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Review

Composting as a Sustainable Solution for Organic Solid Waste Management: Current Practices and Potential Improvements

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Abstract: With increases in global population and urbanization, the production of Municipal Solid Waste (MSW) is growing rapidly, thus contributing to social and environmental concerns for sustainable waste management. This study addresses the research gap in optimizing composting, hypothesizing that integrating best practices and recent innovations can enhance the efficiency of the process. Data were collected through a systematic review of existing literature using Google Scholar and Scopus databases. The review provides an overview of municipal organic waste composting, outlining its processes, benefits, and challenges with the aim of identifying key area of further improvement and possibilities of adopting recent technological innovations. The analysis emphasized that technological advances in composting, as microbial inoculants or in-vessel composting have greatly improved the efficiency and quality of the resulting compost. However, several challenges remain, including managing contaminants such as heavy metals and microplastics, ensuring the compost quality and safety and addressing socioeconomic barriers that prevent widespread adoption. Moreover, process optimization, environmental and economic evaluation, as well as political and public involvement are essential to unlock the whole potential of composting systems.

Keywords: nutrient recycling; organic waste composting; municipal waste management; sustainable resource utilization; soil amendment

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1. Introduction

Population growth, urbanization, and economic advances have directly accelerated and contributed to increased generation of municipal solid waste (MSW) [1,2]. Such surging waste production leads to significant concerns and challenges for sustainable waste management systems development, environment conservation, and resource recovery [3]. Among the different constituents of MSW, the organic fraction, primarily food waste, garden wastes, and other biodegradable materials accounts for a large fraction (40–70%), particularly higher in developing countries [2]. This organic fraction represents a challenge and an opportunity for innovative waste treatment solutions development [4,5]. The negative environmental consequences of traditional waste disposal methods have aroused growing criticisms, landfilling and incineration leading to greenhouse gas (GHG) emissions, leachate production, and valuable organic carbon loss [6,7]. Landfilling biodegradable organic waste generates significant amounts of methane (CH_4) and ammonia (NH_3), powerful GHGs that contribute to climate change [8–10]. On the other hand, incineration generates CO_2 emissions together with other potentially toxic contaminants such as dioxins [2]. In this context, the need for sustainable waste management practices that not only address environmental hazard mitigation but also actively promote resource recovery is more pressing than ever. Composting involves a series of aerobic transformations of organics through microorganisms' activity with the production of a stable product known as compost [11–13]. Composting offers numerous environmental advantages such as reducing the volume of waste landfilled, reducing pestilential odors associated with the anaerobic degradation of organic waste, reducing methane emissions, and transforming organic wastes into valuable nutrient-enriched soil amendments [14,15]. Moreover, using compost as a soil amendment has the potential to enhance soil fertility, increase carbon sequestration, and improve soil structure, physical, chemical, and biological properties [16]. Thus, the process of composting perfectly integrates into the desired circular economy context by promoting nutrient recycling and diminishing the demand for synthetic fertilizers supporting, at the same time, sustainable agriculture practices and long-term food security [17,18].

Improvements in composting technology and practices have increased its efficacy and relevance. Techniques such as in-vessel composting, vermicomposting, and the use of microbial inoculants have augmented the composting efficiency and the quality of the compost. Moreover, the merger of composting with different waste administration solutions like anaerobic digestion has created supplementary alternatives for useful resource restoration and power generation [19].

Beyond having multiple environmental and economic benefits, the widespread adoption of the composting process as a mainstream waste management solution faces some technical challenges and socio-economic barriers. Most concerns are related to the presence of contaminants like heavy metals and microplastics in feedstock and final compost and the predictability of quality and safety of compost produced [11]. To alleviate these issues well-rounded management practices, regulatory frameworks and policy implementation plans are necessary.

The main objective of this paper is to provide a comprehensive review of organic solid waste composting in terms of processes, benefits, and challenges, and it also includes a synthesis of current knowledge and identified research gaps, trying to provide new insights into modern composting technology and practices and future research opportunities to strengthen the composting science and practices and to foster sustainability and resilience of waste management.

2. Review Methodology

The study was based on high-impact scientific papers identified in international databases (such as Science Direct, Web of Science, Scopus, IEEE Xplore, and Google Scholar), with an accent on recent studies. Of the multiple results, 173 research papers were included in the review, responding to the main research area of interest. Of these papers, 38 were published in 2023, 39 in 2022, and 25 in 2021 showing the high interest researchers have in composting municipal solid waste. The research studied was categorized in the main review chapters, focusing on municipal waste composition, composting process, nutrient transformation, the fate of contaminants during composting, benefits and challenges, case studies, and future directions.

3. Composition of Municipal Organic Waste

MSW contains a wide variety of materials, primarily originating from residential households, commercial, and garden sources with biodegradable organic waste as a predominant fraction. This fraction includes kitchen waste, yard trimmings, and other biodegradable materials susceptible to recuperative treatment through anaerobic digestion, composting, or a combination of both technologies thus contributing to the goals of the European Circular Economy Package and reducing emissions associated with landfill disposal [20]. In particular, there are several types of organic wastes, which can be classified by constitution in paper and cardboard, textiles, biodegradable plastics, biodegradable kitchen waste, and garden trimmings. For example, paper waste can be composed of receipts and newspapers, whereas cardboard waste may consist of egg cartons or contaminated pizza boxes, as examples. Textiles can be represented by obsolete clothing items made of natural fibers such as cotton, hemp, silk, or linen. Compostable, biodegradable plastics present in the organic fraction of MSW may be represented, for instance by starch or cellulose-based plastics, polyhydroxyalkanoates, polybutylene succinate, or others. Kitchen waste fraction refers to the organic waste generated from food preparation and consumption in households, restaurants, and other food service establishments and explicitly consists of items like food scraps (vegetable and fruit peelings, leftovers and spoiled food, eggshells and husks, coffee grounds and tea bags, paper towel and napkins) [21]. Yard trimmings are the organic waste materials resulting from gardening and landscaping and consist of grass clippings, leaves, trimmings, garden debris, weeds, woodchip bark, etc.

The main challenges when using biodegradable organic fractions of municipal solid waste as feedstock for composting are represented by the need to identify the proper balance of components to ensure the optimum C: N ratio and the potential presence of contaminant/microcontaminants [2].

Organic waste streams present substantial variation in macronutrient concentrations, such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), Magnesium (Mg), and Sulfur (S) as well as, in many cases, micronutrients such as boron, copper, manganese, and zinc (Table 1) [22–24]. Their concentrations and availability within the final compost are influenced by factors such as the initial organic waste composition, animal farming strategies, waste treatment processes, and additives. Sources of waste such as animal manure, biogas digestates, and composts can be extremely rich in macronutrients like N, P, and K, in the desired concentration range for plant growth. For example, animal manures and biogas digestates can have high variability in their nutrient concentrations caused by variations in feed composition and animal species [25].

Table 1. Composition and role of macronutrients.

Nutrient	Role as Macronutrient	Typical Range (g/kg)	References
Nitrogen (N)	Essential for the growth of microorganisms, helps in the decomposition	10–20	[26]
Phosphorus (P)	Helps plants growth	2–5	[27,28]
Potassium (K)	Enhances plant health and disease resistance	3–15	[27,29]
Calcium (Ca)	Enhances the disease resistance and plant growth	4–6	[30,31]
Magnesium (Mg)	Essential nutrient for plants	<0.1	[30,31]
Sulfur (S)	Microbial activity and some functions of plants	1–3	[32,33]

Nitrogen (N) has the highest concentration in compost (10–20 g/kg) compared to other nutrients, also playing a significant role in plant growth and microbial activity.

All listed nutrients (N, P, K, Ca, Mg, S) are essential for various plant functions including growth, disease resistance, plant health, and microbial activity.

The variability of nutrient concentrations leads to the necessity of knowing precisely what the actual concentrations are, both to supply crops with optimal amounts of nutrients and to minimize environmental problems due to over-fertilization [34,35]. The nutrient content of organic wastes and composts can be determined by classical chemical analyses, or by alternative methods such as X-ray fluorescence (XRF) spectrometry and near-infrared spectrometry (NIRS) [25,35]. These techniques have proven, due to their speed, non-destructive nature, and potential for automation, promising for assessing the bioavailability of both macronutrients and micro-nutrients; nevertheless, their accuracy varies because of the heterogeneity of the samples [36]. To meet this challenge, standardized sampling and sample preparation protocols backed by the use of appropriate calibration methods with well-characterized reference materials, and regular complementary analysis using traditional chemical methods should be implemented in large-scale composting facilities to reach a more comprehensive image of the nutrient content. The organic waste treatment solution applied, either composting or vermicomposting, can influence both the nutritional content and the availability of compost [34].

Though composting is one of the most valuable methods for converting organic waste into a nutrient-rich soil amendment, it should be mentioned that the presence of potentially toxic substances (PTS) in MSW is a specific issue of concern [37,38]. The most challenging PTS is potentially present in the organic fraction of municipal solid waste (OFMSW) concerning the occurrence are heavy metals, micro- and nano-plastics (MPs and NPs) including those coming from bioplastics (MBPs and NBPs), persistent organic pollutants (POPs), pharmaceuticals and personal care products. This points out OFMSW's composition complexity and the necessity of adopting proper collection strategies and measures to mitigate the occurrence of PTS in the composting feedstock [14,22–24]. Characteristics of PTS can vary widely during composting depending on factors such as composting temperature, moisture content, and feedstock composition.

4. Composting Process Overview

The composting process of municipal organic waste involves several steps designed to ensure mainly proper feedstock management (collection, sorting, screening, pre-processing, and mixing) and optimum biochemical conversion (composting and maturation) towards a stable final product (Figure 1).

Figure 1. Composting process overview.

4.1. Collecting Organic Materials

The first step involves collecting organic materials, such as food scraps, yard trimmings, and agricultural wastes, from residential households and business communities. One of the definite advantages of source separation over mechanical sorting in integrated waste management systems is the fact that it lowers the potential risk of contamination with plastics, metals, or personal care products-related contaminants. The result is a cleaner main feedstock that requires less processing and allows a more balanced carbon-to-nitrogen ratio which translates further into optimum microbial activity, faster decomposition rates, a lower potential for ammonia emissions, and a final compost with fewer contaminants of concern, and a more desirable nutrient profile [39].

4.2. Sorting and Screening

Sorting and screening procedures are designed to ensure a clean feedstock by removing inorganic contaminants such as plastics and metals. Initially, waste is segregated into various categories using mechanical systems that may include shredders, trommels, and magnetic separators to remove metals and other non-organic materials [40]. Additionally, optical sensors, such as infrared and color sensors, are used to further sort waste paper, plastics, and other recyclables, enhancing the efficiency of the sorting process [40]. Moreover, the latest developments in the field include advanced robotic systems using artificial intelligence-based algorithms which are being developed to automate waste sorting, for robust detection and manipulation of waste items, aiming to reduce human labor and improve sorting accuracy [41].

4.3. Pre-Processing of Organic Wastes and Bulking Agents

Pre-processing of organic wastes and bulking agents involves operations of shredding or crushing designed to reduce materials size, increase specific surface area, and increase the number of spaces inside the compost pile that may facilitate optimal gas diffusion, mainly oxygen (O_2) that is essential for the activity of thermophilic microorganisms responsible for breaking down the C-rich organic materials.

4.4. Feedstock Management and Mixing

Proper feedstock management and mixing is the cornerstone of a C/N balanced composting process as it is directly responsible for microbial growth, with an optimal range suggested to be between 25 and 35% [42–44]. In general, carbon-rich "brown" materials, such as dry leaves (30–80:1), straw (40–100:1), sawdust (200–500:1) or paper (150–200:1) are mixed with nitrogen-rich "green" materials, such as grass clippings (15–25:1) food scraps (15–25:1), manure (5–25:1), coffee grounds (20:1) to achieve the optimum balance [2,7,37]. Adjusting the C/N ratio is essential for promoting microbial activity and ensuring efficient composting [44]. A low C/N ratio can lead to higher emissions of GHGs and odorous substances like ammonia due to nitrogen mineralization, while a high C/N ratio can lead to severe issues such as low biological activity, lower degradation rates, insufficient heating of the composting pile, and longer composting periods [39,42,43,45].

4.5. Composting

A controlled mixture of organic matter is prepared and formed into windrows (aerobic piles) outdoors, or placed in enclosed vessels for in-vessel composting. Inside the compost pile, microorganisms including bacteria and fungi use oxygen to decompose the organic matter. This decomposition process results in heat generation leading to a thermophilic phase with temperatures ranging between 45−55 °C with peaks reaching sometimes up to approximately 80 °C [39]. The high temperature destroys pathogens and weed seeds ensuring a sanitized final product. During the composting process, maintaining optimal moisture content (around 50–60%) is essential for supporting microbial activity and maintaining the physical properties of the pile [45]. This is usually performed during regular turning of the compost pile which is crucial also for ensuring proper aeration [46].

4.6. Factors Influencing Composting Effectiveness

Excessive moisture can lead to anaerobic conditions, while too little moisture can inhibit microbial growth and activity and hampers organic matter mineralization as described in a study focused on grape marc and stalks composting [46,47].

Microorganisms have an essential role in municipal organic waste composting by contributing to nutrient mineralization, immobilization, and organic matter degradation. Different raw materials used as feedstock in composting have varied natural microflora, which plays the role of keystone taxa to steady active composting and maturation. Moreover, the addition of microbial inoculants has been identified as a beneficial strategy to enhance the biotransformation of organic materials during composting. The important role played by *Bacillus* and *Thermus genera* in the thermophilic stage is often underlined, with their thermostable enzymes such as proteases, cellulases, and lignin-modifying enzymes that are indispensable during the degradation of organic matter [48–50]. Research confirms that supplementation of microbial agents by thermophilic aerobic bacteria significantly improves organic waste degradation efficiency [48–50], proving that the selection of specific microbial consortia is crucial for the success of composting. In addition, the exploitation and application of valuable yeasts and filamentous fungi that possess high biotechnological potential such as *Pichia kudriavzevii* and *Aspergillus* spp. can act as starter cultures to achieve faster composting [51]. These indicate the importance of selecting specific microbial consortia for improved composting performances [52,53]. During composting, the diversity, composition, and function of microbial communities are significantly influenced by ambient parameters and physicochemical characteristics of feedstock, such as temperature and moisture content as well as total organic carbon, nitrogen, and phosphorus which govern the activity of microbial species, highlighting the importance of microbial interactions in the composting process [17,42,43,54]. Moreover, the presence of bioplastics has been reported to influence the composition and activity of the microbial community during composting, particularly during the aerobic phase [24,50]. Microbial-mediated nitrogen and sulfur cycles are also integral to the decomposition of MSW, affecting carbon cycling and emissions of GHGs [52,53].

4.7. Maturation

The maturation stage of municipal organic waste composting is crucial to ensure the stability and quality of the final compost product. In this stage, the temperature drops and the biological processes that govern the process are represented by the reduction of easily biodegradable carbon fractions, the increase in the concentration of humic substances, and the nitrification, respectively, the transformation of the remaining ammonium into nitrate [55–57]. Thus, the indicators of maturation and stabilization of the final compost are the high concentrations of humic substances and nitrates.

Recent research has indicated that the type of raw material used significantly affects microbial dynamics and enzyme activity during maturation, with different types of waste supporting different microbial communities [58]. For example, fungi tend to dominate in fish sludge compost, while bacteria are more common in manure and municipal sludge compost [59].

5. Nutrient Transformation and Fate of Contaminants during Composting

5.1. Nutrient Transformations

The transformation of biodegradable municipal organic waste into a nutrient-rich compost involves going through a sequence of complex biological and physicochemical processes influenced by various factors, including the composting method, the addition of bulking agents, and the presence of microorganisms. Key nutrient transformations during this process include the mineralization and mobilization of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na). Studies have shown that depending on the composting method chosen (among aerobic composting, anaerobic composting, and co-composting), it significantly influences the total losses of carbon (C) and nitrogen (N), the anaerobic composting method is indicated to have the lowest losses of C and N during the composting process [55,56].

During the composting process, nitrogen compounds undergo several successive transformations that involve both biological processes of ammonification, nitrification, and denitrification, as well as physical-chemical processes of immobilization and loss through leaching or volatilization. The ammonification process involves the enzymatic breakdown of proteins and other nitrogen compounds into amino acids and subsequently into ammonia (NH_3) and ammonium ions (NH_4^+) [57]. Ammonification ensures the availability of nitrogen, in the form of ammonium, for the subsequent processes of nitrification and denitrification [60,61]. The intensity of the ammonification process depends on the type of raw materials subjected to composting and the initial microbiota of the mixture [57,58,62]. Thus, the concentration of ammonium (NH_4^+) increases to a maximum level in the initial, thermophilic phases of composting, followed by a gradual decrease through the transformation of the accumulated ammonium into nitrate as a result of the biological nitrification processes [58–60]. Nitrification begins when the temperature of the composting mixture drops below 40 °C, with the highest nitrate concentrations observed at the end of the maturation phase [59,61]. The biological transformations of different forms of nitrogen, during composting, are enzymatically mediated by enzymes such as nitrate reductase, nitrite reductase, and urease [58]. The composting process generally results in an increase in total nitrogen (Nt) and nitrate nitrogen (N-NO_3^-), while ammonia nitrogen (N-NH_4^+) decreases [54]. However, significant attention must be paid to nitrogen losses that may occur through ammonia volatilization, especially when high ammonia concentrations coincide with high pH values in the composting system [14,62,63]. In addition, prolonged anaerobic conditions can inhibit nitrification, leading to a higher ammonium-to-nitrate ratio and delayed compost maturation [59]. Also, the use of earthworms in vermicomposting can, through the specific enzyme system, additionally improve nitrogen transformation processes, leading to higher concentrations of assimilable nitrogen in the final compost compared to traditional composting methods [64,65].

In composting, Phosphorus (P) can be identified in various forms such as inorganic P, organic P, water-soluble P, citric acid P, etc. Many researchers also reported that phosphorus available form changes considerably during composting processes [36,66,67]. For example, the availability of phosphorus will decrease during the thermophilic phase of composting but increase again during the compost maturation phase. Moreover, the composting feedstock (organic waste) plays an important role in phosphorus form changes during the processes. Studies have shown that poultry and pork manure have higher phosphor contents in comparison with other kinds of organic waste [67]. Microbial activity in the composting process plays an essential role in phosphorus transformation while the inoculation with specific microbial consortia such as *P. chrysosporium*, *T. viride*, and *P. aeruginosa* has been found to boost enzymatic activity, thereby speeding up the composting process and improving the nutritional value of compost [68].

The presence of certain bacteria groups is highly related to the release of inorganic phosphate into the soil and bounded phosphorus forms, especially bacteria harboring the phosphatase gene (phoD). The enzyme activities, such as alkaline phosphatase activity, are closely related to the transformation of P fractions by promoting the conversion of organic P into inorganic P, making it easily available to plants [68]. In particular, the specific case of vermicomposting shows a significant increase in phosphorus (24.9–45.8%) and potassium (24.9–45.8%) which is due to gut enzymes that help to release and mineralize these elements [64]. Moreover, the addition of rock phosphate during composting can further enhance the dissolution of mineral elements, contributing to the overall nutrient content of the compost [69].

The evolution of potassium during the composting process of municipal waste is relatively stable compared to other nutrients, such as nitrogen and phosphorus. This stability is due to potassium's non-volatile nature and its resistance to loss through biochemical or microbiological processes. Thus, as the organic matter decomposes, the potassium originally present in the organic waste remains in the resulting compost in the form of soluble salts, thus becoming easily available to plants [52,69]. As an example, the compost resulting from municipal solid waste has been shown to significantly bind potassium to organic matter, making it a viable alternative to traditional cattle manure for supplying potassium to crops such as lowland rice [70]. Similarly, calcium and magnesium levels increase because of the degradation processes occurring during composting as they are released from the organic matter and become more concentrated in the compost due to the reduction in organic mass through mineralization [10,66]. Sodium levels can also rise initially but may fluctuate depending on the source of the waste and leaching processes. For the specific case of vermicomposting, compared to traditional composting, researchers have reported a higher increase in magnesium (12.2–63.8%) and sodium (30.2–40.5%) concentrations [64]. These elements are important for improving soil structure and fertility.

The composting process is significantly influenced by the carbon dynamics. The dynamics of carbon and humic substances are governed by the microbial degradation processes of organic matter resulting in the release of carbon dioxide and heat concomitant with the generation of humic substances including humic acids, fulvic acids, and humans [44]. The concentration of humic substances increases as the composting process progresses, including during the maturation phase. Thus, at the end of the composting process, humic substances have a significant proportion of organic matter, thus marking the stabilization of the compost and its readiness for further use in agriculture [44,46].

Humic acid (HA) undergoes substantial transformations throughout composting. It has been reported that during the first stages of composting, approximately 50% of the total concentration of HA is reduced, whereas the core HA remains relatively stable [71,72]. This transformation is characterized by a degradation of coating materials, such as polysaccharides, peptides, and lipids, resulting in HA structures of higher aromaticity [72]. The humification process, which involves the formation of humic-like substances, is influenced by the degradation rates of water-soluble carbohydrates and phenols, which serve as precursors to humification [73]. Other studies indicated that the humic acid content typically increases to a peak around 110 days into the composting process, indicating a maturation phase where the organic matter transforms into a more aromatic structure [74]. Detailed analyses of spectroscopy revealed significant structural changes in HA as indicated by the increase in aromatic and phenolic C-containing groups [72]. These transformations collectively demonstrate the dynamic nature of carbon and humic substances during the composting of municipal organic waste. The quantity and quality of humic substances (HS) in compost are considered key indicators of compost maturity and chemical stability [10]. Mature compost usually has higher humus concentrations confirming the transformation of organic matter and nitrogen during composting [10].

5.2. Fate of Contaminants

MSW composts contain heavy metal concentrations that are higher than background soil levels. The most common heavy metals identified in MSW composts are zinc (Zn), lead (Pb), copper (Cu), cadmium (Cd), and nickel (Ni) [75–77]. Their environmental impact and bioavailability for plant uptake is a critical concern. Generally, the composting process changes the speciation of heavy metals, which normally decreases the solubility and bioavailability of heavy metals [76,77]. For example, the complexation of heavy metals with organic matter occurring during aerobic composting plays a key role in the decrease of heavy metals solubility and bioavailability [76,77]. Heavy metals, such as Pb and Cu, have been reported to show a significant reduction in water-extractable fraction during composting, thus indicating a shift towards more stable forms [78]. The mobility and, implicitly, the bioavailability of heavy metals in composts are influenced by several factors, such as pH, organic matter content, and humification degree. Thus, a higher pH level in MSW compost leads to reduced heavy metals mobility. However, this correlation between pH and metal mobility is not definitive and straightforward [78,79]. The stabilized organic matter is another key factor that affects the heavy metals' mobility, the more stable organic matter is, the less mobility of heavy metals occurs [78,79].

Another critical environmental and technological concern is the occurrence and evolution of POPs. POPs include, among other substances, polychlorinated biphenyls (PCBs), dioxins, and certain pesticides, which are initially present in the composting feedstock due to their widespread use and environmental persistence. The capacity of the composting process to fully degrade the persistent organic pollutants varies significantly depending on the nature of the compounds. For instance, sodium linear dodecylbenzene sulfonate (LAS) shows a high mineralization rate of 51%, while nonylphenol (NP) and glyphosate exhibit intermediate rates of 29% and 24%, respectively. Fluoranthene, however, shows negligible mineralization [80]. A significant portion of some pollutants becomes non-extractable residues (NER). For example, 45% of NP and 37% of glyphosate are found as NER at the end of the composting process. This indicates that these compounds are stabilized in the compost matrix, reducing their bioavailability [71]. A study identified 121 volatile organic compounds (VOCs) generated during the composting of municipal biowaste, including highly toxic N-containing compounds. These emissions were influenced by the type of waste and the composting conditions [81].

Microplastics persist and fragment during the composting of municipal organic waste, with both conventional plastics and bioplastics contributing to their presence in compost [82,83]. For example, macroplastics such as expanded polystyrene (EPS), polypropylene (PP), and polyethylene (PE) can release numerous MP particles due to mechanical forces, oxidation, and biodegradation [84]. Additionally, the degradation of bioplastics in composting environments varies, with some bioplastics showing significant degradation while others persist. For instance, starch-based shopping bags (SBSB) and polylactic acid (PLA) tableware showed different degradation rates, with complete degradation expected in 1.6 years for SBSB and 7.2 years for PLA [85,86]. The presence of microplastics (MPs) in the composting process of organic waste can significantly influence various aspects of compost quality, microbial communities, and the overall composting dynamics. Microplastics can alter the humification process during composting. For instance, the addition of different types of MPs such as PE, polyvinyl chloride (PVC), and polyhydroxyalkanoates (PHA) have been shown to reduce the humic acid to fulvic acid ratio, indicating a lower degree of humification compared to control treatments without MPs [87]. This suggests that MPs can negatively impact the quality of the compost by affecting the formation of stable organic matter. Moreover, the presence of MPs has been reported also to influence the microbial and fungal communities within the compost by decreasing the diversity and richness of fungal communities, particularly during the thermophilic stage of composting. For example, the addition of PHA and PE MPs increased the relative abundance of phytopathogenic fungi, leading to a simpler and more unstable fungal community structure [87]. Similarly, the bacterial community's richness and diversity were reduced in the presence of MPs, with significant changes observed in the microbial community structure, especially in the presence of polyvinyl MPs [88]. Given these aspects, it is no surprise that several studies have identified the compost obtained from municipal solid waste as a potential source and carrier of microplastics into the environment [82,83,86] emphasizing once more the need to adopt improved waste management practices and source separation strategies to mitigate environmental contamination [82,83].

Pharmaceuticals and personal care products (PPCPs) are a wide range of substances including antibiotics, painkillers, hormones, and cosmetic ingredients that may occur in the municipal solid waste stream used as feedstock in composting. Several studies have investigated the occurrence and fate of PPCPs during composting processes and the environmental impact of their application on soil as fertilizer.

Research has shown that certain PPCPs are degraded during the composting process with varied efficiencies depending on the specific particularities of the chemical compound and the composting process conditions. Thomas et al. (2020) emphasized that during septage co-composting using an in-vessel technology the pharmaceutical carbamazepine (CBZ) could be degraded with efficiencies up to 83% during single pollutant degradation, while the personal care product triclosan (TCS) showed a removal rate of 86% under similar conditions. Moreover, the study also indicated that the complexity of the waste matrix can influence the degradation process as the presence of multiple pollutants reduced the degradation efficiency to 66% for CBZ and 83% for TCS [89]. Another study showed that composting significantly reduces levels of extractable antibiotics in livestock manure, with calculated half-lives ranging from 0.9 to 16 days for most antibiotics [90]. In addition, Mitchell et al. (2015) reported the degradation of antibiotic compounds from manure and biosolids with efficiencies greater than 85% within 21 days of thermophilic composting [91]. However, even if antibiotic concentrations can be significantly reduced, the fate of antibiotic resistance genes remains a complex issue that requires further consideration to fully include environmental implications [90,92] (Table 2).

MSW is a mixture of different organic and inorganic materials that can contain a variety of PTS that might threaten human health and the environment if not properly handled. Composting is a promising alternative to managing organics in MSW; however, it is important to know what happens to the PTS in this situation, thus supplementary research is needed to mitigate the risks associated with PTS accumulation in compost and the potential environmental impact.

Table 2. PTS in MSW fractions and potential sources in composting.

PTS Category	Examples in MSW	Potential Sources	References
Heavy metals	Lead (Pb), Cadmium (Cd), Mercury (Hg), Chromium (Cr), Arsenic (As), Copper (Cu)	Batteries, electronics, paints, certain food waste	[2,17,75,77,79]

Table 2. *Cont.*

PTS Category	Examples in MSW	Potential Sources	References
Persistent Organic Pollutants (POPs)	Polychlorinated Biphenyls (PCBs), Dioxins, Flame Retardants	Treated wood, plastics, and certain textiles	[36,80]
Microplastics	Microplastic fragments <5 mm	Packaging and textiles synthetic fibers, atmospheric deposition	[24,82,83,85,93]
Pharmaceuticals and Personal Care Products (PPCPs)	Antibiotics, Hormones, Medications	Improper disposal	[89,90,92]

6. Composting Benefits and Challenges

Municipal organic waste composting offers significant environmental benefits over traditional landfill disposal such as a reduction in GHG emissions, landfill life extension, reduction of environmental pollution, production of valuable compost, and resource conservation.

Literature data indicate that composting municipal organic waste can considerably lower GHG emissions and enhance carbon sequestration. Composting organic waste is widely known to help divert it from landfills, thereby diminishing methane (CH_4) emissions, a potent GHG, generally generated through anaerobic decomposition in landfills [45,94–96]. For instance, a case study performed for a university revealed that composting source-separated organic waste could reduce net GHG emissions by up to 47% compared to traditional landfilling [95]. Correspondingly, in Bangladesh, an integrated system of pyrolysis and composting of municipal organic waste was reported to reduce GHG emissions by 503 CO_2e t^{-1} municipal waste annually [97]. In addition to contributing to GHG emissions mitigation, composting also helps to reintegrate significant amounts of recycled nutrients back into the soil, improving soil properties by increasing soil organic carbon (SOC), enhancing microbial activity, and improving water retention and nutrient availability [10,98,99]. This consequently leads to a decreased requirement for synthetic fertilizers, thus the GHG emissions from their production and application are also reduced [12,98,100,101]. However, it is worth mentioning the composting process can also produce GHGs like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), but in comparison to landfilling the GHG emissions are generally at low levels and can be mitigated to some extent by using effective management practices of the composting process such as proper aeration [45,102,103].

Municipal organic waste composting is proven to significantly prolong landfill operational life because it reduces important waste volumes that otherwise would be landfilled. A study focusing on composting food and garden waste highlighted the possibility of reducing the volumetric waste disposal while keeping the same waste production and thus, increasing the landfill life from half a year to 4 years depending on the scenario and year considered [104]. In the same way, composting may presumably resolve the landfilling issues poor countries have. Organic waste may be removed by composting between 40% and 50% of total landfill waste in Ukraine contributing to the considerable mitigation of waste accumulation in landfills, decreasing the ecological impact of landfilling, and enhancing environmental safety [105]. In addition, the degradation of solid waste by aerobic methods within landfill sites, as documented in Georgia (USA), increases the rate of waste degradation; thereby, extending the operational life of the landfill and reducing associated methane gas and leachate production [106].

Organic waste composting is a very important process with high potential to serve as a tool for managing different types of environmental pollution in sectors such as air pollution, soil pollution, water pollution, etc., [107]. Separating biodegradable organic waste from landfills suppresses methane emissions associated with uncontrolled anaerobic degradation of organic matter. In addition, a properly managed composting system can minimize the emission of other air pollutants including volatile organic compounds (VOCs) and ammonia NH_3 [108,109]. At the same time, composting can also contribute to soil health by improving soil structure and nutrient profile or by enhancing soil microbial activity which can help immobilize heavy metals and other contaminants, thus reducing soil pollution [110–112]. Furthermore, by minimizing the production of leachate that is normally generated in landfills, composting can also help tackle water pollution as leachate could contaminate both groundwater and surface water [113,114]. In essence, municipal organic waste composting is an eco-friendly treatment method not only for recycling precious nutrients back into the soil but also for minimizing the significant environmental effects caused by waste disposal [113,115].

The reduction of secondary pollutants through source separation of the organic fraction and municipal organic waste composting is another environmental benefit. Source separation of organic waste prevents contamination with heavy metals and other pollutants, resulting in higher-quality compost. This method minimizes the need for extensive waste pretreatment, thereby reducing the generation of bioaerosols and malodors during the composting process [2]. Furthermore, it has also been shown that source-separated composting reduces methane emissions and elution of ammonium nitrogen, both common forms of contamination associated with mixed waste composting [116]. Ensuring that only clean organic material enters the composting process minimizes the levels of carcinogens and other potentially toxic contaminants occurring within the final compost product. By reducing these hazardous materials, the public acceptance and marketability of the compost itself are enhanced [117]. Furthermore, by collecting organic waste separately from specific sources, such as restaurants operating in vegetable markets, there is no concern about toxic materials, thus making the final product much safer, by not having to address secondary pollution [118].

OFMSW composting is a sustainable waste management solution, but also a way to enrich soils. As studies demonstrated, the composting process leads to a biofertilizer with increased levels of essential elements for crops such as nitrogen (N), phosphorous (P), and potassium (K) that can be used for soil amendment and fertilization [16,119,120]. For instance, a study focusing on thermophile pre-composting of MSW for 3 weeks followed by vermicomposting with the addition of cow dung has been found to enhance the decomposition and mineralization rates, resulting in a final compost with higher nutrient content [119]. Additionally, the integration of biological processes like anaerobic digestion and ozonation can further improve the quality of the compost by reducing organic contaminants, thus making it safer for soil application [121]. Field studies have demonstrated higher yields for crops such as corn and rice and better condition of soil health when compost resulting from MSW has been applied [16,122].

Composting of municipal organic waste also provides economic benefits for the community as it is a sustainable waste management method. The economic advantages of composting include extended landfill life [90,109,123], reduced waste management cost, revenue generation by selling compost, and mitigated emission of GHGs which can generate capital by carbon credits [97,124,125]. Medium-scale to lower large-scale composting plants are reported as the most economically viable option as they are capable of ensuring better control of waste input, better process control, and consequently a high-quality end-product. At these scales, there are further opportunities to earn money for closed-loop systems and other income like tipping fees and carbon credits [124]. Therefore, composting can create labor, develop local economies by the establishment of new industries for compost production and sales, help the circular economy by closing the waste loop, and enhance sustainable waste management practices [126,127].

Compost-amended soils have more diverse and stable microbial communities, and this may improve the ability of these soils to withstand adverse conditions and promote more sustainable agricultural practices [128]. In addition, composting using inorganic bulking agents has been shown to enhance the nutrient profile of the compost, making it a feasible component for potting soil or garden soil amendments [10]. Thus, utilization of organic amendments from composting processes can result in the formation of sustainable soils by enhancing soil functionality and fertility through efficient recycling of organic resources [129].

Composting municipal organic waste, although beneficial for soil amendment and waste management, presents several challenges and potential drawbacks, including potential environmental problems (odors, bioaerosols, heavy metals, leachate, gas emissions), operational difficulties (segregation, pathogen detection, composting duration, low levels of adoption) and management constraints (toxic substances, lack of information, efficient pricing systems and regulations). The high variability in the composition of organic waste is a key issue that can have a large impact on the quality and consistency of the final composts produced. For example, different types of organic waste may contain varying concentrations of nutrients and heavy metals, which further affects the intensity of the composting process, the quality of the final compost, and its suitability for reuse in agriculture [130–132]. In addition, impurities and contaminants such as plastics and metals complicate the composting process and lower the quality of composts in production [133,134]. The main challenges regarding environmental impact are related to GHG (e.g., methane and nitrous oxide) emissions, odors, and heavy metals management. Odor problems may occur during the composting process as the result of volatile organic compounds (VOCs) such as ethyl isovalerate and terpenes generation and release, leading to complaints and potential facility closures [75,135]. Bioaerosols are another environmental issue related to bacteria and fungi in the emissions of composting facilities or during compost application, which may pose a potential health risk to workers, the local environment, and overall community health [136,137]. These emissions not only contribute to climate change but also affect the local environment and community health [134,138]. Finally, the management of heavy metals and other pollutants in compost is absolute to prevent soil contamination and secure compost's safety for agriculture applications [2,138]. Efficient source separation of organic waste is mandatory to prevent contamination (with heavy metals and other contaminants) and improve the composting process efficiency [2].

The health risk related to potential pathogens occurring in compost derived from municipal organic waste is another issue of concern. Studies show a varied degree of pathogen reduction achieved depending on the composting method of choice (especially delineating between composting and vermicomposting of OFMSW); several studies reported that vermicomposting resulted in higher pathogenic bacteria reduction, including *E. coli*, compared to traditional composting, most probably due to all the complex digestive processes in earthworm guts [139,140].

Moreover, bioaugmentation with specific microbial inoculants such as the white-rot fungi proved to enhance the compost degradation intensity and maturation resulting also in decreased pathogen loads [141]. However, the occurrence of pathogenic Candida species in the early stage of composting demonstrated the necessity of thorough monitoring and control measures [142]. Thus, further research is necessary to fully understand the mechanisms of pathogen reduction in both composting and vermicomposting processes to ensure the production of safe and high-quality compost [142,143].

At last, the economic and operational challenges for the broad adoption of composting as a viable and sustainable waste management strategy are related to the high costs of infrastructure and the need for continuous monitoring and optimization of the composting process [144,145].

As summarized in Table 3, several benefits arise from the composting of municipal organic waste: It diverts that material from landfills, and, as waste that is not put into a landfill decomposes, it does not instead break down into methane. Composting also recycles organic nutrients in the waste back into the soil—nearly closed-loop by some models and beneficial to even the most sustainable agriculture practices. Nevertheless, composting organic waste from municipalities is difficult due to its mixed constitution. This is mainly due to the different recalcitrant elements of the wood–cellulose complex in the overall waste composition, which can extend the composting time and reduce the quality of the final product. The emissions of greenhouse gases and air pollutants that take place during composting are a downside to this seemingly eco-friendly process, for which pile management and aeration are key aspects for mitigating the ineffective public engaging strategies of this technology.

Table 3. Composting Municipal Organic Waste: Benefits and Challenges.

Aspect	Benefit	Challenge
Greenhouse Gas Emissions (GHG)	Reduces methane emissions from landfills and increases carbon sequestration in soil	Low-level GHG emissions during composting
Landfill Life	Reduces waste volume sent to landfills thus extending landfills lifespan	
Pollution Reduction	Reduces air pollution (VOCs, ammonia) Reduces soil pollution (heavy metals) Reduces water pollution (leachate)	Odors from composting process Management of heavy metals in compost
Compost Production	Creates nutrient-rich fertilizer for soil amendment	
Economic Benefits	Reduced waste management costs Revenue generation from compost sales Carbon credits for mitigated GHG emissions	High infrastructure costs Operational difficulties (monitoring, optimization) Low adoption rates
Soil Enhancement	Improves soil health (structure, water retention, nutrients) Promotes sustainable agriculture	Potential for pathogen presence in compost

A comparison of municipal solid waste composting, vermicomposting, and larvae or cricket production for organic waste management is presented in Table 4.

Table 4. Benchmarking of municipal organic waste composting, vermicomposting, and larvae or cricket production.

	Composting	Vermicomposting	Larvae or Cricket Production
Feedstock	Mixed organic waste	Food scraps and yard trimmings	Organic waste streams (including food scraps)
Process	Decomposition by microorganisms in piles or bins	Decomposition by worms in bins or containers	Decomposition by insect larvae in containers
End product	Compost	Vermicompost	Insect frass (manure) for animal feed or fertilizer,
			Insects as protein source for animal feed
Advantages	Large-scale processing	Smaller-scale processing suitable for households	Efficient waste conversion
	Reduces landfill waste	Low odor	High-protein insect production
	Creates soil amendment	High-quality compost	Reduces reliance on fishmeal
		Reduced pathogen load	
Disadvantages	Requires proper management to avoid odor and methane emissions	Lower processing rates than composting	Requires careful management to prevent escapes
	Risk of pathogen contamination	Requires specific feedstock for worms	Potential allergens

All three methods divert waste from landfills. A 2022 study by Nigussie et al. [146] found vermicomposting to be particularly effective, potentially diverting up to 70% of organic waste. Composting produces a good soil amendment but may have lower nutrient content than vermicompost. Studies showed vermicompost to have higher levels of available nitrogen and phosphorus [9,67]. Insect frass can also be a valuable fertilizer, but its specific composition depends on the insect species and feedstock [147].

Throughput and processing time are important factors. Composting can handle large volumes but has a longer processing time. Vermicomposting excels in smaller-scale settings while having a higher time requirement. Insect production can be efficient, with studies like that by Manaa et al. [148] in 2024 demonstrating high conversion rates of organic waste into insect biomass.

Labor, equipment, and maintenance vary. Composting facilities often require significant infrastructure investment, while vermicomposting has lower operational costs but limited scalability. Insect production can be cost-effective, with research by Li et al. [149] in 2023 suggesting potential economic benefits.

Odor, greenhouse gas (GHG) emissions, and leachate generation are critical sustainability considerations. While all three methods can be managed to minimize odor, vermicomposting generally has lower emissions. A 2021 study by Sayara et al. [150] highlights the potential for composting to generate methane, a potent GHG. On the contrary, insect production can also contribute to GHG reduction compared to traditional protein sources.

Thus, the ideal organic waste management approach depends on specific circumstances. Composting excels in large-scale waste diversion, vermicomposting performs better in smaller settings and low-odor applications, while insect production offers a promising future for waste reduction and protein production.

7. Case Studies and Success Stories

Various case studies emphasize the potential of using municipal organic waste as a sustainable waste management and nutrient recycling, while improving soil. Compost-derived nutrients offer a sustainable solution for improving soil and fertility in various applications, including soil modification, agricultural use and landscape. The process of composting biodegradable organic waste not only recycles nutrients, but also contributes to improving the productivity of crops and soil health by increasing the chemical, physical and biological properties of soils [34,119,151]. In agriculture, it has been shown that the application of compost deviates organic waste from landfills, thus reducing methane emissions [130]. The application of compost or vermicompost on soils has demonstrated positive effects on tomato yield and nutritional status, indicating the potential of these organic changes to replace mineral fertilizers in intense agriculture [152]. Furthermore, application of organic amendments such as compost has been shown to influence soil microbial communities, which play a critical role in soil health and nutrient cycling [98,153]. Composting municipal waste with agricultural by-products can produce high-quality composts for agricultural soils recovery, emphasizing the versatility of compost applications [154,155]. In landscaping and soil remediation, MSW compost represents a potential renewable P source, improving soil P status without posing significant environmental risks [155]. Following MSW compost repeated application, soil C and N content has been enriched, enzymatic activities have been modified and microbial community dynamics impacted, relevant to both agricultural and landscaping uses [45]. Another study emphasized that application of garden waste compost improves desalination efficiency, nutrient availability, and microbial diversity in coastal saline soils, ensuring an ecological restoration practice [129]. In vineyards, compost application has been recently considered because of its potential to improve soil health, whilst considering the key environmental trade-off—GHGs emissions [156].

One of the major initiatives is composting the organic fraction of municipal solid waste—to minimize landfill disposal, as has been emphasized by several studies [104,106,126]. However, its adoption varies from country to country due to socio-demographic factors and the need for greater awareness and social commitment to encourage its use [157]. Another innovative approach reported in the literature includes composting of MSW with earthworms and ligno-cellulolytic microbial consortia for sustainable reclamation of degraded sodic soils, highlighting the potential of compost to improve soil health and productivity [42,64].

The success of OFMSW composting programs relies on a combination of policy support, community engagement, and technological advancements. Additionally, policy incentives play a crucial role in encouraging consumers to adopt environmentally friendly disposal strategies, which aligns economic competitiveness with environmental objectives, thereby incentivizing residents to minimize GHGs emissions through preferred disposal patterns [158,159].

Key factors on the community engagement level are education and social interactions, that have the most contribution to adopting sustainable practices. Using compost from OFMSW can improve sustainability and research confirm that education level, peer or social network suggesting and level of interest in adopting OFMSW compost correlated significantly. This indicates the role of institutions and policymakers to facilitate the knowledge and support the success of local initiatives in the future [13].

From the perspective of minimization of the environmental and health impacts associated with organic waste treatment, technological advancements have been made in fields such as optimized composting processes and bioaerosols management in composting plants. By advancing bioaerosol management, exposure levels were lowered and risk assessments improved, thus enhancing the environmental performance of composting facilities [160,161]. Additionally, applying life cycle assessment (LCA) methodologies to evaluate the environmental impacts of waste management facilities, including the potential for renewable energy solutions, demonstrates the benefits of these advancements in reducing environmental impacts and improving energy efficiency [132]. Furthermore, the development of technologies for the composting of MSW using earthworms and microbial consortia showcases the potential for enhancing the nutrient content of compost [162,163]. Finally, research studies on nutrients and potentially toxic elements contents emphasize the importance of monitoring and managing the compost's quality to ensure its safe application on soils [163].

The impact of legislation on landfilled waste and composting is clear in waste disposal European statistics (Figure 2). The EU Landfill directive implementation resulted in a continuous decrease in landfilled waste volumes, as well as in an acceleration in other processing approaches. In the last twenty years, an increase of over 200% in the composted waste quantities has been identified, contributing to a considerable reduction in landfilled waste reduction.

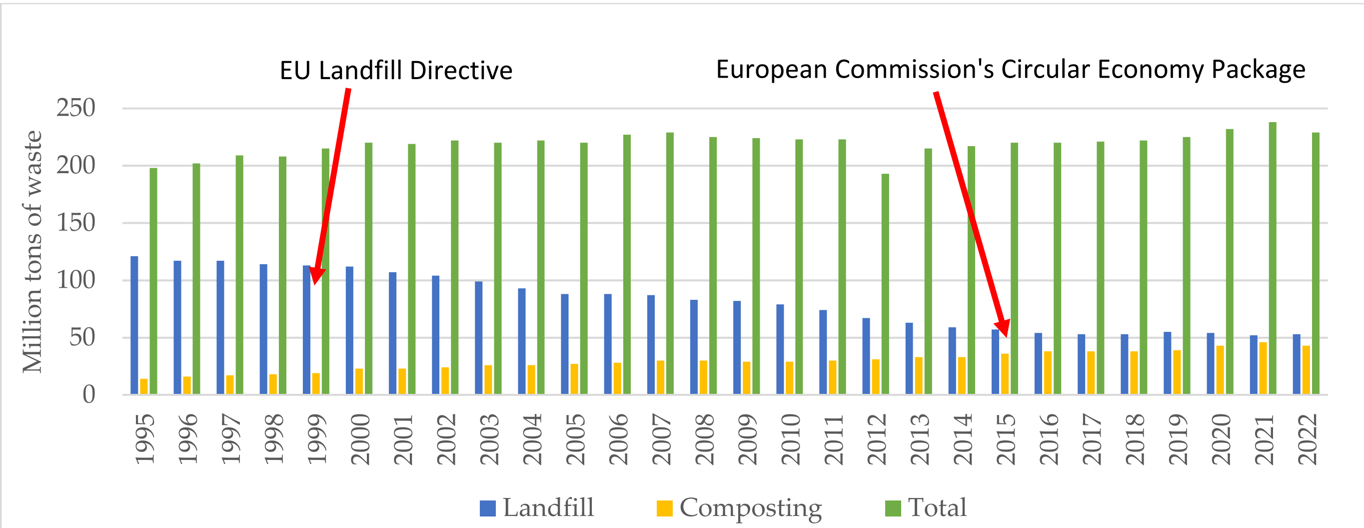

Figure 2. Municipal waste treatment in Europe (1995–2022). Source: Eurostat.

Another key change in waste management approach in Europe was the implementation of the European Commission's Circular economy package, that emphasized the importance of resources recovery thus accelerating the implementation of treatment methods other than landfilling.

Local initiatives also have significant contributions on separate organic waste collection and composting. Two examples are the Mandatory Organics Recycling Ordinance (2009) form San Francisco, California that envisages separate organics collection from all residents and businesses and Organics Recycling Law (2014) in Maine that offers technical assistance to food waste generators to divert it to composting instead of landfilling. Both initiatives led to decreased landfilled waste volumes and increased compost production.

8. Discussions and Future Directions

The demand for improved, greener, and certainly scalable composting solutions is even more important considering growing cities, and higher quantities of waste being generated. Serious opportunities for coping with the ever-mounting problems of waste management and the imperatives of resource sustainability are presented in the field of intensive composting of organic urban waste. This chapter explores future directions and current research needs in order to advance the field of intensive municipal organic waste. Future research and innovation in technological progress, microbial and biochemical perspectives, process optimization, environmental and economic evaluation, as well as political and public involvement are essential to unlock the full potential of composting systems.

Given the great importance of the quality and homogeneity of the organic waste feedstock for the efficiency of composting processes and for the predictability of the final compost quality, it is necessary to identify future research actions aiming to develop advanced technologies for organic waste separation and pre-treatment with proper efficiency and minimum monetary and environmental costs. The study on the viability of the used technologies is proposed by the development of macro-screening inspection assemblies integrated with sorting and inspection of waste streams, in terms of organic and inorganic waste contamination. Automated sorting and current separating systems, supported by artificial intelligence (AI) systems and by machine learning (ML) techniques, will allow the enhancement of sorting accuracy and efficiency.

Because the efficiency of the composting process and the quality of compost are influenced by the main operational parameters, it is critically important to maintain proper aeration, humidity, and temperature in order to achieve an efficient composting process [157]. Thanks to the advancements of sensor technologies and Internet of Things (IoT), it is becoming possible to monitor and control composting parameters in real time. Future research should be focused on developing intelligent composting systems to automatically adjust aeration and temperature to optimize the microbial activity and accelerate composting. In this field of research, continuous thermophilic composting has become more important because it has the potential to reduce processing time and improve compost stability, thus becoming more attractive for commercial applications [164].

Moreover, improved control and efficiency of the composting process and tailored nutrient transformations can be achieved by a deeper understanding of microbial community dynamics. Identification of key microbial species and their interactions towards optimized degradation of organic wastes and improved physico-chemical dynamics during composting should also be a focus of future research [10,23]. Dedicated metagenomic and metatranscriptomic approaches can provide insights into microbial functions and the pathways involved in composting. Integrated metagenomic and metatranscriptomic analyses could offer the means to understand microbial gene composition and expression in complex environments, such as the composting systems. Thus, these combined approaches might elucidate the functional roles of microbial communities, identify key metabolic pathways involved in organic matter degradation, and provide insights into the dynamic interactions within the microbial ecosystem [165,166].

In addition, researchers might explore whether certain enzymes can be added to composting systems to hasten the decomposition of complex organic compounds [167–169]. Additionally, genetic engineering techniques could be employed to enhance the activity and stability of these enzymes under composting conditions.

The quality of the final compost product is critical for acceptance and use as amendment or fertilizer. Future studies should be focused on technologies to improve the compost quality including optimal feedstock ratio, duration of composting, maturation processes. In this regard, researches on the impact of different waste compositions on the nutrient value, pathogen reduction, potential additives, presence of beneficial microorganism in finished compost, should be investigated. For example, Gaspar et al. (2022) showed that the phosphorus bioavailable content and the overall quality of the compost is improved when specific microbial inoculants are added to the process [39]. In addition, the potential of the biochar, especially oxidized biochar, to improve nitrogen retention during composting has an innovative research path, which suggests the need to deepen more in the physiochemical interactions between BioChar and Compost materials [98,170]. Moreover, detailed studies on the selection and optimization of compost amendments would allow to improve nutrient retention and organic matter degradation, including its effect on microbial community structure and metabolic function [10]. Another area of research is to investigate the occurrence and fate of contaminants and their potential environmental impact, as well as the mechanisms responsible for their removal during composting [127].

In order to reach full sustainability, the progress of the composting process should target also the sustainable use of energy and water resources. Thus, research should investigate the use of alternative energy sources, such as solar energy or bioenergy, to power composting installations while different methods for minimizing water use should be developed or strategies to reuse process water should be implemented. In order for intensive composting systems to be adopted at a wide-scale, it is important that their economic viability is assessed. The research should look into cost-effective composting technologies and business models that can be scaled to different installations. In addition, attempts should be made to develop markets for compost products, this includes establishing quality standards and certifications to build consumer trust and demand [171–173]. Future research could also focus on developing standardized LCA methodologies allowing to benchmark various composting technologies and practices. The assessments will provide valuable information on the overall sustainability of composting systems and could lead to knowledge-based solutions for process improvement [171].

Effective regulatory frameworks are needed in order to facilitate the expansion of intensive composting of municipal organic waste. To define the future research agenda, existing regulations should be examined and potential gaps or obstructions to the implementation of composting projects should be noted. Actions and incentives that encourage composting should be prepared to address the results obtained from this research.

In order for city composting programs to be successful, public engagement is mandatory. Research should also focus on identifying optimal opinion campaigns to teach and grow public support for composting and recycling of organic waste. Public involvement events can allow cities to explain how composting works and what they're trying to accomplish in countywide composting programs.

9. Conclusions

Composting municipal organic waste is an essential part of sustainable waste management and agricultural practices as it is a valuable method of recycling nutrients. Far from being a mere disposal method, composting contributes positively to soil health and food production, and therefore to environmental sustainability and food security. Composting offers substantial environmental benefits, including extending the life of landfills, reducing GHGs emissions by diverting organic waste from landfills, and improving soil quality and structure by using the compost produced as fertilizer. This practice could contribute to the transition to a circular economy by closing the nutrient loop, decreasing dependence on finite resources, and encouraging resource conservation and resilience. Although, apparently, composting is a simple process and takes place in various conditions, careful management of the process and control of minimum parameters such as temperature, humidity, oxygen concentration and the C/N ratio would ensure the successful decomposition of municipal organic waste in a valuable final product, rich in nutrients. These critical parameters govern both the progress of the composting process and the potentially associated processes that lead to the production of GHGs. Parameters control ensures proper waste degradation and good quality compost, which, in turn, encourages correct waste management and use of the resulting compost. Despite its benefits, composting faces challenges such as nutrient leaching and potential heavy metal contamination. Proper management practices and monitoring are required to meet these challenges and to guarantee the quality and safety of compost products. Successful nutrient recycling initiatives rely also on strong policy frameworks, community engagement and infrastructure support. In the future, an effort needs to be made to fill research gaps, develop more effective and efficient composting systems, establish alternative recovery pathways, and scale composting to the facilities necessary for this platform to achieve extensive, impactful use as a circular economy tool. Scaling globally would have far-reaching implications in terms of food waste reduction, soil restoration, climate change mitigation, and leaping to a more sustainable and resilient future.

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