European Journal of Sustainable Development Research
2025, 9(4), em0319
e-ISSN: 2542-4742
https://www.ejosdr.com/

MODESTUM

Review Article

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Sustainable waste management through commercial composting: Challenges, opportunities, and future directions for circular economy

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Citation: Saqib, Z., & Sadef, Y. (2025). Sustainable waste management through commercial composting: Challenges, opportunities, and future directions for circular economy. *European Journal of Sustainable Development Research, 9*(4), em0319. https://doi.org/10.29333/ejosdr/16579

ARTICLE INFO

Received: 30 Dec. 2024

Accepted: 16 May 2025

ABSTRACT

This study conducted a systematic literature review and content analysis to examine the state of the art in organic waste composting through commercial adoption for the circular economy (CE) and reduced environmental consequences in advancing sustainable waste management within a CE framework. Commercial composting diverts substantial amounts of organic waste from landfills, reducing methane emissions. For instance, the Japanese food processing industry generates 9.5 million tons of organic waste annually, with 25% directed to composting, highlighting its role in waste reduction. This research utilizes extensive life cycle assessments to assess the environmental and economic viability of various composting techniques, while comparative studies examine the pros and cons of technologies such as in-vessel systems and forced aerated windrows. Additionally, a bibliometric analysis reveals significant research trends, regulatory shortcomings, and worldwide policy measures influencing the adoption of commercial composting practices. The results show that integrating the Internet of things (IoT)-enabled sensors and biochar can optimize composting processes, improving nutrient retention and reducing emissions. Moreover, decentralized composting can reduce municipal collection costs by 15-25% and extend landfill lifespans by 5-10 years. Community-based models, such as New York City compost project, demonstrate how policy support and public engagement can enhance composting's socio-economic benefits and promote zero waste initiatives. The study highlights technological solutions to tackle these issues, i.e., the application of biochar, IoT-based monitoring systems, and small-scale composting methods. The research underscores the importance of implementing effective policies and strategies to encourage public participation, which are crucial for widespread adoption and long-term sustainability. Addressing these issues through technological innovation, policy development, and public education is crucial for strengthening composting's role in sustainable resource management.

Keywords: circular economy, methane emissions, waste reduction, decentralized composting, zero waste, sustainable resources

INTRODUCTION

Sustainable waste management involves the effective management, treatment, and recycling of waste to reduce environmental impacts and enhance the recovery of resources (Geissdoerfer et al., 2017). Composting is essential in this process as it transforms organic waste into compost that is rich in nutrients, lessening the reliance on landfills and decreasing methane emissions. Organic waste can be converted into valuable resources, such as bio-based chemicals, energy, and fertilizers. This contributes to environmental sustainability by reducing waste and promoting recycling (Bocken et al., 2016). Proper management of organic waste within the circular economy (CE) can lead to reduced greenhouse gas (GHG) emissions and support environmental improvement (Saqib et al., 2018). By implementing strategies such as composting, anaerobic digestion (AD), and bioenergy production, organic waste can be transformed into valuable resources like biofuels, biogas, and fertilizers. This approach not only diverts waste from landfills (source of methane emissions) but also helps sequester carbon in soils, which can enhance soil fertility and reduce reliance on synthetic fertilizers, promoting overall environmental sustainability (Geerken et al., 2019; Liu et al., 2017). The implementation of the "reduce, reuse, and recycle (3Rs)" principle lowers operational costs and enhances resource efficiency (Liu et al., 2017). Recently, the linear economy has played an essential role in economic development but it has put unprecedented pressure on natural resources and led to improper waste management. The integrated CE and organic waste management approaches can

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positively impact the environment, society, and economy (Saqib et al., 2023a). CE principles encourage innovation in business models, creating new investment opportunities and employment in green sectors (Maina et al., 2017; Nizami et al., 2017). Underdeveloped composting techniques, especially in less industrialized nations, coupled with expensive logistical requirements, continue to pose significant challenges. In Sri Lanka, for instance, despite governmental backing for composting initiatives, only 30% of organic waste undergoes processing due to high operational expenses and insufficient infrastructure. Likewise, in Japan, while a quarter of food industry waste is converted into compost, the remainder is burned because of financial limitations (Braz et al., 2018; Geissdoerfer et al., 2017). Organic waste supply can be affected by seasonality and environmental conditions, impacting the efficiency and consistency of resource recovery (Gontard et al., 2018). The CE promotes innovative waste-to-resource strategies to develop bio-refineries and alternative, eco-friendly business models. The CE model promotes the integration of waste streams into production processes, closing material and energy loops, and improving the overall efficiency of industries (Berg et al., 2018). The absence of clear public policies and technical standards for bio-based products can hinder the growth of CE-based organic waste management initiatives (Morone, 2018; Philp, 2018). Low public awareness and insufficient technical expertise at the local level can prevent effective project implementation and adoption of CE practices (Yukalang et al., 2017).

Circular Economy and Composting

Composting is increasingly recognized as a crucial element of waste management within the circular economic framework. It helps reduce material inputs and promotes the cyclical use of resources, contributing to sustainable development (D'Amato et al., 2017). The CE model emphasizes waste reuse and resource efficiency as crucial strategies to achieve the UN's sustainable development goals, particularly Goal 12 on sustainable consumption and production (Saqib et al., 2023b). The European Union's (EU) CE action plan targets recycling at least 65% of municipal waste by 2030 (Fidélis et al., 2021). The CE approach also promotes resource recovery, where organic waste is turned into compost, which in turn enhances soil fertility and reduces the cost of imported fertilizers (Bekchanov & Mirzabaev, 2018; Fidélis et al., 2021).

Review Objectives

1. To identify the associated challenges in process control and opportunities for scaling up commercial composting.
2. To assess the possibility of large-scale commercial composting with focused on waste minimization.
3. Explore future directions for integrating composting into sustainable waste management practices.

COMMERCIAL COMPOSTING

While domestic composting focuses on small-scale organic waste management, commercial composting functions at an industrial level, processing massive volumes of organic waste efficiently. Commercial composting refers to the controlled process of converting organic waste into a stable, humus-like product using microbial action under aerobic conditions (de Mendonça Costa et al., 2017). This review distinguishes these approaches and highlights how commercial composting contributes to the CE.

Composting Process

The composting process in commercial settings are as follows:

Thermophilic phase

In the initial stages, temperatures rapidly rose to above 50 °C within 3 days, sustained above 55 °C for over two weeks. This high-temperature period ensures pathogen reduction according to European compost sanitation standards (Bernal et al., 2017; Gontard et al., 2018).

Maturation phase

Following the thermophilic stage, the temperature gradually declines, transitioning to the mesophilic phase (⩽ 40 °C) around day 36. The composting process is typically completed after this phase, often around 38 days, once the temperature stabilizes (Villar et al., 2016).

Scale of Operations: Small, Medium, and Large-Scale Systems

Composting systems for municipal solid waste (MSW) management, decentralized or small-scale composting has gained attention for effectively treating the organic fraction of MSW at the local level. This approach is promoted as the "best available practice" due to its benefits in reducing transportation needs and costs associated with large-scale waste management processes. Small-scale composting have been effectively implemented in settings such as households, neighborhoods, and institutions, offering low-cost waste treatment with environmental and community engagement benefits. However, challenges such as maintaining thermophilic temperatures (> 55 °C for pathogen reduction) to meet sanitization standards like the USEPA's PFRPs are more pronounced in small-scale systems due to lower thermal inertia, especially in colder climates (Sánchez et al., 2017). Medium-scale systems often utilize a more controlled setup with either partial or full homogenization mechanisms, improving composting conditions such as moisture and aeration. Although centralized composting systems provide greater efficiency and better pathogen control, they necessitate a significant amount of land and lead to increased transportation emissions due to waste pickup logistics. On the other hand, decentralized composting reduces waste transport expenses and reliance on landfills, yet it encounters difficulties in sustaining temperature stability and processing uniformity, especially in cooler climates (Arrigoni et al., 2018). These large-scale facilities are typically more capable of managing waste in larger volumes, maintaining optimal temperatures, and ensuring complete sanitization across the compost matrix, making them viable for urban and municipal applications on a larger scale. The Japanese food processing industry generates 9.5 million tons of organic waste annually, of which 25% is composted or used as intermediate material for the production of animal feed, 25% is dried, 5% is used for energy generation, and 40% is incinerated or landfilled (Liu et al., 2016). In the Japanese City of Nagoya, food waste is collected and composted with financial support from the government (Zheng et al., 2016).

Materials Suitable For Composting

Commercial composting facilities process various organic materials, including food scraps, manure, and green waste. However, contamination from plastics and heavy metals poses a significant challenge, requiring stricter waste segregation policies (Bernal et al., 2017).

Agricultural and agro-industry by-products

These materials contribute to nutrient-rich compost that supports microbial activity and aids in organic waste management (Lin et al., 2018).

Livestock wastes

These provide a source of nitrogen and other nutrients essential for microbial growth in the composting process (Bernal et al., 2017).

Sewage sludge

Sewage sludge aids in nutrient recovery, though it may require careful management to control heavy metals and other contaminants (Bernal et al., 2017).

Organic fraction of municipal solid waste

It includes food scraps and green waste, which are ideal for composting due to their high organic content and biodegradability (Proietti et al., 2016; Saqib et al., 2024). These wastes are typically combined with bulking materials to optimize moisture, pH, and aeration, all crucial for the composting process.

ROLE OF COMMERCIAL COMPOSTING IN THE CIRCULAR ECONOMY

Commercial composting significantly contributes to waste reduction and resource recovery, integral to CE practices. By converting organic food waste (OFW) into compost, waste that would traditionally be directed to landfills is diverted, thus minimizing environmental pollutants such as methane emissions. In Makkah, composting could potentially reduce OFW by up to 1.6 million tons by 2030, converting it into an estimated 0.23-0.40 million tons of compost, which helps in closing the resource loop by turning waste into a valuable soil amendment (Rashid & Shahzad, 2021) (**Figure 1**). The recovered compost can act as a substitute for commercial fertilizers, reducing reliance on chemical inputs like urea, diammonium phosphate (DAP), and sulfate of potash. As a result, composting supports nutrient cycling within agricultural systems, providing essential nutrients while preserving finite resources. Additionally, resource recovery through composting aligns with Saudi Arabia's vision 2030 objectives by promoting sustainable waste management and reducing dependency on fossil-based fertilizers, which ultimately contributes to a resilient, sustainable economy (Dahiya et al., 2018; Rashid & Shahzad, 2021).

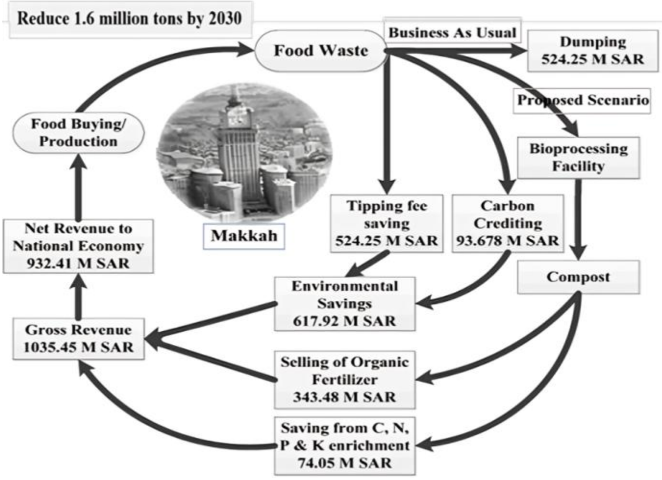

Figure 1. The benefits of recycling OFW for compost in Makkah City highlight indicators of the circular economy (Rashid & Shahzad, 2021)

Nutrient Cycling and Soil Health Benefits

By incorporating compost into agricultural practices, nutrient retention is improved (Awasthi et al., 2019; Singh et al., 2022). The application of compost enhances soil structure, increases organic matter (OM) content, and improves water retention and aeration, which are vital for sustainable food production and agricultural resilience (Günther et al., 2018; Saqib et al., 2022).

Mitigating Greenhouse Gas Emissions

Commercial composting reduces GHG emissions associated with the production and application of fossil fuel-based fertilizers. By utilizing compost instead of synthetic fertilizers, emissions linked to fertilizer manufacturing are diminished. The composting process can also be optimized to minimize methane emissions, a potent GHG produced during organic waste decomposition in landfills (Awasthi et al., 2019).

RESEARCH METHODOLOGY

Most of the researchers have utilized the systematic literature review aligning with quantitative and qualitative approaches for the management of compost production and its management for sustainable agriculture and commercial purposes (Liu et al., 2021; Sołowiej et al., 2021). This study used systematic review with bibliometric approaches. It aims to resolve compost complications and manufacturing procedures (Czekała, 2022; Obidziński et al., 2022).

Data Collection

This research utilizes detailed life cycle assessments (LCA) to assess the environmental and economic sustainability of various composting techniques, while comparative evaluations highlight the benefits and drawbacks of technologies such as in-vessel systems and forced aerated windrows. The data for this study were collected from various research articles, reviews, and case studies of composting initiatives. The terms organic waste and CE are interrelated and many studies included research dynamics that utilized organic waste management for economic purposes and reduced environmental effects on ecosystems (Czekała, 2022; Dazzi et al., 2021; Liu et al., 2021; Saxena & Agrawal, 2022; Sołowiej et al., 2021). These sources provide insights into the processes, technologies, and trends in commercial composting, facilitating a well-rounded analysis of its role in sustainable waste management within a CE framework.

Research Approach

The literature on sustainable waste management identifies four key criteria for selecting effective technologies: environmental impact, economic feasibility, scalability, and operational efficiency (Bernal et al., 2017). Studies emphasize the need for technologies that reduce GHG emissions and enhance soil quality, essential for mitigating environmental harm. Economic feasibility is critical, with a focus on cost-effective solutions applicable across various scales, from local to industrial levels (Saxena & Agrawal, 2022). Scalability is also crucial, advocating for adaptable technologies suitable for urban and rural contexts. Finally, innovative options, such as in-vessel composting and the Internet of things (IoT)-based monitoring, are noted for enhancing process efficiency and enabling precise, data-driven waste management. These criteria guide the selection of sustainable technologies that align with environmental and operational goals (Czekała, 2022).

Analytical Framework

The analytical framework for evaluating composting technologies and market trends includes key tools and theoretical perspectives. Comparative analysis, such as SWOT, assesses strengths, weaknesses, opportunities, and threats in methods like in-vessel and windrow composting (Dsouza et al., 2021). Market analysis tools, including Porter's Five Forces, examine industry competition, market opportunities, and entry barriers. Environmental impact assessments, notably LCA, evaluate environmental costs and benefits across the composting process (Serafini et al., 2023). The theoretical framework applies CE principles to emphasize composting's role in waste-to-resource conversion and closed-loop systems, integrating sustainability with renewable energy and waste policies (Serafini et al., 2023).

TECHNOLOGIES AND INNOVATIONS IN COMMERCIAL COMPOSTING

Commercial composting has evolved with technologies like in-vessel and aerated static pile systems, which accelerate composting while controlling odors and emissions. Innovations like automated compost turners, IoT-enabled sensors, and biofilters improve process efficiency and reduce GHG emissions (Obidziński et al., 2022; Serafini et al., 2023). Additionally, integrating AD generates biogas before composting digestate, maximizing resource recovery.

Aerobic Composting Method

Aerobic composting is typically faster and occurs in the presence of oxygen, allowing microorganisms to decompose OM efficiently (Waliszewska et al., 2019). This process requires adequate aeration to facilitate the respiration of aerobic organisms (Sołowiej et al., 2021). The final product of aerobic composting is compost, a nutrient-rich fertilizer that enhances soil health and fertility. Composting recycles nutrients and improves soil structure and water retention, contributing to sustainable agricultural practices (Czekała, 2022).

Anaerobic Composting Method

AD involves the decomposition of biodegradable waste in the absence of oxygen. This process is conducted by specific microorganisms that thrive in anaerobic conditions, leading to the breakdown of organic materials (Waliszewska et al., 2019). The outputs of AD are biogas and digestate. Biogas, primarily composed of methane, can be utilized as a renewable energy source, while digestate can be processed further to recover nutrients and OM for agricultural use (Koryś et al., 2019). This process effectively reduces waste volume and produces renewable energy, offering a dual benefit of waste management and energy recovery (Sołowiej et al., 2021). However, it requires strict management of operational conditions to maintain anaerobic environments (Koryś et al., 2019; Obidziński et al., 2022).

Emerging Technologies (Biochar, Vermicomposting, and Smart Composting)

Advanced sorting, biochar integration, and machine learning for quality control further enhance product consistency and environmental benefits. These innovations make commercial composting more efficient, supporting waste reduction and sustainable practices within the CE (Singh et al., 2022; Sołowiej et al., 2021).

Role of biochar in circular bioeconomy

Despite its potential, the widespread use of biochar is hindered by expensive production expenses and the requirement for specific infrastructure. Furthermore, commercial deployment encounters regulatory challenges related to quality assurance, market acceptance, and standards for soil application, especially in areas with minimal government support. It's increasingly utilized in sustainable technologies, including waste-to-energy (WTE) transformations and as a replacement for chemical fertilizers (Sołowiej et al., 2021). Nonetheless, high production expenses and the need for specialized infrastructure hinder its widespread adoption, especially in developing nations. Another obstacle is the absence of standardization in biochar application for composting, which differs based on the type of feedstock and pyrolysis conditions. A significant case study is Japan's incorporation of biochar into composting, where its use in municipal composting plants led to a considerable decrease in methane emissions. Likewise, research conducted in China has shown that corn stover biochar enhanced methane yield by 29% during AD, highlighting its potential for biogas production. However, the challenge of commercial scalability persists, necessitating financial backing and policy support for wider implementation (Liu et al., 2021). **Figure 2** shows bioengineering methods of biochar and sustainability goals. **Figure 3** depicts biochar interactions with pollutants.

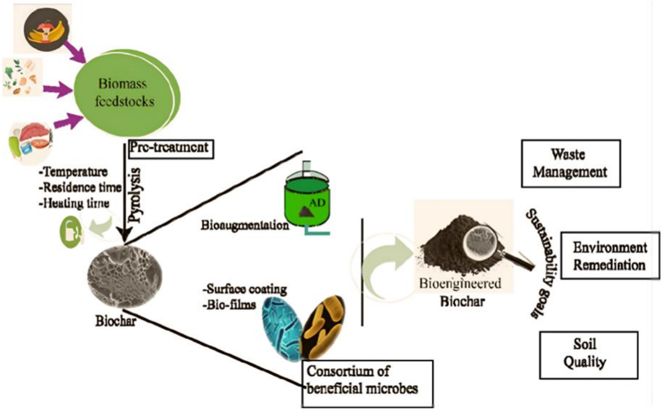

Figure 2. Bioengineering methods of biochar and sustainability goals (Adapted from Liu et al., 2021)

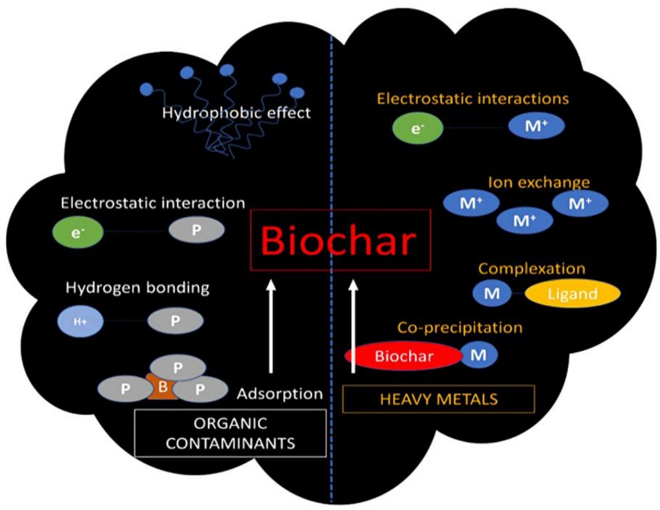

Figure 3. Biochar interactions with pollutants (M: Metal particles; M^+: Charged ions; e: Electron; P: Pollutant; & B: Biochar) (Liu et al., 2021)

Application in waste management and pollution mitigation:

Aerobic digestion (composting): Integrating biochar into composting increases aeration, reduces GHG emissions (CO_2, methane [CH_4], and nitrous oxid [N_2O]), and accelerates OM decomposition, making it a key innovation in circular bioeconomy strategies. Its porous structure helps retain nutrients like ammonium (NH_4^+) and reduces the emission of nitrogen gases (Singh et al., 2022).

Anaerobic digestion: Biochar enhances methane production and maintains system pH, which helps stabilize the microbial community and improves process efficiency, i.e., corn stover biochar has been shown to increase methane yield by up to 29% (Liu et al., 2021).

Pollutant adsorption (organic pollutant): Engineered biochar demonstrates high adsorption for pollutants like antibiotics (e.g., sulfonamides) and dyes (e.g., methylene blue). The adsorption mechanisms include hydrophobic interactions and electrostatic interactions facilitated by biochar's surface functional groups (Waliszewska et al., 2019).

Inorganic pollutants: Biochar's surface properties make it effective at adsorbing heavy metals like lead (Pb), cadmium (Cd), and chromium (Cr). Modified biochar (e.g., biochar with magnetic properties) shows even higher adsorption capacities for heavy metals, proving beneficial for soil and water purification (Ren et al., 2018).

Vermicomposting

Vermicomposting is a controlled process for the degradation of OM, utilizing earthworms to accelerate the stabilization of waste. This method produces a nutrient-rich material known as vermicompost, which can enhance soil quality and promote plant growth with benefits including increased biomass and crop yield (Vuković et al., 2021). Application of vermicompost enhances soil structure, decreases bulk density, increases porosity, improves water retention, and promotes aeration. Vermicomposting fosters beneficial microbial communities that help suppress plant diseases and pests (Aslam et al., 2019). Despite its benefits, vermicomposting comes with certain drawbacks, such as a longer duration for processing, susceptibility to environmental changes, and the necessity for meticulous management of worms to avoid deaths caused by temperature changes or improper feeding. A case study focused on the agricultural sector in India showed that vermicomposting enhanced soil quality and increased crop yields, positioning it as a feasible alternative to synthetic fertilizers. In Turkey, automated reactors for vermicomposting have been implemented to boost production, with heat treatment guaranteeing compost free from pathogens. Nevertheless, the challenge of scaling up vermicomposting for industrial applications remains due to limited automation and labor-intensive methods, indicating a need for further technological innovations to improve efficiency (Bellitürk, 2018; Vuković et al., 2021).

Process phases:

1. ***Active decomposition:*** During this phase, earthworms ingest and digest OM, improving its assimilation and facilitating the movement of microorganisms. Earthworms also increase the surface area available to other decomposers, allowing for a more effective breakdown of OM (Liu et al., 2021).
2. ***Maturation phase:*** Earthworms migrate to fresh layers of organic waste, ensuring continuous processing while allowing for the harvesting of vermicompost (Vuković et al., 2021).

Vermicomposting practices and economic potential in Turkey: In Turkey, common vermicomposting feedstocks include cow, cattle, horse, sheep-goat manure, yard waste, and agricultural residues (Bellitürk, 2016) (**Figure 4**). Traditional systems face inefficiencies, leading to modern automated technologies like continuous flow reactors, which enhance production (Bellitürk, 2018). Heat treatment is required for certification, ensuring pathogen-free vermicompost (Bellitürk, 2018).

The vermicompost sector in Turkey is economically promising, with prices ranging from 2,000 to 3,000 TL per ton for solid vermicompost and 25,000 to 60,000 TL for liquid vermicompost (Bellitürk, 2018). Although prices are higher than conventional compost, the market has grown rapidly, creating jobs and offering better yields due to higher nutrient

Figure 4. Instrumentation for vermicomposting: (A) Automated flow reactor, Turkey; (B) Heat treatment (sterilization) machine, Turkey; (C) Rotating vermicompost separation system developed by Riverm Company, Turkey; & (D) Ventilator for solid vermicompost drying (Bellitürk, 2018)

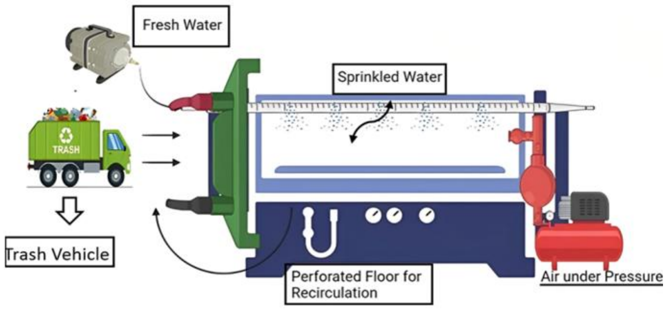

Figure 5. Schematic diagram of tunnel composting system (Adapted from Koutsoumanis et al., 2020)

density. Government support and education may further encourage adoption among farmers (Bellitürk, 2018).

Smart composting

Technological advancements in managing biodegradable solid waste have yet to achieve a rapid and fully eco-friendly solution. While AD offers energy generation via biogas, it faces limitations such as feedstock purity, compost quality, odor emissions, and high initial investment costs, making its economic feasibility challenging compared to WTE plants, which produce five times more electricity per ton (Yaser et al., 2022). Composting, however, remains the primary solution due to its environmental and agricultural benefits, and research has optimized key factors like the carbon-to-nitrogen ratio, temperature, moisture, and oxygen levels. Various traditional composting methods, such as the Bangalore and Indore methods, are effective but face issues with odor and leachate control, prompting a need for more rapid, sustainable approaches (Awasthi et al., 2022). Researchers are now exploring advanced composting systems, including centralized facilities outside urban areas for organic fraction municipal solid waste (OFMSW) and decentralized systems within cities, both designed for efficient, localized composting (Fogarassy et al., 2022). The integration of IoT into composting has transformed waste management by automating monitoring tasks, enhancing efficiency, and lowering GHG emissions. Sensors equipped with IoT technology monitor temperature, moisture, and oxygen levels in real-time, enabling composting facilities to fine-tune aeration and decomposition processes without the need for manual oversight. This leads to a decrease in labor expenses and guarantees uniformity in compost quality. Nevertheless, implementing IoT-based composting can be costly, necessitating substantial investments in infrastructure, upkeep, and technical know-how. Additionally, it might be less viable for smaller operations that seek more affordable solutions. A case study conducted in the Netherlands highlighted the effectiveness of IoT-enabled composting in municipal waste facilities, where sensor-based aeration management led to a 30% reduction in energy use and a 40% decrease in methane emissions. In New York City, a smart composting initiative was trialed as part of the Big Reuse Project, incorporating IoT technology to enhance the processing of organic waste, showcasing its feasibility for extensive urban composting. Nonetheless, there are still hurdles to overcome in making IoT solutions cost-effective and accessible for decentralized and rural composting systems (Baptista, 2018; City of New York, 2021).

Centralized composting system: Centralized composting provides financial advantages, including lower landfill expenses and income from compost sales. For instance, the New York City compost project (NYCCP) diverts over 200 tons of organic waste annually, resulting in a $3 million reduction in municipal waste disposal costs while also fostering local green employment opportunities (Morrow & Davies, 2022). This method, particularly windrow composting, ensures effective monitoring while reducing processing costs and GHG emissions (Chazirakis et al., 2022; Sakarika et al., 2019). Emerging technologies, such as unmanned aerial vehicles, hold promise for enhancing waste management, despite their limited current use. India’s Swachh Bharat mission highlights innovative interventions, integrating technologies like vehicle tracking systems to optimize waste collection processes, demonstrating that centralized composting and modern technology can improve urban waste management effectively (Dalal et al., 2022; Nenciu et al., 2022; Storino et al., 2017).

Centralized tunnel composting system: Centralized tunnel composting systems address the crucial challenge of odor control, maintaining an aerobic environment, and preventing emissions. These systems efficiently process 15-20 tons of waste per year by allowing for daily compost removal and incorporating leachate management and biofilters for odor control (Koutsoumanis et al., 2020) (**Figure 5**). Effective design of natural ventilation enhances composting outcomes through innovative structures like hanging roofs and wall ventilators (Tham et al., 2022). Research in mechanical composting primarily targets open systems like windrows and static heaps. A centralized mechanical composting plant in Chania, Greece, serves 156,585 residents and processes about 91,500 kg of urban solid waste annually (Chazirakis et al., 2022). The study highlighted the recovery of significant biogenic carbon and the potential use of compost-like products as green manure. However, concerns about compost quality arise from the origin of raw materials, often sent to landfills. To ensure sustainable treatment of OFMSW within a CE framework, it is essential to separate organic waste from residuals at the source to minimize impurities (Chazirakis et al., 2022).

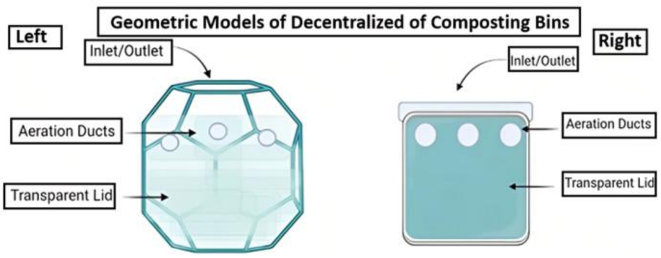

Figure 6. Various geometric models of decentralized composting bins: hexagonal-prism bin (left) and cube-shaped bin (right) (Adapted from Sharma et al., 2023)

Decentralized composting system: While centralized tunnel composting systems effectively handle large waste volumes, many European countries, including Austria and Germany, are shifting towards door-to-door collection (Sakarika et al., 2019). Centralized systems face challenges such as pathogen risks and lower-grade compost, complicating fertilizer integration in agriculture. Compaction and moisture release hinder AD and slow valorization. In contrast, decentralized composting reduces processing costs and the space needed for organic waste decomposition. This approach generates pre-compost at the waste source, enhancing waste management and source segregation while improving biodegradation from the outset (Kurmana & Srinivas, 2021).

Decentralized compost bin: Decentralized compost bins, made from plastic, metal, or concrete, create controlled environments for composting, incorporating features like thermostats for temperature control, agitators for aeration, and activated carbon for odor management. These bins, ranging from 40 to 500 L, significantly reduce composting time by optimizing conditions. However, their smaller mass may lead to lower thermal inertia, making it challenging to reach recommended sanitization temperatures in colder climates (Arrigoni et al., 2018). In contrast, these systems perform well under tropical or controlled lab conditions (Sánchez et al., 2017). While effective in MSW management, small-scale decentralized composting may struggle in colder areas to achieve thermophilic temperatures (> 55 °C) due to insufficient mass. Composting source-separated kitchen waste and grass clippings can effectively maintain sanitization temperatures for at least three days. This sustained temperature control is crucial for pathogen reduction and creating safe, high-quality compost, underscoring the effectiveness of source-separated organic materials in achieving sanitization standards during composting (Arrigoni et al., 2018). The composting process took 244 days, revealing a consistent C ratio between 24 and 29 across layers, indicating balanced compost quality. The geometric design affects composting performance, with hexagonal-prism and cube-shaped bins outperforming rectangular ones (Dazzi et al., 2021). Initiatives like Poland's "composter for everyone" and India's "Swachh Bharat Abhiyan" aim to enhance waste recovery and management at the local level (Kumar et al., 2017; Saxena & Agrawal, 2022; Sulewski et al., 2021). **Figure 6** shows various geometric models of decentralized composting bins.

Decentralized rotary drum composter: The rotary drum composter is an efficient technology for decentralized composting, reducing processing time to 2 to 3 weeks by providing optimal aeration and agitation for aerobic microorganisms. Batch systems suit agricultural waste, and while previous studies have explored turning intervals, the effect of slow-speed continuous rotation needs further investigation. The composting process was successfully implemented through the mesophilic and thermophilic phases; however, heat loss was observed due to inadequate aeration (Alkoaik et al., 2018). Reduced the composting time to a few hours for tomato and chicken manure mixes, yielding stable compost suitable for soil amendment (Rashwan et al., 2021). Evaluated three kitchen waste composting methods: solar-assisted, bio-enhanced, and heat-dewatering, all of which met organic fertilizer standards, with the solar-assisted and bio-enhanced methods proving to be profitable (Wang et al., 2023). **Figure 7** depicts a decentralized rotary drum composter with isolated composting compartments.

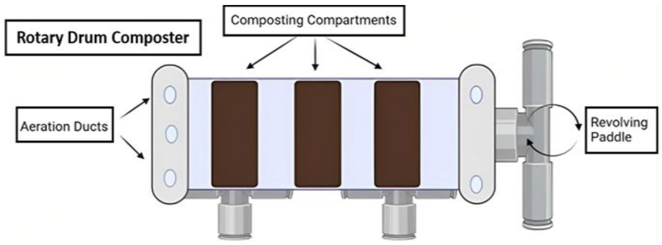

Figure 7. A decentralized rotary drum composter with isolated composting compartments (Adapted from Sharma et al., 2023)

Decentralized pre-composting system: Pre-composting at waste disposal sites enhances the biodegradation process, reducing overall composting time, space, and transport needs (Sakarika et al., 2019). The effective management of 2,235 kg of fruits and vegetables within 14 days enhanced efficiency and minimized environmental impact (Nenciu et al., 2022). Developed a 200 L pre-composter equipped with an agitator and aeration system, achieving significant reductions in mass, volume, and leachate. Challenges included community collection costs, aeration optimization, reactor design, and public acceptance (Sakarika et al., 2019). Decentralized composting facilities are more cost-effective than centralized ones in Bilaspur, India (Rathore et al., 2022). An implemented a two-step process, achieving a 33% mass reduction and a final C ratio of 12:1, indicating nutrient-rich compost (Sakarika et al., 2019). This transition requires adaptable decision-making methodologies to effectively address MSW generation (Datta & Kapoor, 2022), and pre-composting supports better waste segregation (Kuznetsova et al., 2019). **Figure 8** shows a decentralized pre-composting operating approach.

Automation and Efficiency: Technological Enhancements

Automatic composting addresses low adoption issues by reducing time, space, and monitoring needs, making composting feasible for urban residents who lack awareness or the time for manual methods (Hashemi et al., 2021).

Forced aerated windrow composting

It involves installing blowers at the end of perforated pipes to direct airflow into compost heaps, particularly during the active composting stage, to supply oxygen essential for microbial activity. This airflow can be regulated by adjusting

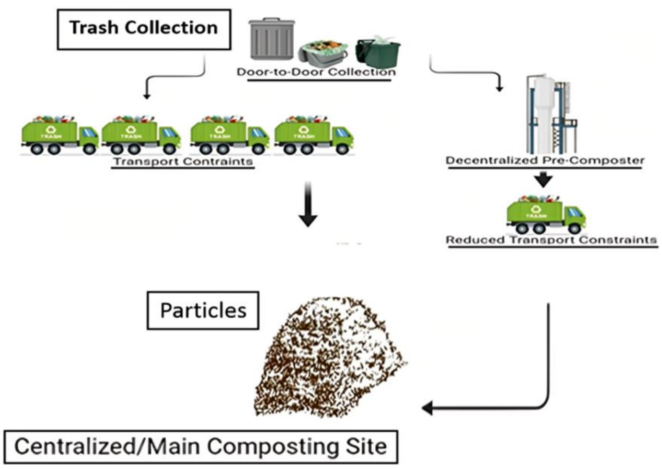

Figure 8. A decentralized pre-composting operating approach (Adapted from Sharma et al., 2023)

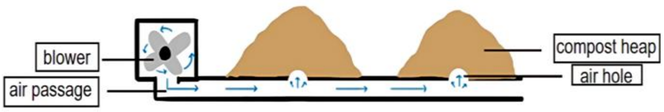

Figure 9. Forced aerated windrow composting (Larney & Olson, 2006; Michel et al., 2022)

the blower's frequency and duration. Insulating compost heaps helps retain heat, maintaining thermophilic temperatures throughout, which accelerates the decomposition process. This method shortens composting time and reduces labor, as turning is unnecessary. However, the system requires a significant investment for blowers and aeration channels, along with high maintenance and space requirements (**Figure 9**).

Automatic turning in-vessel composting

Automatic in-vessel composting technologies vary in design, size, and equipment. One type is the motorized turning in-vessel composter, which utilizes a powered motor to rotate the vessels for aeration and can be scheduled for specific rotation times and frequencies. These systems often incorporate temperature and humidity sensors to automatically monitor key parameters, significantly reducing the labor required for manual composting. However, the need for high-torque motors to rotate heavy waste-filled vessels requires substantial investment and ongoing maintenance to ensure effective operation.

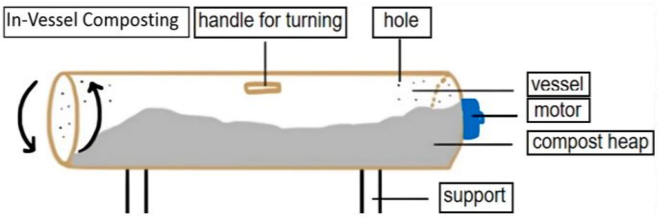

Figure 10. Automatic turning in-vessel composting (Adapted from Azis et al., 2022)

Despite these challenges, in-vessel composting is space-efficient and requires minimal labor (Mishra & Yadav, 2021) (**Figure 10**).

Electric home composter

An electric composter is an indoor unit that uses aeration, heat, and pulverization to reduce food waste volume, emissions, and odor. These composters, which can be countertop-sized or larger for indoor and outdoor use, typically break down waste within 24 hours to a few days (Fakharulrazi & Yakub, 2020). They accelerate mesophilic and thermophilic phases through heat, quickly reducing moisture. Ground organic materials are mixed with soil or additives to enhance microbial activity. The final product cools to room temperature, resulting in a dry, sterile output due to the lack of a maturation phase, while most electric composters operate on a three-phase cycle drying, grinding, and cooling some include a curing phase, allowing partial stabilization of materials and extending the process to up to two weeks for garden-ready compost (Miller, 2019).

Table 1 presented the electrical home composting process, which begins with a drying phase, where the unit heats up to approximately 70 °C to simulate the natural heat of a compost heap. This heat, along with aeration, is evenly spread by grinding gears, which turn gently to ensure all surfaces are sanitized and methane-free. Carbon filters help to manage airflow, discharging air through the back of the unit. This initial drying step significantly reduces the volume of organic materials. Following this, internal gears grind the dried food waste into fine, powder-like particles, making it easier to blend with soil. In the cooling phase, the contents return to room temperature, continuing the aeration and dehumidification process for safe handling. Finally, in the curing phase, the compost undergoes a controlled stabilization process with regulated aeration and moisture over several weeks, allowing it to become fully mature (Azis et al., 2022; Miller, 2019).

Table 1. Comprehensive explanations of every stage in an electrical household composter (modified from Miller, 2019)

Phase cycle	Process
Drying	Temperature: Heats to approximately 70 °C, representing compost heap conditions. Process: Grinding components evenly disperse heat and aeration, disinfecting surfaces and guaranteeing a methane-free environment. Airflow: Air passes through carbon filters and exits the machine. Outcome: Minimize the volume of organic materials.
Crushing	Process: Interior gears crush food waste into fine, powder-like particles. Purpose: Facilitates easy mixing with soil.
Cooling	Temperature: Returns unit and contents to room temperature (25 °C). Process: Continues aeration and dehumidification for safe handling.
Curing	Process: Contents are aerated and moisture-controlled to stabilize over weeks. Duration: Typically, longer than other phases.

Table 2. List of some available electrical home composters in the market (modified from Azis et al., 2022)

Product name	Specifications	Cost	Reference
Vitamix Food Cycler FC-50	Dimensions: 12×11×14 inches Mass: 27 pounds Volume: 2.5 Litters Energy: 0.8 kWh/cycle Processing: 4 to 8 hours Phases: Drying, crushing, and cooling	$400	Vitamix (2020)
Beyond Green Composter	Dimensions: 20×12×20 inches Mass: 22 pounds Volume: 5 pounds/day Process: 5 days (compostable) & 2 weeks (high-nitrogen) Phases: All	$380	Beyond GREEN (2021)
Nature Mill Ultra Composter	Dimensions: 20×20×12.6 inches Mass: 25 pounds Volume: 120 pounds/month Energy: 5 kWh/month & 5 kilowatt hours/month Process: 2 weeks Phases: All	$500	Machines (2013)
Lomi Composter	Dimensions: 16×12×13 inches Mass: 7 pounds Energy: 1 kilowatt/hour Process: 20 h Phases: Drying, grinding, and cooling	$499	Gadget (2021)

Table 2 presents various electrical home composters on the market that offer distinct features tailored to different household needs. The compact Vitamix Food Cycler FC-50, with a 2.5-liter capacity, processed waste efficiently within 4 to 8 hours, utilizing drying, grinding, and cooling phases (Azis et al., 2022). The Beyond Green Composter, a larger model, manages 5 pounds of waste per day, completing a standard compost cycle in 5 days and high-nitrogen materials in 2 weeks, providing a comprehensive composting process. The Nature Mill Ultra Composter, designed for larger volumes, handles up to 120 pounds of waste monthly, completing its cycle in around 2 weeks (Azis et al., 2022). Finally, the Lomi Composter, with a 7-pound capacity, rapidly processes waste within 20 hours, employing drying, grinding, and cooling phases to produce ready-to-use compost quickly and conveniently. These composters offer a range of processing speeds, capacities, and features to suit different composting preferences and household sizes (Azis et al., 2022).

CHALLENGES IN COMMERCIAL COMPOSTING

The challenges in commercial composting included operational barriers (contamination and process efficiency), economic and market challenges (cost of processing and market demand), public participation and awareness gaps, and regulatory and policy challenges (Wei et al., 2017).

Operational Barriers (Contamination and Process Inefficiency)

Odor and GHG emissions are primary operational barriers. Organic waste with high ammonia content emits strong odors immediately after composting. Processes like fly larvae composting release heat, volatile compounds, and obnoxious gases, contributing to air pollution and potential health hazards for nearby workers (Wei et al., 2017). Furthermore, composting and vermicomposting processes can generate secondary pollution through GHG emissions, reducing environmental benefits. Effective management practices such as reducing nitrogen intake in feed, shortening storage times, lowering temperatures, and using semipermeable covers can help mitigate CH_4 and N_2O emissions (Azis et al., 2022; Wei et al., 2017).

Economic and Market Challenges

Composting plants need an initial investment ranging from $500,000 to $2 million, influenced by their size and level of automation. Nevertheless, cities such as San Francisco have indicated that they recover 60-80% of their costs through the sale of compost and savings on landfill expenses (Michel et al., 2022). Recycling organic waste from livestock often involves excess antibiotics, heavy metals, and hormones, affecting microbial growth and potentially causing environmental deterioration when applied to land (Wei et al., 2017). Financial support from the government can help reduce expenses for composting facilities. For instance, the EU provides funding that can cover as much as 40% of the costs associated with composting infrastructure through the CE package (Badgett & Milbrandt, 2021). Strict environmental regulations limit the use of recycled fertilizers with toxic elements above safe levels, which impacts market demand and profitability. High processing costs and consumer reluctance to buy products made from recycled animal waste add to economic challenges (Azis et al., 2022).

Public Participation and Awareness Gaps

Public acceptance and awareness are critical but challenging aspects of recycling. Communities near recycling plants often oppose them due to odor concerns and fears about pathogen spread. Educating communities and farmers on the societal, economic, and environmental benefits of recycling could help shift perceptions and increase acceptance (Lin et al., 2018). Negative consumer perceptions about products derived from organic waste recycling also impact marketability and revenue (Wei et al., 2017).

Regulatory and Policy Challenges

Scaling up recycling operations is often limited by specific biological and logistical needs, especially in approaches like fly larvae composting, which require adequate space and specific biological conditions (Fakharulrazi & Yakub, 2020). Regulatory frameworks must enforce quality control for recycled products to ensure market consistency, but this often necessitates additional costly treatments (Wei et al., 2017). Addressing these challenges involves government action to boost public awareness, support cooperative initiatives, and foster technological innovations for more efficient recycling.

OPPORTUNITIES AND SOLUTIONS

For the shift to a CE, commercial composting needs to address economic and operational challenges. Important approaches consist of government incentives, initiatives to raise public awareness, and improvements in smart composting technologies (Michel et al., 2022). The NYCCP offers significant opportunities for enhancing commercial composting through grassroots participation, training initiatives, supportive policies, and increased funding. Founded by the Department of Sanitation (DSNY) in 1993, the NYCCP has engaged thousands of New Yorkers, with 2,470 participants in composting workshops in 2014 alone (DSNY, 2015). The Master Composter training program has equipped hundreds of individuals to establish their own community composting operations. In response to a commitment to zero waste and sustainability, the NYCCP received additional funding from DSNY between 2014 and 2016, resulting in 24 new positions dedicated to compost outreach and education and the establishment of seven community composting demonstration sites across the five boroughs (Wei et al., 2017). However, public investment in composting has declined since 2018, leading to cuts in funding for kerbside and community composting in the 2021 municipal budget. Despite these challenges, grassroots activism through the save our compost campaign restored $2.86 million to community composting initiatives (NRDC, 2020). These efforts highlight the potential for commercial composting as a viable and socially inclusive strategy for urban waste management (Baptista, 2018; City of New York, 2021).

Expanding Markets for Compost

The NYCCP plays a crucial role in enhancing urban greening efforts by supporting over 100 community projects focused on compost distribution (Michel et al., 2022). This definition encourages broader participation in composting initiatives, ultimately leading to increased community engagement in sustainable practices. For example, the Big Reuse has established programs that help community members access compost and utilize it effectively in their gardening and greening efforts (Baptista, 2018).

Policy Support and Financial Incentives

The NYCCP is supported by approximately $2 million in annual public funding, which ensures that compost remains a public resource and is available to all residents. A notable collaboration is seen at Red Hook Community Farm, which engages over 200 members from the Park Slope Food Coop (Michel et al., 2022; Miller, 2019). This partnership not only promotes community involvement but also provides a platform for residents to learn about composting and its benefits (Getter, 2023). Furthermore, the Green City Force program recruits 100 young adults each year from public housing to train them in green enterprises. This program equips participants with skills in composting labor, thereby fostering community resilience and environmental stewardship.

Initiatives to Improve Composting Efficiency

In New York City, community composting initiatives have demonstrated the effectiveness of commercial composting in managing organic waste. Volunteers manage operations that process substantial amounts of food waste, contributing to local gardens and fostering a CE (Getter, 2023). This model retains food waste within the community, promoting social responsibility and enhancing soil health. For instance, community composting can handle over 225 tons of organic material annually, making commercial composting a viable solution for organic waste management in urban settings (Davies, 2020). In Ghana, the Green Africa Youth Organization promotes composting within communities, generating job opportunities for young entrepreneurs and minimizing waste in landfills (Boateng, 2022).

RESULTS AND DISCUSSION

This study analyzed the composting procedures and efficacy. It also devised a comparative analysis of various technologies and approaches for the composting process (Davies, 2020; Getter, 2023). It also analyzed the centralized and on-site treatment of composting and acknowledged the socio-economic and environmental concerns regarding the sustainability perspectives.

Findings on Composting Efficacy

Household food waste contains high moisture content (80-95%), salt, protein, starch, fat, and various OM. It is also rich in nitrogen, phosphorus, potassium, calcium, and other trace elements (Michel et al., 2022). Additionally, it can contain complex chemicals, pathogenic microorganisms, flies, cockroaches, and vermin. Due to these characteristics, household food waste often requires daily disposal in areas with high temperatures, such as southern China and parts of South Asia. For instance, in a city with 200,000 households, assuming each household disposes of approximately 1 kg of food waste per day, this could amount to approximately 200,000 kg daily (Azis et al., 2022).

Comparative Analysis of Technologies

Traditional disposal method

To reduce costs, household food waste is often mixed with other MSW for landfill disposal, a method that has harmful environmental impacts (Sharma et al., 2023).

Governmental shifts

Many governments are beginning to adopt new food waste treatment systems due to environmental concerns, influenced by factors like policy, long-term planning, geography, urbanization, and community awareness (Serafini et al., 2023).

System models

There are two main disposal models from primary processing points: centralized and on-site/decentralized treatment systems. Technologies for these systems include biological treatment, mechanical biological treatment, thermal technologies, and landfill technologies (Sharma et al., 2023).

Socio-Cultural and Economic Implications: Effects of Composting on Communities and Economies

Community composting schemes have been identified as activities that achieve wider social and environmental objectives, such as increasing awareness and actions related to recycling and reuse, supporting individuals to develop healthier diets, and providing opportunities to learn meaningful life and work skills (Rathore et al., 2022). Outputs from community composting extend beyond the simple metrics of landfill diversion to include education events, volunteer involvement, and skills development that support community gardens and kitchens. Research found that community composting can lower management costs and GHG emissions significantly, with studies indicating over a one-third reduction in Europe and Canada (Sharma et al., 2023).

Interpretation of Challenges and Opportunities

Growing environmental concerns have led to changes in waste treatment practices (Singh et al., 2022). However, the success of these systems is impacted by available resources, urban planning, income levels, cultural practices, and community awareness. On-site treatment, such as home composting or using food waste processors, is common in regions with suitable infrastructure (Sharma et al., 2023). Centralized systems, managed by local governments, involve organized collection and separation, which varies by regulatory requirements (Rathore et al., 2022).

FUTURE DIRECTIONS AND RESEARCH NEEDS

Innovative research suggests that composting systems equipped with IoT technology can improve temperature regulation, leading to a 30% decrease in composting duration and a 40% decrease in methane emissions, making them viable for widespread adoption (Saxena & Agrawal, 2022; Serafini et al., 2023). Furthermore, the use of microbial inoculants has demonstrated promise in speeding up the breakdown of OM, which can improve the quality of the compost. For example, studying alternative drying and cooling techniques could make composting more energy-efficient (Rashid & Shahzad, 2021). Incorporating IoT-enabled sensors and AI-driven analytics can optimize temperature, moisture, and aeration levels in real time, ensuring better process control and uniform compost quality. Combining composting with AD and biochar production could increase resource recovery. Research on integrating these processes could produce high-quality compost and additional byproducts like bioenergy and biochar (Awasthi et al., 2019). Additional research is needed to ensure compost sanitation, especially in removing pathogens and microplastics. Advanced filtration and sanitization techniques could improve compost safety for agricultural use (Singh et al., 2022).

Innovations in Composting Techniques (Biochar Integration and Microbial Additives)

Biochar is integrated into composting to enhance aeration, reduce GHG emissions (CO_2, CH_4, and N_2O), and accelerate OM breakdown (Saxena & Agrawal, 2022). It retains nutrients like ammonium and reduces nitrogen emissions, benefiting both aerobic and anaerobic composting processes. Microbial additives further accelerate decomposition and help optimize conditions for pathogen reduction (Rashwan et al., 2021).

Policy Recommendations

Developing policies that address clear standards for compost quality, provide financial incentives for diversion from landfills, and encourage compost usage in agricultural practices is essential. States that incorporate composting into carbon markets could earn between $50 and $100 for each ton of CO_2 emissions they prevent, presenting a viable strategy for sustainability. Support from regulatory bodies can also foster public awareness and acceptance of commercial composting, enhancing marketability (Wang et al., 2023). Long-term environmental impact studies are critical to evaluate composting's role in emission reductions and landfill dependency (Awasthi et al., 2019). Research should also explore socio-economic aspects, such as job creation, economic benefits to agriculture, and improved soil health (Wang et al., 2023).

Integrating Composting With Other Waste Management Practices

Expanding composting operations through centralized and decentralized systems can enhance waste management. Integrating composting with waste recovery methods, such as AD, supports CE goals by producing renewable energy and compost products that improve soil quality (Dsouza et al., 2021; Serafini et al., 2023).

CONCLUSION

Commercial composting serves as a cornerstone for sustainable waste management, offering considerable environmental and economic benefits. By converting OFW into compost, it significantly reduces waste directed to landfills, thus decreasing methane emissions, a major GHG. In Makkah, the potential reduction of OFW by up to 1.6 million tons by 2030 could yield 0.23-0.40 million tons of compost, promoting nutrient cycling and reducing dependency on chemical fertilizers. The composting process enhances soil fertility and agricultural productivity, replacing fertilizers like urea and DAP. The incorporation of technologies such as in-vessel composting and IoT-enabled sensors further streamlines the process, ensuring efficiency and better-quality outputs. Moreover, community-based initiatives like the NYCCP illustrate the social and educational impacts of composting, involving thousands in workshops and training programs, fostering skills, and promoting community well-being. To tackle these issues, a comprehensive strategy is necessary:

(1) funding affordable composting technologies like automated in-vessel systems and biochar-enhanced methods to boost efficiency,

(2) legislative backing through subsidies and incentives to promote the adoption of commercial composting, and

(3) community education initiatives aimed at increasing participation and minimizing contamination in compost materials.

A well-structured plan is essential for unlocking the full potential of composting. In the short term (0-2 years) launch subsidies, tax benefits, and awareness initiatives. In the medium term (3-5 years) enact municipal composting regulations, establish quality benchmarks, and promote extensive integration. In the long term (5+ years) implement national composting requirements and invest in artificial intelligence-powered automation. Agriculture should utilize compost enriched with biochar, the food sector should incorporate in-vessel composting, and local governments should focus on IoT-enabled solutions. Community composting initiatives should be broadened to decrease reliance on landfills. Composting presents both economic and environmental advantages; however, financial and regulatory obstacles must be tackled through governmental support, policy-making, and cooperation within the industry to position it as a fundamental component of the CE. By enacting these strategies, composting can be integrated as a widespread solution in the CE. Addressing these issues through technological advancements, supportive policies, and public engagement will enhance the efficacy of composting and solidify its role in the CE. By integrating composting with other waste management practices, a comprehensive approach can be achieved, contributing to both environmental sustainability and socio-economic developments.

Author contributions: ZS & YS: conceptualization, processes and methodology; **ZS:** investigation, resources, data collection, writing – editing & revising; **YS:** reviewing, editing, supervision. Both authors have agreed with results and conclusions.

Funding: No funding source is reported for this study.

Ethical statement: The authors stated that the study did not involve any human or animal subjects and ethical approval was not required.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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