (HA), signaling higher-quality

compost in terms of organic matter [16]. The amendment types and their specific roles are summarized in Table 8.

Table 7. Bulking agents their characteristics and considerations [3,35,79,81].

Bulking Agent	Characteristics	Benefits of Sludge Composting
Wood Chips	<ul style="list-style-type: none"> • High carbon content • Good aeration and drainage properties • Decompose slowly—might increase composting time 	<ul style="list-style-type: none"> • Improves aeration and reduces compaction in composting piles. • Offers a readily available source of carbon.
Sawdust	<ul style="list-style-type: none"> • High carbon content • Moisture absorption capacity • Denser than wood chips 	<ul style="list-style-type: none"> • Effective for moisture management in sludge with high water content. • Contributes to balancing the C:N ratio.
Straw	<ul style="list-style-type: none"> • High readily available carbon content • Dense structure 	<ul style="list-style-type: none"> • Provides a readily available source of carbon. • Offers cost-effective bulking material for large composting operations.
Yard Trimmings and Leaves	<ul style="list-style-type: none"> • Moderate carbon content • Decomposes faster than wood chips or straw • High moisture content 	<ul style="list-style-type: none"> • Readily available source of bulking material, often from municipal green waste collection. • Fast decomposition, can contribute to reduced composting time
Chopped Bark	<ul style="list-style-type: none"> • Moderate carbon content • Good aeration and drainage properties • Slower decomposition than yard trimmings but faster than wood chips 	<ul style="list-style-type: none"> • Provides a long-lasting bulking material with good aeration properties. • Offers a readily available source of carbon from forestry or landscaping waste.

Table 8. Amendments and their role in sludge composting [26,29,82].

Amendment Type	Description and Scope
Nutrients	<ul style="list-style-type: none"> • Materials rich in nutrients (nitrogen, phosphorus, or micronutrients) • Covers nutrient deficiencies in sludge for optimal microbial activity. • Can be organic materials or inorganic supplements like ammonium sulfate or urea can also be used.
Lime (CaCO ₃)	<ul style="list-style-type: none"> • Limestone or quicklime • Creates a more favorable environment for microbial activity by increasing the pH level of acidic sludge. • Can contribute to increased pathogen reduction by creating a more alkaline environment. • Can reduce the mobility of heavy metals and improve compost quality.
Bulking agents with additional benefits	<ul style="list-style-type: none"> • Specific materials or compost • Biochar can improve moisture retention, contribute to odor control, and enhance nutrient availability. • Composted materials are used as an inoculum.

Using amendments has several benefits, including improved decomposition rate, compost quality improvement, adjusted pH level, and odor control. By knowing the characteristics and benefits of various bulking agents, composters can make knowledgeable decisions as to what is best for their compost. The careful selection and proper management of these materials are essential for a successful and efficient operation (Table 9).

Table 9. Bulking agents and their contribution to sludge composting.

Sewage Sludge Type	Bulking Agent	Ratio (Sewage Sludge: Bulking Agent)	Benefits	Drawbacks	Citations
Primary Sludge (High Moisture)	Wood chips, sawdust, straw, leaves, cardboard (shredded)	1:1 (dry weight basis)	High Carbon Content (2:1 C:N) Improves aeration Reduces moisture content (50–60% ideal) Promotes microbial activity Readily available	Requires grinding/shredding May contain contaminants Not always readily available	[83]
Secondary Sludge (Lower Moisture)	Composted wood chips, yard trimmings, forestry residues, rice hulls, empty fruit bunches (palm oil industry)	1:2 (dry weight basis)	Readily available (composted wood chips) Sustainable source (yard trimmings) Promotes microbial diversity (forestry residues) Low bulk density (improves aeration) High nutrient content (empty fruit bunches)	Requires composting wood chips beforehand Seasonal availability (yard trimmings) May require processing (forestry residues) High transportation costs (rice hulls) Limited availability (empty fruit bunches)	[84]
Anaerobic Digestate (Low Carbon)	Biochar (10–20% by weight), mushroom compost (spent) (1:1), animal manure (1:2)	As a percentage of the total mix or ratio with sludge	High surface area (biochar) Supplements nutrients (mushroom compost) Improves microbial activity (animal manure)	High production cost (biochar) Limited availability (spent mushroom compost) Potential for pathogens (animal manure)	[85–87]

3.3. Factors Influencing the Composting Process

The composting process of sludge from municipal wastewater treatment is influenced by several factors, including the initial treatment processes, the C:N ratio, the presence of microorganisms, and the use of amendments and bulking agents. The initial treatment processes, such as thermal hydrolysis, will determine the energy balance and the potential of the treated sludge, with some of the treatments not reaching the criteria for a fertilizing product [3]. During the composting process, the C:N ratio mainly decides the growth of microorganisms. An inferior C:N ratio can accentuate GHG emissions and odorous substances like ammonia [87]. Relevant microorganisms, especially anammox bacteria, reduce the environmental pollution from NH₃ and provide H⁺ for nitrification [13]. Adding lignocellulosic amendments and bulking agents can impact compost stability and maturity, which will significantly influence the thermophilic phase's duration and the entire composting time for obtaining a stable and mature product [58]. Various substrates, including polyacrylamids, biolysed sludge, and Fe(III)/CaO, can modify physical–chemical parameters, nitrogen conversion, and humification in composting; some treatments can enhance nitrogen retention rate and compost maturity [17]. The final quality of the compost depends heavily on the choice of the feedstock composition, the selection of bulking agents, and sludge pre-treatment methods, as they have a considerable influence on soil–compost interactions and the nutrient leaching/ sequestering behavior of the soil [15]. In addition, the mitigation cost-effectiveness and compost quality in terms of remediation potential may also vary depending on the source of sewage sludge and the mixtures chosen during

composting [79]. Table 10 summarizes the factors that affect the composting process of wastewater treatment residual sludges.

Table 10. Factors that affect the composting process of wastewater treatment residual sludges [6,18,23,79].

Factor	Description	Impact on Sludge Composting
Sludge characteristics	Solid content, organic matter content, presence of heavy metals and pathogens.	High solid content can lead to moisture management issues. Organic matter content influences the decomposition rate. Heavy metals can limit compost use and require pre-treatment. Pathogen presence requires proper sanitation.
Bulking agents	Materials that improve composting piles aeration and humidity distribution (wood chips, sawdust, or straw).	Important for moisture contents and porosity management, considering the dense structure of sludge.
C:N ratio adjustment	In most cases sludge has a reduced C:N ratio, needing supplementary carbon sources (e.g., wood chips).	Maintaining the C:N ratio in the optimal range is essential for both microbial activity and control of odor.
Pre-treatment methods	Techniques that aim to improve sludge characteristics for composting.	Increase solid content, increase sludge dewaterability, and address pathogen concerns.
Temperature management	High temperatures are required for pathogen destruction.	Ensuring proper insulation and turning the piles are essential for sustaining thermophilic composting conditions.
Nutrient availability	Sewage sludge is likely to have a lower concentration of some necessary nutrients for microbial growth.	Supplementation of nutrients might be necessary for decomposition to work in an optimal way.
Composting technology	Open windrow systems, in-vessel composting systems.	Different technologies might be various as to aeration, temperature control, odor management, and processing time.

Several other aspects should be considered to achieve the successful composting of sewage sludges. A key element for the final compost to be considered safe, prepared, and adaptable in any of the envisaged applications, and to guarantee thereby the safety of the environment and public health, is compliance with local regulations concerning heavy metal content and pathogen reduction. Also, mitigating unwanted smells is a critical component of any efficient waste management system. Odors are often cited as one of the most significant factors affecting the acceptability of composting facilities and programs and may significantly reduce their overall support in communities. The effective strategies for odor control are crucial for the success of composting efforts. Several basic, validated strategies are available to help manage odorous emissions from composting operations. Co-composting mixtures of compostable waste with appropriate bulking ingredients can help ensure that enough air passages are present in the compost for air movement. The proper management of moisture corroborated with aeration limit odors formed as compost decomposes. Control of nitrogen and carbon ratio, temperature of compost, and proper turning aerates compost mixtures to assist decomposition and remove odor.

Some innovative odor control strategies in the composting of sewage sludge have been developed. One innovative alternative includes deodorants made of plant material, which can comprise a mixture of essential oils from coconuts, lemons, and tea trees, preliminarily tested to be very efficient in reducing odorous compounds such as ammonia, alcohols, aromatics, and carbonyls by spraying onto compost windrows. Removal efficiencies realized in this case for some of these compounds were as high as 83% [88]. Another design is the bio-liquor circulation system already implemented with very good results in swine housing facilities to mitigate the odor emissions. Another approach focuses on adjusting the oxidation–reduction potential and pH time profiles on a real-time basis to ensure an optimized biochemical environment to reduce odors and manage nutrients [89].

Composting integrated with vermicomposting also improved the degradation process with reduced foul odors when municipal solid waste is combined with activated sludge [90]. The use of *Trichoderma*-enriched compost has also been highlighted, which can suppress pathogens and thus reduce disease incidents in crops. This would indirectly control odors by maintaining a healthier composting environment [91]. Further, the addition of fly ash during the composting process helps in the stabilization of heavy metals that might combine with other elements to precipitate odor-forming reactions [92,93]. Fly ashes with heavy metals can lead to a higher pH of the compost mass that means more nitrogen loss and also the immobility of micro-elements, as well as reduced populations of helpful microorganisms. Some of the process gases, particularly CO, CO₂, NO, and O₂, have been controlled through the use of aeration and turning frequencies to optimize odor-free composting conditions and reduce odorous emissions related to the presence of these elements. Hygienization methods, such as mesophilic fermentation, inactivate the pathogens present in manure and sewage sludge responsible for odor generation through microbial activity [94]. The co-composting of olive mill pomace with sewage sludge was found to produce microbiologically safe compost. The compost product has a high value as a fertilizer and low odor problems [95]. These new strategies together present a multifaceted approach to odor control in composting sewage sludge, combining chemical, biological, and process management techniques to derive important improvements in odor reduction and overall compost quality.

Various sludge pretreatment techniques have been explored, including hydrodynamic disintegration, freeze/thaw, ozonation, sonication, thermal hydrolysis, and alkaline/acid pretreatment. Hydrodynamic and freeze/thaw disintegration methods have the advantage of significantly reduce pathogenic bacteria and parasite eggs, while the hybrid method (combining hydrodynamic cavitation and dry ice disintegration) shows the highest reduction rates, thus improving compost safety and quality [96]. Ozonation and ultrasonic pretreatment improve the composting process by significantly reducing volatile solids, total organic carbon, and coliform concentrations while increasing nutrient bioavailability [96]. Also, the application of thermal hydrolysis before anaerobic digestion, although energy-consuming, can be beneficial when followed by composting, as it increases the concentration of humic acids and total nitrogen, reduces ammonia emissions, and lowers the total cost of sludge treatment [3]. Thermal pretreatment alternatives, such as conventional heating, microwave heating, and radiofrequency heating have been shown to improve sludge disintegration and bioenergy production, with radiofrequency pretreatment as the most sustainable option as it produces a net positive energy [97]. The combination of pot composting with sawdust as a bulking agent and thermal processing significantly reduces the number of microbes, including harmful pathogens such as *Salmonella* and *Shigella*, and improves the physicochemical properties of the sludge [98]. The addition of green waste as a bulking agent in composting mixtures not only improves nitrogen stabilization and retention, but also helps to achieve a good level of sanitation and reduce antibiotic resistance, which is essential for safe field application [35]. Producing high-quality compost with increased humic substances and reduced nitrogen losses is essential for soil health and combating desertification. Thus, pretreatment alternatives play a vital role in achieving these results [58]. Alkaline/acidic and thermal pretreatments release different substrates that enrich specific functional microbial populations, thus improving digestion performance and methane (CH₄) production during anaerobic digestion, which can be beneficial when integrated with composting [99]. Thus, the aerobic stabilization of digestates from co-digestion processes results in higher composting efficiency, better nutrient profiles, and suitability for phytoremediation, underscoring the importance of selecting appropriate pretreatment methods to improve compost quality and benefit the environment [18]. Moreover, integrating these pre-treatment methods into the composting process not only improves organic matter degradation and pathogen reduction but also improves the nutritional profile and safety of the final compost product.

3.4. Aerobic Decomposition and Microbial Activity

Aerobic decomposition serves as a vital phase in the composting process of municipal wastewater treatment sludge, primarily driven by microbial activity. The C:N ratio is a critical controlling factor for microbial communities; a low C:N ratio leads to elevated GHGs and odorous substances emissions, such as ammonia volatilization, which severely affects composting efficiency and environmental health.

Sludge composting naturally occurs when existing or inoculated microbial communities spontaneously colonize and initiate the decomposition process. However, there are instances where microbial augmentation or amendments have proven beneficial in optimizing this process. Microbial augmentation involves the deliberate introduction of certain strains of bacteria or fungi into the composting system. Usually available commercially, these strains have various roles as rapidly adding microbes to enhance the decomposition process, accelerating the conversion of organic matter, identifying any pollutants or pathogens, and helping to degrade them, thus improving the overall quality of the compost.

Amendments are additional materials other than manure and crop material in compost material added to promote microbial activity and provide optimal conditions for decomposition. Either macro- or micronutrients can be added as supplements for microbial growth when the composting materials are deprived of essential nutrients. Bulking agents, such as sawdust, wood chips, or straw, are integrated into the composting blend to provide improved structure and drainage. These factors provide a setup for enhanced microbial action and rapid degradation. Inoculums are also used in the initial composition to introduce beneficial populations for accelerating the composting startup and operations. These serve as repositories of viable organisms, enhancing the biotransformation of organic material and stimulating augmented microbial activity.

Anammox bacteria are active in composting and are efficient in nitrogen removal, suggesting a method to improve the process and lessen air pollution without the need for additional energy in aeration [13]. In wastewater treatment, the structure and function of the microbial community, particularly under aerobic conditions, are necessary for the breakdown of organic matter into harmless byproducts. Moreover, the essential role of microbial communities in the bioconversion of wastes (depicted by [100]) into “bioorganic” fertilizers has also been brought into the limelight by several studies, where the involvement of different microbial species has been studied in different parts of nutrient recovery and waste valorization steps, thus opening a wide range of possibilities for microbial control for sustainable agriculture practices and waste management/indexation. In composting municipal sewage sludge, it has been observed that the temperature has a vital effect on microbial activity and biomass; thus, it is possible to attain optimal composting rates by regulating temperatures within certain limits [101]. Research into co-composting has shown that for compost to be of high quality and for the process to be efficient, the succession of bacterial and fungal communities is vital, with different taxa of microbes dominating at different stages of the process [102]. Table 11 shows the primary microorganisms driving the decomposition of organic matter in sludge composting. Using a synergy of different microbial communities, complex organic matter is converted into simplified, stable forms.

Table 11. Microorganisms involved in sludge composting [100–102].

Microbial Group	Specific Examples	Role in Decomposition
Bacteria	<i>Thermomonas</i> spp., <i>Bacillus</i> spp., <i>Pseudomonas</i> spp.	Dominant in the thermophilic phase, responsible for the breakdown of simple sugars, proteins, and fats.
Actinomycetes	<i>Streptomyces</i> spp., <i>Nocardia</i> spp.	Breakdown of complex polymers, e.g., cellulose, and hemicellulose.
Fungi	<i>Aspergillus</i> spp., <i>Penicillium</i> spp., <i>Trichoderma</i> spp.	Directly involved throughout the process, the breakdown of complex organic matter, contributes to compost structure.

Recent studies provided evidence that microorganism addition and organic amendments are considerable enhancement methods applied in MSS composting. The bioaug-

mentation, especially the added aerobic cell culture, significantly reduced NH_3 and H_2S gas emissions in sewage sludge composting while improving the retention of total N and SO_4^{2-} . Analogously, the application of cow dung and cellulolytic bacteria in municipal MSW composting has accelerated humification, indicating that microbial consortia will improve compost maturity [103,104]. The application of microbial augmentation and organic amendment in composting processes integrated with the municipal-based wastewater treatment system can lead to significant improvement in compost quality, soil health, and environmental sustainability.

4. Laboratory and Full-Scale Experiences

4.1. Case Studies and Experimental Research

Studies of composting research examine best practices in processing improvement, compost quality enhancement, and limited environmental effects. Research has explored using sludge in construction materials, adding amendments to reduce pollutants, and using worms in producing nutrient-rich fertilizer. The composting of sludge from WWTPs has been studied through numerous cases and experiments, examining alternative methods, molecular behavior, and the potential for farming.

Experiments that have been performed in the laboratory and at a full scale for composting raw municipal wastewater treatment sludge show various strategies and results [20] and have provided details about the necessary conditions for obtaining increased compost quality. The co-composting of MSS with green waste is successful in reducing hazards such as heavy metals and pathogens, but some occurrences of antimicrobial resistance of *Enterococcus* spp. strains were also observed [35]. The co-composting of OFMSW with MSS and MC demonstrated that some mixtures can yield mature and stabilized compost that is safe enough for agricultural use [77]. The addition of synthetic chemicals initiating struvite formation during composting was shown to dramatically reduce nitrogen losses and also increase the nutritional value of the compost [105]. The existence of anammox bacteria during composting indicates a potentially efficient way for nitrogen removal without aerating, which requires extra energy [13]. The thermophilic phase of composting can promote the decomposition of aliphatic/proteins and carbohydrates, which can lead to the formation of humic substances that are beneficial for soils, as molecular dynamics studies have confirmed [106]. The use of earthworms, e.g., *Eisenia fetida*, for the vermicomposting of sewage sludge into high-quality organic fertilizer has considerable potential, and the best results were obtained with the co-composting of cow manure and sludge [107]. Tests for innovative treatments of compost leachates through biopiles have also been carried out to guarantee the valorization of composting processes without remarkable increment in the pollutant concentration [108].

Research evaluated the sludge containing grease and oil of food services, whereby its use as organic fertilizer is sustainable following enzymatic composting [25]. The viability of composting of sewage sludge was further evaluated in research performed by studying the improvement in compost quality following aerobic and anaerobic digestion, rendering it appropriate for agriculture applications [3]. The optimization of co-composting MSW with wastewater treatment plant sludge focused on achieving nutrient resource recovery, where the effects of waste-to-sludge ratios and aeration periods were emphasized [13]. Furthermore, the selection of bulking agents and sludge pre-treatment methods were found to be essential for the final quality of compost, as they influence soil–compost interactions and nutrient leaching/sequestration behavior [14]. Numerous studies have focused on the multifaceted approaches and benefits of composting MSS, with their results contributing to sustainable waste management and resource recovery (Table 12).

Scientists are looking into multiple approaches to the safe and efficient management of sludge, such as co-composting with municipal waste, furthering other digestion methods and turning to new technologies to monitor the process.

Table 12. Studies of municipal wastewater treatment sludge composting.

Location/Scale	Feedstock	Composting Method	Key Findings	Advantages	Disadvantages	Source
Vilnius wastewater treatment plant/ Two 8 m × 1.7 m × 3.5 m piles	<ul style="list-style-type: none"> 3.7 tonnes of dewatered anaerobically digested sludge (50%) 2.2 tonnes of leaves, grass (29.73%), 1.5 tonnes of shredded tree and shrub pruning waste (20.27%) 	<ul style="list-style-type: none"> Conventional composting. Semi-anaerobic composting (involves maintaining partially anaerobic conditions during the composting process). 	<ul style="list-style-type: none"> Increased humic acids and total nitrogen concentrations, reduced NH₃ emissions, and the lowest cost price of 53 EUR tonne⁻¹ of sludge dry matter. 	<ul style="list-style-type: none"> Increased concentrations of humic acids (by 63.4%) and total nitrogen (by 21.8%), minimizing NH₃ emissions (by 26.6%). Feasibility and economic viability of co-composting for dewatered sludge treatment after thermal hydrolysis and anaerobic treatment. 	<ul style="list-style-type: none"> Challenges in meeting the criteria for fertilizing products, restricting the potential applications to energy forests only. Negative energy balance of the composting process due to the energy-intensive drying of 59% of the digested sludge. 	[3]
Lab-scale/ Two-stage system: 100 dm ³ aerated bioreactor followed by a periodically turned windrow	<ul style="list-style-type: none"> sewage sludge (79%) and lignocellulosic materials in three proportions: wood chips (13.5% wet mass) and wheat straw (7.5% w.m.) energy willow (13.5% wet mass) and wheat straw (7.5% wet mass) pine bark (13.5% wet mass) and conifer sawdust (7.5% wet mass) 	<ul style="list-style-type: none"> two-stage system utilizing a bioreactor followed by a periodically turned windrow 	<ul style="list-style-type: none"> Effect of bulking agents on compost stability and maturity evaluation. Different lignocellulosic amendments influence the composting process in a two-stage system. 	<ul style="list-style-type: none"> Evaluation of feedstock impact on compost stability and maturity. Specific bulking agents and amendments facilitated organic matter degradation, increased carbon contents, and controlled the composting time needed to obtain a stable and mature product. 	<ul style="list-style-type: none"> Lignocellulosic materials as bulking agents and amendments could limit the protocol's applicability and costs. 	[17]
Lab-scale/ 216 L reactor	<ul style="list-style-type: none"> polyacrylamides added sludge (PS) (15.9 kg), bio lysed sludge (BS) (7.2 kg) Fe (III)/CaO added sludge (SS) (7.1 kg) Wheat straw (12 kg) 	<ul style="list-style-type: none"> Aerobic composting 	<ul style="list-style-type: none"> Biolysed sludge (BS) increases nitrogen retention rate and compost maturity. MSS composting products have higher plant biotoxicity compared to PS and BS. BS and FS promoted the aromaticity and stability of humic acid. 	<ul style="list-style-type: none"> The use of BS promotes dissolved organic matter degradation during the initial stage of composting. BS enhances the total nitrogen (TN) retention rate. BS provides more humic substance (HS) and humic acid (HA) for composting. 	<ul style="list-style-type: none"> The germination index (GI) value of the compost products from FS is lower than that of PS and BS. 	[15]

Table 12. Cont.

Location/Scale	Feedstock	Composting Method	Key Findings	Advantages	Disadvantages	Source
Composting plant pilot experiment/ conical pile: 0.6 m height, 1.5 m diameter	<p>3 experiments:</p> <ul style="list-style-type: none"> fresh sludge (T1) 12:10:3 (sludge, spent mushroom, spent bleaching soil) with 1% microbial inoculum addition(T2) 12:10:3 (sludge, spent mushroom, spent bleaching soil) (T3) 	<ul style="list-style-type: none"> high-temperature aerobic composting with artificial aeration 	<ul style="list-style-type: none"> Composting maturity reached after 26 days in T2, meeting standard agricultural sludge limits. Changes in microbial function in T2 influenced heavy metal passivation and organic oxidizing abilities during composting. 	<ul style="list-style-type: none"> A comprehensive understanding of how factors evolve, contributing to the knowledge base on sludge composting efficiency and heavy metal detoxification. A detailed examination of the dominant bacterial species and their roles in heavy metal passivation and organic oxidization. 	<ul style="list-style-type: none"> Limited generalizability of the findings to other composting scenarios that may involve different materials or conditions. The study lacks a detailed exploration of other potential factors influencing heavy metal detoxification efficiency, such as temperature variations, oxygen levels, or moisture content. 	[109]
Lab-scale/ 6 L containers	<ul style="list-style-type: none"> dewatered sewage sludge (SS) inorganic bulking agents: expanded perlite (EP) and pumice (PU) mixed with sludge at increasing volumes of 12.5%, 25%, and 50% sawdust (as control bulking material) 	<ul style="list-style-type: none"> Aerobic composting with daily manual mixing 	<ul style="list-style-type: none"> The addition of PU and EP at 50% (v/v) resulted in enhanced porosity, optimal initial moisture content, increased temperature rise, and higher CO₂ evolution rates, leading to higher nitrogen content and readily bioavailable nutrients, with significant amounts of phosphates and potassium available for plant uptake. Slow-release nutrient properties of the compost were enhanced. 	<ul style="list-style-type: none"> Enhanced composting parameters by improved porosity, optimal initial moisture content, and increased temperature rise. Nutrient enrichment: higher nitrogen content and readily bioavailable nutrients. Improved nutrient release properties: enhanced slow-release nutrient properties. 	<ul style="list-style-type: none"> The low nutrient content in compost can lead to reduced compost quality, affecting its suitability for horticultural use. Necessity for further research on the readily bioavailable amounts of phosphorus (P) and iron (Fe) when using inorganic porous materials as bulking agents. 	[110]
Lab-scale/ Column reactor of 30 cm diameter and 45 cm height	<ul style="list-style-type: none"> dried sewage sludge (SS) kitchen organic fraction of municipal solid waste (OFMSW) mature compost (MC) <p>mixtures of OFMSW: SS: MC of 3:1:1, 3:2:1, 3:3:1</p>	<ul style="list-style-type: none"> Aerobic composting with daily manual mixing 	<ul style="list-style-type: none"> Optimal composting ratio: 3 parts OFMSW, 1 part SS, 1 part MC. Final compost: C:N ratio 12.17, N content 1.75%, GI 77.4%. Low amounts of heavy metals in final compost products. Significant reduction of pathogens. 	<ul style="list-style-type: none"> Enhanced composting performance with specific mixture ratios. Production of high-quality fertilizer for agriculture and horticulture. Reduction of pathogens and heavy metals. 	<ul style="list-style-type: none"> N/A 	[111]

Table 12. Cont.

Location/Scale	Feedstock	Composting Method	Key Findings	Advantages	Disadvantages	Source
Pilot scale/ windrow pyramid of 1.5 m high, 2 m wide and 4 m long	<ul style="list-style-type: none"> Mixtures of MSS, spent mushrooms (SM), herb residues (HR), and sawdust (SWD) at different ratios: MSS-100%; MSS:SWD = 3:1 MSS:SWD:SM = 3:1:1 MSS:SWD:SM = 3:1:2 MSS:SWD:HR = 3:1:1 MSS:SWD:HR = 3:1:2 	<ul style="list-style-type: none"> Aerobic in-pile composting with daily mixing 	<ul style="list-style-type: none"> SM and HR addition to MSS accelerated the temperature rise, leading to quicker compost maturation. SM and HR incorporation resulted in lower nitrogen losses during composting (22.45 to 24.99 g/kg for TN and 10.2% to 22.4% for nitrogen losses over the control value. The windrow with the highest proportion of SM (3:1:2 MSS:SWD: SM) exhibited the highest TN level and the lowest nitrogen loss. 	<ul style="list-style-type: none"> The addition of SM and HR can reduce composting maturation time. The addition of SM and HR can reduce nitrogen losses during composting. 	<ul style="list-style-type: none"> The correlation of TN with water-soluble inorganic nitrogen was not significant in some experiments. 	[112]
Lab-scale/ 5 L composters	<ul style="list-style-type: none"> dewatered digestate (SS1), co-digestion dewatered digestate (SS2), OFMSW, willow stems as a bulking agent (BA), and grass (G) in the following mixtures: SS1:SS2:OFMSW:BA:G = 20%:0%:60%:15%:5% 0%:20%:60%:15%:5% 30%:0%:50%:15%:5% 0%:30%:60%:15%:5% 	<ul style="list-style-type: none"> Aerobic composting with daily manual mixing 	<ul style="list-style-type: none"> Composts met Polish Regulations for organic fertilizers, suitable for phytoremediation. 	<ul style="list-style-type: none"> Composting with SS2 resulted in higher thermophilic phase temperatures (>55 °C) and a greater loss of organic matter (60%) than with SS1. The compost with 30% SS2 demonstrated potential for enhanced plant growth. 	<ul style="list-style-type: none"> High concentrations of heavy metals in sewage sludge. Elevated content of Helminth eggs in composts from the wastewater plant. 	[18]
Lab-scale/ 12 cm × 36 cm height × diameter composter	<ul style="list-style-type: none"> Pelletized sludge 	<ul style="list-style-type: none"> Vermicomposting of pelletized sludge at controlled temperatures (15 °C, 20 °C, and 25 °C) 	<ul style="list-style-type: none"> 20 °C is optimal for antibiotic resistance genes (args) removal. Vermicomposting at 25 °C did not significantly reduce the args compared to 15 °C and 20 °C. Dynamics of qnra, qnrs, and tetm genes during vermicomposting at 15 °C and 20 °C followed a first-order kinetic model, suggesting gene degradation predictability. 	<ul style="list-style-type: none"> Dynamics of qnra, qnrs, and tetm genes analyzed. Evaluated the importance of temperature control in vermicomposting to enhance ARG removal efficiency and ensure compost biostability. 	<ul style="list-style-type: none"> Other potential factors that could influence ARG fate, such as initial ARG concentrations or specific vermicomposting conditions were not explored. 	[113]

Table 12. Cont.

Location/ Scale	Feedstock	Composting Method	Key Findings	Advantages	Disadvantages	Source
Lab-scale/ 550 mm diameter and a height of 600 mm cells in controlled conditions	<ul style="list-style-type: none"> Co-composting with waste-to-sludge ratios 1:1, 2:1, 3:1, 4:1 	<ul style="list-style-type: none"> Co-composting waste and sludge, manually aerated every 8 h 	<ul style="list-style-type: none"> Co-composting without dewatering sludge improves efficiency. Optimal conditions: 2:1 waste-to-sludge ratio, 8-h aeration period. 	<ul style="list-style-type: none"> Optimized co-composting design by determining the optimal waste-to-sludge ratio, aeration period, percent of porous material, and moisture content. 	<ul style="list-style-type: none"> Excessive porous material affects the COD removal rate. 	[114]

4.2. Challenges and Solutions in Scaling Up

Scaling composting operations from laboratory to full-scale units presents many technical challenges and uncertainties, according to recent research. Rarely do laboratory-scale trials provide good predictive information about full-scale composting performance due to differences in heat retention and microbial ecology. For example, small-scale composting trials performed with oily wastes have demonstrated that reactors with a volume of ≥ 200 L lose heat to the surroundings at a greater rate than can be supplied by biomass alone [115]. This observation implies that laboratory experiments on composting mixed wastes do not always simulate full-scale operations accurately. Likewise, research on the formation and emission of ammonia in the treatment of urban sludge has stressed the problem of scaling, with diverse velocities in different states of maturation detected [116].

Under laboratory conditions, the development of bio-organic fertilizers through anaerobic co-digestion of sewage sludge and agricultural waste has shown promising results; however, upscaling the processes requires careful consideration of nutrient concentrations and plant growth parameters to ensure soil sustainability and productivity at a larger scale [117]. Additionally, composting sewage sludge with the addition of different bulking agents, for example cassava distillery residues, also faced problems of process temperature, organic mass reduction, and volume. All the above-mentioned problems are mainly due to the large scale of the research process [118]. The main aspects of concern for sewage sludge composting scaling-up identified in the literature are mentioned in Table 13.

The complexity of scaling up composting processes for wastewater treatment sludge from lab to full-scale facilities introduces considerable challenges, particularly regarding heat conservation, microbial ecology, and process dynamics. Laboratory experiments frequently fail to mimic the conditions and intricacies of full-scale systems. As such, performance predictions often diverge. One of the major problems is in relation to the conservation and management of the heat produced during composting. Even though laboratory-scale reactors can handle heat rises effectively, large-scale facilities mainly have excess heat, which may have adverse effects on the activities of the microbes during the thermophilic phase. Therefore, systems that can remove heat effectively are necessary to keep the temperatures at an optimum without affecting the composting process or the quality of the final product [119]. Additionally, the microbial ecology in large-scale composting is much more complex, since various dynamic interactions amongst microorganisms, plants, and soil have to be fully duplicated under laboratory conditions. These oftentimes cause differences between the laboratory and the results in the field, which require interdisciplinary collaboration to bridge them [120]. The biodegradation of plant residues using lignocellulolytic microbial consortia shows potential, but its success in the application will need to be substantiated at larger scales to be replicable [121]. Furthermore, the feedstock composition and processing techniques—very different between laboratory- and full-scale operations—can also affect the composting duration and the effectiveness of the all-embracing process [122]. Additionally factoring in the long residence time of the composting process and consequently recalcitrant materials and scaling-up factors poses further difficulty in the scaling of

this technology, as all these factors are likely not to respond in a favorable way and therefore affect the general efficiency [122]. With respect to microbial dynamics, the roles of beneficial soil microorganisms in sustainable agriculture emphasize the desire for a stable and yet balanced microbial community, which is very hard to maintain under large-scale agricultural practices due to fluctuating environmental conditions and microbial communities [123]. Furthermore, it has also been shown that the degradation of pyrogenic organic matter by soil-borne fungi is one of the measures suggesting a role for a better understanding of microbial interactions in compost stability and carbon sequestration [124]. Other problems include large-scale composting environmental challenges, such as odors, bioaerosols, and contamination with heavy metals, which are significant barriers in developing countries, possibly without waste management infrastructure [125]. Source-separated composting, which is a successful practice in developed countries, suggests that some of these problems could be mitigated because of the prevention of contamination and the elimination of the need for elaborate pre-treatment [125]. Finally, there is the potential for added benefits with heat recovery from composting processes, but their means of evaluation and exploitation need to be optimized and tested on a large scale to justify energy efficiency and sustainability [36]. Addressing such scalability challenges will need an inclusive approach to integrate the advances in microbial ecology, process engineering, and environmental management in order to achieve efficient and sustainable large-scale composting operations, for example, improving reactor designs, minimizing heat transfer, refining nutrient concentrations to keep agricultural productivity and soil productivity constant, and using alternative bulking agents to enhance composting efficiency.

Reliability and efficiency in the operation of sewage sludge composting at a larger scale can be improved by strategically approaching reactor design improvement together with reduced heat transfer and substitution of alternative bulking agents. The design of the reactor is one of the most critical factors in making the composting process efficient. For instance, innovative designs in relation to various reactors, such as water jacket methods for small-scale reactors and tube-buried-in pile methods for the composting of lignocellulosic biomass, can go a long way to improve heat recovery and utilization, which is important in assuring ideal temperatures during composting, hence reducing energy use [36]. In addition, the application of such bulking agents as porous inorganic materials resulted in improving porosity, optimizing moisture content, and increasing nutrient bioavailability, which are critical parameters for a well-managed composting processing and nutrient release effectiveness. It is also affected by the initial particle size of the composting material; smaller particle sizes tend to accelerate with the rise in temperature, increase in the thermophily period, and increase the degradation of organic matter with nitrogen fixing, which further increases maturity and heavy metal passivation from the composting end product [126]. Moreover, the addition of microbial inoculants to open composting systems can exhibit a gain in beneficial environmental and economic benefits through increased concentrations of humic acids and total nitrogen, reduced ammonia emissions, and minimized costs [3]. The right bulking agents, as well as all pre-treatment methods of sludge, are also important choices because they affect the final quality of the compost and consequently its application to soil ecology. For example, straw, which falls under the category of bulking agents, generally reduces the bioavailability of heavy metals such as Cu and Zn, thus making the composting of these materials more environmentally friendly for agricultural purposes [127]. Other co-composting materials, for example, spent mushroom and spent bleaching, have also been used to enhance microbial community succession, which is essential in the detoxification of the heavy metals and the oxidation of the organic matter [109]. The long-term application of composted sludge from wastewater in agricultural soil in sugarcane nurseries, among other uses, was observed to restore soil fertility, reduce or avoid the use of mineral fertilizers, and improve sustainable waste management practices in agriculture [128]. Finally, kinetics related to transformations of organic matter and nitrogen during the composting process may provide details for the optimization of

this process, as observed in degradation rates and patterns of nitrogen loss of different composting setups [55].

Table 13. Laboratory to full-scale experiences of sludge composting [8,16,103,108,114,118].

Aspect	Case Studies and Experimental Research	Challenges in Scaling Up	Solutions
Microbial activity and process optimization	Studies comparing different bulking agents and their impact on microbial communities and decomposition rates. Research on the effectiveness of temperature control strategies for pathogen reduction.	Maintaining consistent and optimal conditions for diverse microbial populations across a larger volume. Ensuring efficient heat retention and temperature control in larger piles.	Implementing automated turning systems for improved aeration and moisture management. Utilizing in-vessel composting systems with controlled temperature settings.
Nutrient availability and compost quality	Experiments evaluating co-composting sludge with various organic materials for nutrient balance and compost properties. Research on the impact of pre-treatment methods on final compost quality and nutrient content.	Balancing nutrient composition (especially nitrogen) in large-scale composting operations. Ensuring consistent quality and meeting regulatory standards for heavy metal content in the final compost.	Utilizing co-composting strategies with materials rich in specific nutrients (e.g., yard trimmings for nitrogen). Implementing pre-treatment methods like lime stabilization to address potential heavy metal issues.
Odor control	Research on the effectiveness of bulking agents and moisture management techniques for minimizing odor generation. Studies evaluating odor control technologies like biofilters for full-scale operations.	Managing large volumes of odorous material during turning and pile manipulation. Potential for public nuisance from odors if not properly controlled.	Selecting appropriate bulking agents with high odor adsorption capacity. Implementing odor control systems like biofilters or positive aeration systems in full-scale facilities.
Cost-effectiveness and long-term sustainability	Life cycle assessments comparing different sludge composting technologies. Economic analyses evaluating the cost-benefit of sludge composting compared to alternative disposal methods.	High initial capital investment for large-scale composting facilities. Balancing operational costs with long-term benefits like reduced landfill reliance and potential revenue from compost sales.	Utilizing government grants or public-private partnerships to finance infrastructure development. Exploring innovative marketing strategies to increase the demand for high-quality compost produced from sludge.

5. End-Product Quality and Utilization

5.1. Characteristics of Composted Sludge

Through composting, the nutrient profile of the sludge was improved significantly, especially by increasing the concentrations of HA and TN, which are critical for soil fertility and plant growth [3]. Table 14 presents key characteristics of the composted wastewater treatment sludge, which are essential for its applications in soil amendment and environmental safety. The compost quality, such as the amount and quality of HS, FA, and HA, is viewed as a paramount indication of compost maturity and chemical stability, which is significant in mitigating desertification and ameliorating SOM [55].

Table 14. Key characteristics of composted sludge [6,12,13,87].

Characteristic	Description
Appearance	Dark brown, crumbly material with minimal earthy odor (if managed properly).
Particle Size	Varies depending on initial feedstock and processing methods.
Organic Matter Content	Significant, lower than initial sludge.
Moisture Content	40–60%
Nutrient Content	High nitrogen, phosphorus, and micronutrient contents
C:N Ratio	10:1 to 20:1.
pH Level	Acidic to neutral (pH 6.5–7.5).
Pathogen Levels	Significantly reduced due to high temperatures

As shown in Table 14, composted WWTS exhibits specific characteristics that make it a valuable resource as solid waste compost, due to its nutrient-rich composition and reduction in microorganisms. Also, investigations on composting of various additives like biolysed sludge have shown that nitrogen retention and the humification of additives mixed with compost could contribute to a decrease in nitrogen loss and improve stability and maturity [14]. Mixing the sludge digestate with compost resulted in improved agronomic properties and biological stability of compost products that meet the EU fertilizer standards and reduce environmental risks [55]. Critical indicators for the biological stabilization of composted sludge are volatile fatty acids, volatile solids, the carbon/nitrogen ratio, and humic substances, representing the basis for evaluating the stabilization and safety of compost [87].

5.2. Potential Applications in Agriculture, Landscaping, and Soil Improvement

Composting wastewater sludge treatment provides a sustainable mode for providing agriculture, landscape, and soil improvement for the enrichment of organic matter and nutrients. In agriculture, composted sludge is used as a fertilizer to increase soil fertility and the yields of crops. Field trials have shown that adding municipal sewage sludge at application rates of 15 t/ha and 25 t/ha to agricultural soils significantly increases the yield of soybean and wheat crops without exceeding the maximum values for heavy metals and can enhance the physical, chemical, and biological properties of soil [39]. Also, the incorporation of compost or biochar from sewage sludge in soil is a strategy used to increase the organic matter in soil, which is vital for sustainable land management and agricultural productivity [3]. When it comes to landscaping and the ornamental plant industry, the combination of composted sludge with porous inorganic material, including pumice stone and expanded perlite, could be used as a substrate [53]. This combination ensures better porosity, ideal moisture content, and nutrient-enriched profile, which is beneficial for plant growth and could be used as an alternative to conventional non-renewable media. Composted sludge also has been found to improve soils. In applications as soil improvement, sludge has been found to successfully stabilize collapsible soils. The addition of sludge to soil decreases the void index, increases particle packing, and decreases soil collapsibility [129]. Furthermore, regarding the post-mining land reclamation, the application of municipal sewage sludge compost has significantly enhanced the activity of soil enzymes, indicating an effective soil restoration and the initiation of soil-forming processes [130]. Moreover, composting treatments incorporating sewage sludge have been engineered to produce compost with high-quality indexes, which are suitable for soil recovery in agricultural systems, and circular economy, by recycling waste into valuable resources [40]. These uses of sludge-based composts highlight the multiple ways municipal wastewater treatment sludge composting promotes sustainable agricultural systems, landscaping, and soil management.

Sludge-to-organic-fertilizer conversion is intrinsically linked to principles of the circular economy and sustainability because it emphasizes the reuse and recycling of wastes

in order to attain valuable products that reduce impacts on the environment while conserving resources. In this respect, the conversion of sewage sludge into organic fertilizer falls squarely within the idea of the circular economy by turning waste into a resource enhancing fertility and productivity in agriculture. For example, it has been identified that sewage treatment biosolids are rich in nutrients such as nitrogen, phosphorus, and sulfur—components that can be re-circulated into agriculture soils to make agricultural production cleaner and food safer to eat [54]. Actually, it has been shown that mixes of dried sewage sludge and green liquor dregs with sewage sludge demonstrate significant productivity increases in lettuce crops without disrupting nutritional balances of either crop or soil compared to commercial fertilizers [131]. On the other hand, pathogens and high loads of heavy metals in this sludge present potential health hazards and require strict quality control and legislation to be safely applied [18,132]. Even with these challenges, the agronomic potential of treated sewage sludge has been confirmed to improve both plant growth and physiological status, as noted in studies, or as in the case of PDSS, improving lettuce and carrot growth [133]. Furthermore, the valorization of sludge into energy, for example, biogas, increases the value of this waste stream even more. In Poland, for example, after modernization, WWTPs have been reported to produce enough electricity from biogas to feed energy-positive and environmentally friendly operations [134]. As a matter of fact, the idea of biorefineries is to recover biogas, nutrients, and other valuable products like biopolymers and biofuels from sludge, which would sustain waste management [135]. Moreover, phosphorus recovery in water purification processes produces products like struvite and vivianite, which are equivalent to the conventional use of mineral fertilizers, thereby promoting sustainability in agriculture against phosphorus scarcity [136]. The application of these practices within a circular economy framework yields not only an environmentally friendly method of sludge disposal but also economic and social co-benefits accruable from reduced landfill use, reduced disposal costs, and renewable energy production [137].

5.3. Economic Feasibility and Market Demand

Various factors such as production cost and revenue potential, such as consumer's willingness to pay, determine the economic feasibility and market demand for composted sludge (see Table 15).

Table 15. Key aspects with impact on economic feasibility [138–141].

Factor	Description	Potential Advantages	Potential Disadvantages
Production Costs	Composting process costs (equipment, labor, bulking agents, etc.)	Reduced landfill fees, potential revenue from compost sales	High upfront investment, ongoing operational costs
Transportation Costs	Transporting sludge and finished compost	Economies of scale for larger facilities, potential for local markets	Distance to markets can impact profitability
Compost Quality	Nutrient content, organic matter, level of contaminants	Premium pricing for high-quality compost suitable for specific applications	Lower prices for compost with limited use cases
Market Demand	Demand for composted sludge in agriculture, landscaping, or other applications	Reduced disposal burden, potential for environmental benefit	Fluctuations in demand, competition from other organic fertilizers
Regulations	Government regulations on compost use and safety standards	Ensures safe application, potential government incentives for sustainable practices	Regulatory compliance can add complexity and cost

Several investigations have demonstrated that composting, especially that involving sewage sludge, can have financial sustainability and environmental advantages. For example, composting thermally hydrolyzed anaerobically treated dewatered sludge with green

waste has been able to generate environmental and economic benefits via a significant increment of humic acids and total nitrogen concentrations together with a reduction in NH_3 emissions sustained with competitive cost price [3]. A scenario analysis on the finance of domestic sewage sludge composting for fertilizer revealed that the profit verifies its investment worthiness [138]. Also, the market is expected to move toward composted products, which is promising. Similar profit success levels and a lower risk of loss were associated with the vermicomposting composting process, with waste materials like hazelnut husk and sewage sludge, another kind of compost mixture that is financially viable [138]. Also, the use of anaerobic digested sludge as compost is an alternative to handling sludge in small communities [140]. However, to have robust markets, product standards are required to be established, and compost quality needs to foster consumer confidence and demand [141].

Although it faces challenges, composting sludge displays potential for economic feasibility. Ensuring high-quality compost production, maximizing processing efficiency, and creating an embracing market atmosphere are all vital considerations.

6. Environmental and Regulatory Considerations

There are several environmental benefits and regulatory challenges associated with composting municipal wastewater treatment residual sludge that should be evaluated in this context. The composting process is recognized for its potential to return nutrients to the soil, thus keeping these in the ecological cycle [3,87] and improving the SOM; it thus plays an essential role in reducing Europe's desertification [87].

Nevertheless, it is crucial to manage the environmental performance, including the emissions of GHG and air pollutants (ammonia (NH_3), volatile organic compounds, CH_4 , and nitrous oxide (N_2O)), which are extremely triggering in terms of the variations in the constituents of waste materials, pretreatment procedures, and composting operation [58].

Regulatory aspects are vital, as the quality of compost—including its stability, pathogen contents, and heavy metal concentrations—must meet rigorous standards that guarantee its safety and effectiveness for agricultural usage [17,25]. The presence of heavy metals and antibiotic resistance genes in sewage-sludge-derived compost implies rigorous monitoring and control to make sure United States and European Union Member States' standards are satisfied [55].

Furthermore, a high degree of biological stabilization must be achieved during the composting process, with special attention being paid to the C:N ratio, to prevent the excessive formation of odorous compounds, as well as guarantee the agronomic value of the composted product [13,142]. Innovative treatments, like the use of microbial inoculants or the selection of specific bulking agents, have been shown to improve compost quality through increasing humic acid contents and ameliorating nitrogen retention, thereby sustainably encouraging composting of MSS from both the environmental and economic perspectives [35,80].

Furthermore, environmental risks can be addressed and nutrient content valorized by integrating anaerobic digestion and composting, meeting EU fertilizer regulations, and yielding the agronomic use of digestate-based mixtures.

6.1. Impact on GHG Emissions

There are several different aspects of how MSS composting affects GHG emissions. There are certain ways it could lead to a decrease and other ways it could lead to an increase. Some of the things that determine which way it goes are the composting method used, the composition of the sludge being composted, and how well it is being managed. There are potential environmental benefits with composting sludge, but also some drawbacks, particularly with GHGs (Table 16). One of the ways that composting sludge can decrease GHG emissions is by acting as a substitute for nitrogen fertilizers in agriculture, which decreases N_2O , CH_4 , and CO_2 emissions from synthetic fertilizer production and use [143].

Not only does this substitution decrease the global warming potential, but it also increases soil organic carbon, improving soil health and potentially sequestering carbon [144].

Table 16. Impact on GHG emissions [143–145].

Aspect	Impact on GHG Emissions	Explanation
Landfilling vs. Composting	Positive	During anaerobic decomposition, CH ₄ is produced in landfills, a GHG. CH ₄ production is reduced by aerobic composting.
Fertilizer Replacement	Positive	Composting reduces the need for energy-intensive synthetic fertilizers.
Incomplete Composting	Negative	If composting is mismanaged, CH ₄ is produced.
Nitrous Oxide Emissions	Negative	Composting can also generate nitrous oxide, another harmful GHG.
Energy Use	Negative (potentially)	Operating composting facilities use energy, possibly producing additional harmful emissions depending on its source.

Regardless, the process of composting can in itself lead to GHG emissions, in particular CH₄ and N₂O, which are potent GHGs. In composting, anammox bacteria capable of nitrogen removal are present, which suggests a way to reduce N₂O emissions during composting, because N₂O is a byproduct of nitrogen mineralization in composting processes with low C:N ratios [146]. In addition to this, the combination of sewage sludge and maize straw composting has shown that temperature changes and ammonia volatilization are directly related to the percentage of sludge content, and thus the proportion in the addition of bulking agents could be a possible factor influencing GHG emissions during the composting process [147]. In certain cases, research has shown that CH₄ resulting in cropland may be increased by composted sludge and other alternative natural amendments, representing a potential mitigation strategy for CH₄ under some environmental conditions [148]. However, GHG reduction depends on how compost is managed after treatment. For example, if sludge-based compost is spread on land, it may not be a long-term carbon sink and could balance out some of the benefits of GHG mitigation [149]. Although MSS composting can reduce GHG emissions by replacing synthetic fertilizers and by increasing soil carbon sequestration, the composting operation and subsequent handling practices emit GHG as well. To maximize the GHG mitigation potential of sludge composting, it is crucial to optimize composting conditions, such as the C:N ratio, adding bulking agents, and carefully managing final compost products.

For example, it was shown that different mixing ratios of pelletized wheat straw and sewage sludge had a major influence on CO₂ and CH₄ emissions, with vermicomposting reducing the latter by 18–38% but increasing the former by 64–89% compared to standard composting [150]. In addition, another study reported that total carbon emissions from aerobic composting are much higher than those associated with vermicomposting, where aerobic composting units accounted for CO₂ emission factors equaling 43,900 kg/ton [151]. Furthermore, emission factors for GHGs during traditional sewage sludge composting were found to be 2.30×10^2 kg CO_{2eq}·Mg⁻¹ DM-SS [152]. The use of bulking agents like maize stir has been known to reduce the amount of ammonia gas released into the environment, and less leachate has also been generated, although this comes with strong CO₂ emissions at thermophilic stages of composting process [153].

Many industrial fertilizers make a large contribution to GHG emissions, mainly due to the production process for nitrogen-based fertilizers. One such example is inorganic N fertilizers applied to grasslands, which can result in a net 3 Mg CO_{2e} ha⁻¹ emission for a three-year project. While this is low compared to the manure slurries, it still presents a large number [154]. In contrast, the composting of sewage sludge can be expected to be a more sustainable option with GHG savings. Indeed, whereas some composting processes could totally avoid, or at best reduce, GHG emissions, especially if linked with anaerobic

digestion. For instance, composted manure and plant waste can result in net GHG offsets of 23 Mg CO₂e ha⁻¹ over three years, dominated by avoidance associated with diverting organic waste from high-emission waste management practices, alongside benefits from enhanced soil carbon sequestration and reduced requirement for commercial feeds [154]. Additionally, co-composting sewage sludge and green waste with microbial inoculants in semi-anaerobic conditions could evidently reduce NH₃ emissions by up to 26.6% while greatly increasing the humic acid and total nitrogen concentration, leading to further improvement in soil fertility and reduced fertilizer consumptions [3]. The environmental benefits of composting are also manifested regarding significant reductions in emissions of N₂O—one of the most important contributors to global warming potential (GWP) from nitrogen-rich wastes. For example, composting may decrease N₂O emissions as high as 90% in comparison to conventional NPK fertilizers, based on the fact that the application of these fertilizers could contribute up to 15.7 kg N ha⁻¹ of N₂O under heavy-rainfall conditions [155]. Added to this, large CH₄ reduction can be achieved by composting sewage sludge since CH₄ accounted for around 80% of the total GWP100 for yard waste composting [80]. It had been demonstrated that good pile management and aeration reduced CH₄ emissions during composting because, according to studies, the majority of CH₄, together with CO₂, was emitted during the initial three weeks of composting [156]. Moreover, sewage sludge co-digestion with agri-food wastes may improve energy recovery (from biogas production) and GHG reduction potential [157]. However, the economic feasibility of composting is challenging because the cost of purchasing and transporting composted manure is higher than that of synthetic fertilizers. Nevertheless, the long-term nutrient release from organic amendments can provide additional savings [158]. While industrial fertilizer production is highly GHG-intensive, composting sewage sludge offers a viable and environmentally friendly alternative, achieving substantial GHG savings and promoting sustainable agriculture. Producing compost from sewage sludge may economically be an advantage over commercial composting.

6.2. Pathogen Reduction and Safety Considerations

Composting MSS is a suitable method for pathogen destruction and obtaining safe composts for agricultural use. Several studies have demonstrated the effectiveness of different composting technologies in inactivating or substantially reducing microbial pathogens, including bacteria, viruses, and parasites, which affect public health and the environment. It has been proven that whether vermicomposting technology or traditional technology is used, composting completely reduces or lowers fecal coliform and also completely removes parasite eggs such as ascaris in a relatively short period to meet the strict standards of compost [159]. Additionally, previous studies have suggested that in-vessel composting using sawdust as a bulking agent was effective in significantly reducing total heterotrophic bacteria, coliforms, *Salmonella* sp., and *Shigella* sp., indicating the treated sludge is safe for land application [160]. Additionally, hyperthermophilic composting is remarkably efficient at removing ARGs and mobile genetic elements from wastes, sharpening the safety of compost for agricultural purposes [35]. Yet, the existence of harmful elements and the persistence of particular germs, as well as *Salmonella* serovar Enteritidis, in intermediate composts stresses that the sanitation conditions of composting should be meticulously implemented to ensure pathogen's total inactivation [62,161]. Another aspect of composting that greatly affects the stability and quality of compost is the incoming microbial diversity in sewage sludges, which is decided by the characteristics of sludge sources and treatment conditions [150]. A new low-tech method of sanitization presents itself with several advantages: nutrients are being retained while killing off pathogens, comprising soil gram-negative bacteria, enterococci, yeasts, viruses, and parasites that cause disease in poultry and pigs, with minimal mass loss [162]. The use of this method, in conjunction with well-managed composting techniques, can considerably curtail the hazards, which come with the adoption of MSS in agriculture, guaranteeing environmental and public health safety.

6.3. Compliance with Environmental Regulations and Standards

The compliance of sludge compost with environmental regulations and standards is multi-faceted, including the heavy metal content, pathogen reduction, nutrient stabilization, and impact on soil and plant health. Studies suggest the heavy metal concentration in composted MSS can attain the demands established by the USA and European Union countries (Table 17), but it could fall short of some of the strictest among them, considering that the initial sludge contents are essential [35]. Blending composts with digestates has been pinpointed as a measure to safeguard the environment and optimize nutrient content, all while upholding the EU fertilizer decree requisites [55]. The Part 503 regulation of the US Environmental Protection Agency to protect public health and the environment from pollutants in biosolids is based upon risk assessments for chemical constituents but not pathogens. This underscores the need for future scientific work in this area to manage uncertainties in the context of human health effects [163].

Table 17. Regulations and standards for sludge compost use (European Union and USA) [35,55,98,163].

Regulation	Key Points	Impact on Sludge Compost Use
Sludge Directive (86/278/EEC)	Sets limits for contaminants (heavy metals, pathogens) in sludge for agricultural use.	Ensures composted sludge used on land meets safety and quality standards.
Landfill Directive (1999/31/EC) (Policy-Driven)	Promotes diverting waste from landfills.	Creates potential demand for compost as a soil amendment (indirect encouragement).
Waste Framework Directive (2008/98/EC) (Policy-Driven)	Establishes waste hierarchy prioritizing reuse/recycling over disposal.	Positions compost use favorably by utilizing a recycled product.
U.S. EPA Part 503 Rule	Sets national standards for land application of sewage sludge (biosolids).	Establishes pollutant limits for heavy metals, and pathogens. Requires monitoring, and recordkeeping.—Restricts use on specific crops/areas.
Individual State Regulations	Most states have stricter standards than the federal rule.	May have lower pollutant limits. May have additional use restrictions. May require permits for compost facilities.

To sum up, complying with sludge composting regulations and standards for the environment requires a holistic view of many factors. The original quality of the sludge, the techniques used to treat and compost it, and the long-term impacts of the soil on plant health must be considered.

7. Future Directions and Conclusions

7.1. Emerging Trends and Innovations

New techniques for sludge composting treatments are being tested, and they have the following improvements as a target: in the sludge composting process, efficiency increases, and the compost quality increase (Table 18). One of the most important trends is the application of advanced pre-treatment processes like thermal hydrolysis, ozonation, or ultrasonic to sewage sludge, which increases the biodegradability and composting efficiency [3,13]. Also, the application of microbial inoculants together with specific microbial groups discussed above like anammox bacteria is also interesting. The main aim of this trend is to improve nitrogen removal as well as decrease GHG and odorous compound emissions during composting [150].

Sludge composting is a continuously changing field. New challenges have surfaced, and a few have gone. Several technologies have been developed to meet the challenges and improve efficiency. These new trends and innovations continue to show sludge composting technologies that are sustainable, effective, and environmentally friendly in handling sewage sludge.

Table 18. Key trends and innovations in sludge composting [3,17,102,103,107,108,118].

Trend/Innovation	Description	Potential Benefits
Advanced in-vessel composting systems	Using closed composting systems, where the temperature, aeration, and moisture are all controlled.	This leads to uniform and optimum composting conditions resulting in speedy decomposition and minimized odor emissions. There is potential for capturing and using biogas for generating energy. It causes a minimum amount of impact on the surrounding environment because of the controlled conditions.
Microbial augmentation with targeted strains	Adding certain strains of bacteria or fungi to help the decomposition of more complex organic matter in the sludge.	It will increase the speed of composting and the breakdown of specific pollutants. It creates the possibility of modifying microbial communities to deal with specific sludge characteristics.
Thermal hydrolysis pre-treatment	Pre-treating sludge with high temperature and pressure to break down complex organics and improve dewaterability.	There would be improved biodegradability of the sludge, and it can be composted in a shorter time and higher quality. It decreases amount of sludge, so less money is required for moving and treating sludge.
Vermicomposting	Adding earthworms to traditional composting to give an extra boost to decomposition, enhancing compost quality.	It generates a compost that is rich in nutrients and has excellent soil-enriching properties. Compared to traditional composting, there is potential for odor reduction.
Use of alternative bulking agents	Using new constituents like biochar, composted food waste, or agricultural residues as bulking agents.	These are sustainable and readily available alternatives to traditional bulking agents (wood chips, straw). Biochar can improve moisture-holding capacity and conceivably diminish odor and volatile emissions. Composted food scraps can increase the nutrient content of the finished compost.

7.2. Recommendations for Further Research

Future studies on sludge composting should direct more attention to several key aspects to make the process optimal and beneficial in terms of both environmental and economic factors. Firstly, the exploration of anammox bacteria's role and its optimization in composting processes would further reduce pollution to the atmosphere associated with nitrogen and produce more effective nitrogen removal results, which are challenging due to low C:N ratios [13]. Researching the environmental and economic impacts of using microbial inoculants in composting, specifically with semi-anaerobic conditions, can enhance the quality and cost efficiency of composting thermally hydrolyzed anaerobically treated dewatered sludge [3]. Also, there is a need for understanding how various aeration strategies influence humic substance electron transfer ability, as well spectral character under the condition of sludge composting, which provides anchor for an effective method for soil amendments [163]. It has been indicated that vermicomposting can be potentially used to reduce potential toxic heavy metals in sewage sludge and bioaccumulation in earthworm tissues. It would be constructive to find a safer way to compost sewage sludge [150]. Exploring the different sludge additives' effects on nitrogen conversion, humification, and composting maturity can have the benefit of producing good-quality and environmentally safe compost [30]. Further research recommendations and their potential impact are summarized in Table 19.

Table 19. Further research recommendations.

Research Area	Description	Potential Impact
Improving the composting process for specific types of sludge	Study the optimal composting conditions (temperature, aeration, bulking agents) for different types of sludge (primary, secondary, waste activated sludge).	Design composting procedures to enable the best composting results and compost quality for different types of sludge
Assessing the long-term consequences of composted sludge on soil health	Undertake long-term research to examine the impact of applying composted sludge on soil properties, microbial communities, and crop productivity.	Generate reliable data for establishing safe and effective long-term approaches to employing sludge in agriculture.
Life cycle assessments (LCAs) of emerging technologies	Conduct comprehensive LCAs of emerging technological solutions.	Optimize these technologies for maximum sustainability.
Minimizing emissions from composting processes	Develop control strategies for further reducing ammonia (NH ₃) and nitrous oxide (N ₂ O) emissions during composting while maintaining process efficiency.	Contribute to lower overall GHG emissions from sludge composting.
Public perception and social acceptance	Investigate drivers of public perception of sludge composting and develop strategies for promoting sludge composting's environmental and economic benefits.	Address public concerns and build social acceptability for expanded application of sludge composting.

These research themes are moving towards a better way of composting sludge that not only delivers environmental benefits but also presents economic advantages. If research is concentrated on those specific areas, it could increase the level of precision and decrease environmental pollution while maintaining the economic and environmental benefits of this sustainable waste management.

For example, sludge composting is a time-dependent process; therefore, the kinetic study in the composting process, mainly bringing the optimal C:N ratio for sewage sludge composting, would improve the degradation process and increase the compost's stability [60].

Implementing the full-scale composting of wastewater treatment sludge to produce sustainable and efficient bio-organic fertilizers faces several challenges, necessitating further research into iterative scaling strategies. A significant issue in this process is the variability in sludge quality and the presence of pollutants and contaminants, such as heavy metals and microplastics. These contaminants pose substantial environmental risks if not properly managed [18,164]. It has been shown that different methods of composting, such as aerobic composting and vermicomposting, affect organic matter degradation and nutrient retention—including nitrogen, in particular—which is crucial for maturity and quality during this composting process [15,165]. For instance, biolysed sludge has been shown to perform better than other processes in improving nitrogen retention and humification; these refer to the fact that with optimized composting procedures, the quality of the final output could be superior [15]. However, microplastics potentially present in sewage sludge underscore the need to develop advanced technologies to ensure safe sludge management and prevent contaminations of soil [164].

Scaling strategies must be part of the development of solutions to address the current technical and economic challenges impeding full-scale deployment. For example, co-digestion and pre-treatment methods have proven effective in increasing biogas production and sludge biodegradability, reducing treatment costs, and enhancing energy recovery in wastewater treatment plants. Further research is required to explore nutrient recycling and sludge treatment, as well as innovative technologies designed to address heavy metal contamination and microplastic pollution and to minimize carbon emissions [166]. Additionally, the presence of potential pathogens might require further post-treatment to ensure the resulting compost is safe for land application. Thus, comprehensive research

and iterative scaling strategies are essential to address these challenges, enabling the production of sustainable and efficient bio-organic fertilizers from wastewater treatment sludge [18,164,166–168].

7.3. Summary of Key Findings and Conclusions

The review highlights that composting municipal wastewater sludge is a promising and sustainable method for waste management, aligning with circular economy principles by recycling waste into nutrient-rich compost. Traditional methods like landfilling and incineration pose significant environmental and health risks, while composting, particularly with the use of various amendments and bulking agents, improves compost quality and nutrient stabilization.

The environmental and economic benefits of composting municipal wastewater sludge are substantial. Composting reduces landfill reliance, lowers GHG emissions, and provides cost-effective solutions by producing high-quality compost that meets regulatory standards for safety and nutrient content. Ensuring compliance with environmental regulations, particularly regarding heavy metals and pathogens, is crucial for safe agricultural use.

Case studies and identified experimental research demonstrate the effectiveness of composting in reducing the risks associated with contamination with heavy metals and potentially pathogenic agents. Innovative technologies, including microbial growth and thermal hydrolysis, are explored to increase compost quality and efficiency. However, transitioning from laboratory to full-scale composting presents challenges regarding temperature distribution, microbial consistency, and odor management, necessitating advanced pre-treatments and process optimizations.

Thus, future research should focus on optimizing composting processes for specific sludge types, understanding long-term soil health impacts, and enhancing public perception and acceptance. Overall, composting municipal wastewater sludge offers a viable and sustainable strategy for waste management, contributing significantly to sustainable development and environmental conservation. The review also emphasizes the importance of complying with regulations and environmental standards to ensure the safe use and efficacy of the composted sludge. By embracing advanced technologies and accession to strict regulatory standards, the benefits of composting can be maximized, contributing to the sustainability of the environment and the recovery of resources. Future research should focus on optimizing composting processes, improving compost quality, and approaching environmental and economic challenges to ensure the large-scale adoption and success of sludge composting practices.

Author Contributions: Conceptualization E.E.M. and C.B.; formal analysis, C.B.; investigation C.B. and E.E.M.; writing—original draft preparation, all authors; writing—review and editing, all authors; project administration, C.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was carried out through the “Nucleu” Program within the National Research Development and Innovation Plan 2022-2027 with the support of the Romanian Ministry of Research, Innovation and Digitalization, contract no. 3N/2022, Project code PN 23 22 03 02.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

Abbreviation List

Abbreviation	Meaning
ARG	Antibiotic resistance genes
BA	Bulking agents
BS	Biolysed sludge
C:N ratio	Carbon-to-nitrogen ratio
COD	Chemical oxygen demand
EU	European Union
EC	European Commission
FA	Fatty acids
FAO	Food and Agriculture Organization
FS	Fecal sludge
GHG	Greenhouse gas
GI	Germination index
HA	humic acids
HR	herb residue
HS	humic substances
LCA	Life Cycle Assessment
MC	Mature compost
MSS	Municipal sewage sludge
MSW	Municipal solid waste
OFMSW	Organic fraction of municipal solid waste
PTE	Potential toxic elements
SM	spent mushroom
SOM	Soil organic matter
SWD	Sawdust
TK	Total potassium
TN	Total nitrogen
TP	Total phosphorus
WHO	World Health Organization
WWTP	Waste Water Treatment Plant

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