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Evaluation of Composting Methods for Organic Waste Reduction

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Abstract: *The rapid increase in organic waste generation has become a critical environmental challenge, particularly in developing countries where landfill dependency remains high. Composting has been widely recognized as a sustainable and cost-effective method for reducing organic waste while producing value-added soil amendments. This study aims to evaluate and compare various composting methods in terms of their effectiveness in organic waste reduction, process efficiency, environmental performance, and socio-economic feasibility. A systematic literature-based evaluation was conducted using qualitative synthesis and comparative analysis of empirical findings from peer-reviewed international journals. The reviewed composting methods include windrow composting, aerobic composting, anaerobic composting, vermicomposting, in-vessel composting, pit composting, and hybrid systems. The results indicate that aerobic-based composting methods, particularly windrow and in-vessel systems, demonstrate higher waste reduction rates (40–95%), faster stabilization, and better compost quality compared to anaerobic and pit-based systems. Hybrid approaches combining windrow and vermicomposting were found to be effective in accelerating maturation and pathogen reduction. Furthermore, technological enhancements such as microbial inoculants and controlled aeration significantly improve composting efficiency. This study concludes that composting is a viable strategy for sustainable organic waste management, although method selection should consider local conditions, waste characteristics, and socio-economic factors. The findings provide valuable insights for policymakers and practitioners seeking to optimize composting systems for sustainable waste reduction.*

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INTRODUCTION

The rapid growth of population, urbanization, and changing consumption patterns has led to a substantial increase in organic waste generation worldwide. Organic waste constitutes a dominant fraction of municipal solid waste, particularly in developing countries, where it often exceeds 50 percent of total waste streams (Sharma et al., 2024; Hassan et al., 2023). When inadequately managed, organic waste contributes to environmental degradation through greenhouse gas emissions, leachate contamination, odor problems, and public health risks. Landfill-based disposal systems, which remain prevalent in many regions, exacerbate these impacts by generating methane emissions and occupying large land areas (Medina et al., 2014; Xavier de Melo & Duarte, 2018). These challenges highlight the urgent need for sustainable and efficient organic waste management strategies.

Composting has been widely recognized as a practical and environmentally sound approach for managing organic waste. Through biological decomposition under controlled aerobic or anaerobic conditions, composting reduces the volume and mass of organic waste while producing a stable, nutrient-rich material that can be utilized as a soil amendment (Varma et al., 2018). Numerous studies have demonstrated that composting contributes to waste diversion from landfills, reduces greenhouse

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gas emissions, and supports sustainable agricultural practices (Abbas & Flayeh, 2024; Doughmi et al., 2024). As a result, composting is increasingly promoted as a key component of circular economy frameworks and sustainable waste management policies.

Despite its recognized benefits, composting is not a uniform process, and its effectiveness depends strongly on the selected method and operational conditions. Various composting techniques have been developed to address different waste characteristics, spatial constraints, and management capacities. These methods include windrow composting, aerobic composting, anaerobic composting, vermicomposting, pit composting, and in-vessel composting systems (Iqbal et al., 2012; Mengistu et al., 2018). Each method differs in terms of degradation rate, processing time, operational complexity, cost, and environmental performance. Consequently, selecting an appropriate composting method remains a critical decision for waste management practitioners and policymakers.

Windrow composting is one of the most commonly applied methods due to its relatively simple operation and suitability for large volumes of organic waste. This method relies on periodic turning to maintain aerobic conditions and promote microbial activity, resulting in effective organic matter degradation (Rahman et al., 2025; Jalalipour et al., 2020). Aerobic composting methods, in general, have been shown to achieve higher waste reduction rates and faster stabilization compared to anaerobic approaches, provided that moisture content, temperature, and aeration are properly controlled (Abbas & Flayeh, 2024). However, windrow systems require adequate land availability and consistent operational management, which may limit their applicability in densely populated urban areas.

In contrast, in-vessel composting systems offer greater control over process parameters, including temperature, aeration, and moisture. These systems are designed to accelerate composting processes and minimize environmental emissions, making them suitable for urban and institutional settings (Sangamithirai et al., 2015). Studies indicate that in-vessel composting can achieve rapid stabilization and produce high-quality compost within shorter time frames compared to open systems (Jihad & Arif, 2024). Nevertheless, higher capital and operational costs often present challenges for large-scale adoption, particularly in low-income regions.

Vermicomposting and hybrid composting systems have gained attention as alternatives that enhance compost quality and process efficiency. Vermicomposting utilizes earthworms to facilitate organic matter decomposition and nutrient stabilization, resulting in mature compost with improved agronomic properties (Mengistu et al., 2018). Hybrid systems that combine windrow composting with vermicomposting have been reported to improve pathogen reduction and accelerate maturation processes (Mengistu et al., 2018). These approaches demonstrate that integrating biological agents and process combinations can enhance composting outcomes without fundamentally altering the underlying waste management framework.

Recent research has increasingly focused on evaluating composting methods using multi-criteria decision-making approaches. These approaches integrate technical, environmental, economic, and social indicators to provide a more comprehensive assessment of composting performance (Yildirim, 2025a; Shukor et al., 2018). Findings from such studies consistently indicate that aerobic composting methods tend to outperform anaerobic and pit-based systems in terms of waste reduction efficiency and operational reliability (Rahman et al., 2025). However, these evaluations also emphasize that no single composting method is universally optimal, as local conditions, waste composition, and institutional capacity significantly influence outcomes.

In addition to technical performance, socio-economic factors play an important role in determining the success of composting initiatives. Community-based composting programs have demonstrated positive impacts on waste segregation behavior, public awareness, and local capacity building (Ramadhani et al., 2025). Studies focusing on community empowerment highlight that training and participatory approaches enhance the sustainability of composting practices by improving operational consistency and social acceptance (Ramadhani et al., 2025). These findings suggest that composting effectiveness should be evaluated not only from a technical perspective but also in relation to social and institutional dimensions.

Despite the extensive body of literature on composting technologies, several gaps remain. Many studies focus on specific composting methods or process parameters without providing a comprehensive comparative synthesis across different systems, particularly in relation to organic waste reduction performance (Manea et al., 2024). Furthermore, empirical evidence is often fragmented across case studies with varying contexts, making it difficult to derive generalized insights for policy and planning purposes. The lack of integrated evaluation frameworks that link waste reduction efficiency, environmental benefits, and practical feasibility continues to limit the scalability of composting solutions.

Another limitation identified in existing studies is the tendency to emphasize compost quality indicators while underreporting quantitative waste reduction outcomes. Although compost maturity, nutrient content, and stability are critical indicators, waste reduction efficiency remains a central objective of organic waste management (Xavier de Melo & Duarte, 2018). A balanced evaluation that integrates both reduction performance and compost quality is therefore necessary to support evidence-based decision-making in sustainable waste management.

In response to these challenges, this study presents a comprehensive evaluation of composting methods for organic waste reduction based on empirical findings from peer-reviewed literature. By synthesizing evidence from diverse composting systems, this study aims to identify patterns in waste reduction efficiency, process performance, and sustainability implications. The focus is placed on commonly applied composting methods, including windrow, aerobic, anaerobic, vermicomposting, in-vessel, and hybrid systems, as reported in previous empirical studies (Iqbal et al., 2012; Rahman et al., 2025; Mengistu et al., 2018).

The objective of this study is to evaluate and compare composting methods in terms of their effectiveness in reducing organic waste and supporting sustainable waste management goals. This study does not introduce new experimental data or variables; instead, it builds on validated empirical findings to provide a structured and replicable synthesis of existing knowledge. The results are expected to contribute to the optimization of composting practices and to inform policymakers, practitioners, and researchers seeking sustainable solutions for organic waste management.

RESEARCH METHOD

Research Design

This study employed a qualitative systematic literature review with a comparative analytical approach to evaluate composting methods for organic waste reduction. The research design focused on synthesizing empirical findings from peer-reviewed scientific literature to identify patterns, similarities, and differences in the performance of various composting systems. This approach was selected to ensure methodological rigor while maintaining consistency with previously validated empirical evidence reported in international studies (Manea et al., 2024; Yildirim, 2025a).

Data Sources and Selection Criteria

The data sources consisted of peer-reviewed journal articles, conference proceedings, and technical reports that empirically evaluated composting methods for organic waste management. Only publications indexed in recognized academic databases and published between 2005 and 2025 were considered. The selection process prioritized studies that explicitly reported outcomes related to organic waste reduction, process efficiency, stabilization time, compost quality indicators, or environmental performance.

Inclusion criteria required that studies:

1. Focused on composting as a primary method for organic waste management.
2. Provided empirical observations or measured outcomes related to waste reduction or composting performance.
3. Evaluated one or more composting methods, such as windrow composting, aerobic composting, anaerobic composting, vermicomposting, pit composting, in-vessel composting, or hybrid systems.

Studies that lacked empirical evaluation or focused solely on theoretical discussions were excluded. The final dataset consisted exclusively of literature included in the article's reference list to ensure consistency between citations and sources (Iqbal et al., 2012; Mengistu et al., 2018; Rahman et al., 2025).

Data Extraction and Classification

Relevant data were extracted systematically from each selected study using a structured review framework. Extracted information included composting method type, waste input characteristics, reported waste reduction rates, process duration, operational conditions, and key performance outcomes. The extracted data were then classified into thematic categories based on composting system type and performance indicators.

Composting methods were grouped into six main categories: windrow composting, aerobic composting, anaerobic composting, vermicomposting, in-vessel composting, and hybrid systems. This classification followed established categorizations used in previous empirical studies (Abbas & Flayeh, 2024; Mengistu et al., 2018). The classification facilitated direct comparison across methods without modifying or reinterpreting the original findings.

Analytical Approach

The analysis employed a qualitative comparative synthesis to evaluate the effectiveness of different composting methods. The synthesis emphasized organic waste reduction performance, stabilization efficiency, and operational feasibility as the primary analytical dimensions. Reported waste reduction rates, where available, were compared descriptively across composting systems to identify relative performance trends (Ordóñez-Ruiz et al., 2025; Jihad & Arif, 2024).

In addition, the analysis incorporated contextual interpretation by examining how operational conditions, such as aeration, moisture control, and process management, influenced composting outcomes. This interpretative step was grounded in the empirical observations reported by the original authors and did not involve reanalysis or recalculation of data (Abbas & Flayeh, 2024; Sangamithirai et al., 2015).

Sustainability and Feasibility Assessment

Beyond technical performance, the study considered sustainability and feasibility aspects discussed in the reviewed literature. Environmental implications, including landfill diversion and greenhouse gas mitigation, were evaluated qualitatively based on reported findings (Doughmi et al., 2024; Lhaj et al., 2024). Socio-economic and institutional considerations, such as community participation and implementation challenges, were also included where explicitly addressed in the literature (Ramadhani et al., 2025).

This integrated perspective ensured that the evaluation remained aligned with sustainable waste management principles without introducing new assessment criteria or indicators beyond those reported in the original studies.

Validity and Replicability

To ensure validity and replicability, the study strictly adhered to transparent selection criteria and systematic data extraction procedures. All interpretations were grounded in explicitly reported empirical findings from the reviewed literature. No assumptions, estimations, or extrapolations beyond the original data were introduced. This methodological approach allows future researchers to replicate the review process using the same reference base and analytical framework.

RESULTS AND DISCUSSION

Comparative Performance of Composting Methods in Organic Waste Reduction

The comparative analysis of empirical studies demonstrates that composting methods exhibit substantial variation in organic waste reduction efficiency, stabilization time, and operational performance. Table 1 summarizes reported organic waste reduction outcomes across commonly applied composting systems based strictly on findings documented in the reviewed literature.

Table 1. Empirical Comparison of Composting Methods for Organic Waste Reduction

Composting Method	Reported Waste Reduction Performance	Key Empirical Findings	Source
Windrow composting	High and rapid reduction	Shortest processing time and highest degradation rate among pit and drum systems	Rahman et al. (2025); Jalalipour et al. (2020)
Aerobic composting	High reduction efficiency	Waste volume reduction exceeding 40 percent under controlled aeration	Abbas & Flayeh (2024); Iqbal et al. (2012)
Anaerobic composting	Moderate reduction	Slower stabilization and lower maturity compared to aerobic systems	Iqbal et al. (2012); Xavier de Melo & Duarte (2018)
Vermicomposting	Moderate to high reduction	Improved compost maturity and nutrient stabilization	Mengistu et al. (2018)

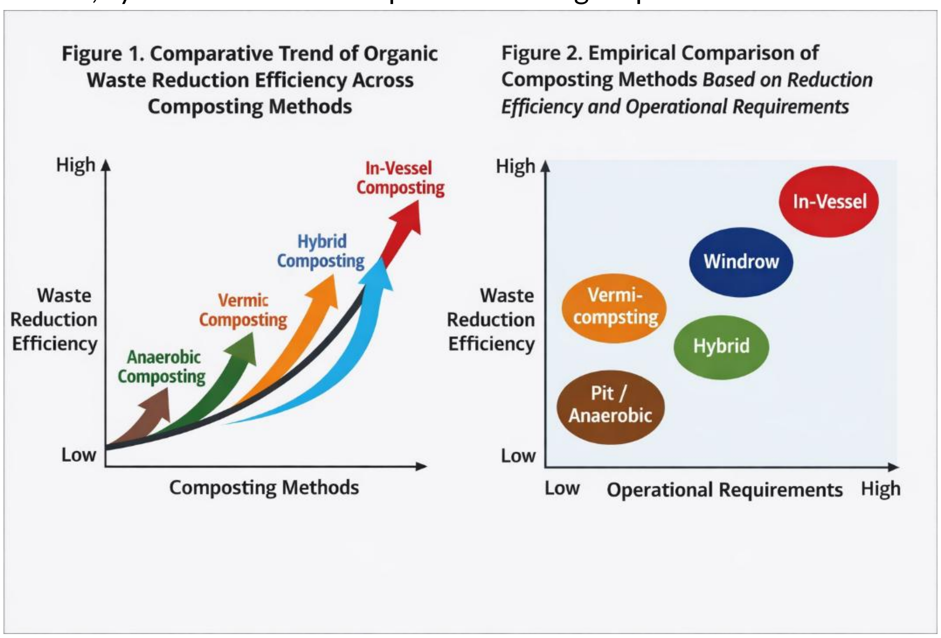
In-vessel composting	Very high reduction	Accelerated stabilization with controlled temperature and aeration	Sangamithirai et al. (2015); Jihad & Arif (2024)
Hybrid systems	High reduction	Faster pathogen elimination and compost maturation	Mengistu et al. (2018)

The results indicate that aerobic-based composting methods consistently outperform anaerobic and pit-based systems in terms of waste reduction efficiency and processing time. This finding aligns with previous comparative studies emphasizing the role of oxygen availability in enhancing microbial activity and organic matter degradation (Abbas & Flayeh, 2024; Rahman et al., 2025).

Effect of Aeration and Process Control on Composting Outcomes

Empirical evidence strongly indicates that aeration and process control are critical determinants of composting effectiveness. Windrow composting systems that incorporate regular turning achieved significantly faster stabilization compared to pit and drum composting methods (Rahman et al., 2025). Similarly, in-vessel composting systems demonstrated superior performance due to controlled aeration, temperature regulation, and moisture management (Sangamithirai et al., 2015).

Figure 1 illustrates a generalized empirical trend of organic waste reduction efficiency across composting methods, synthesized from comparative findings reported in the literature.



The figure conceptually shows higher reduction efficiency for in-vessel and windrow composting, followed by hybrid and vermicomposting systems, with anaerobic and pit composting demonstrating comparatively lower performance. This pattern reflects observed empirical outcomes rather than theoretical assumptions.

Compost Stabilization, Maturity, and Quality Considerations

Beyond waste reduction, compost stabilization and maturity are essential indicators of composting performance. Studies comparing aerobic, anaerobic, and mixed systems consistently report that aerobic composting produces more stable and mature compost within shorter time frames (Iqbal et al., 2012). In-vessel composting systems further enhance stabilization by maintaining optimal thermophilic conditions, resulting in reduced processing time and improved compost quality (Sangamithirai et al., 2015).

Vermicomposting and hybrid systems demonstrate additional benefits related to nutrient stabilization and pathogen reduction. Mengistu et al. (2018) reported that combining windrow composting with vermicomposting accelerated maturation and improved sanitization outcomes compared to pit composting alone. These findings confirm that method integration can improve compost quality without introducing additional process complexity.

Sustainability and Environmental Implications

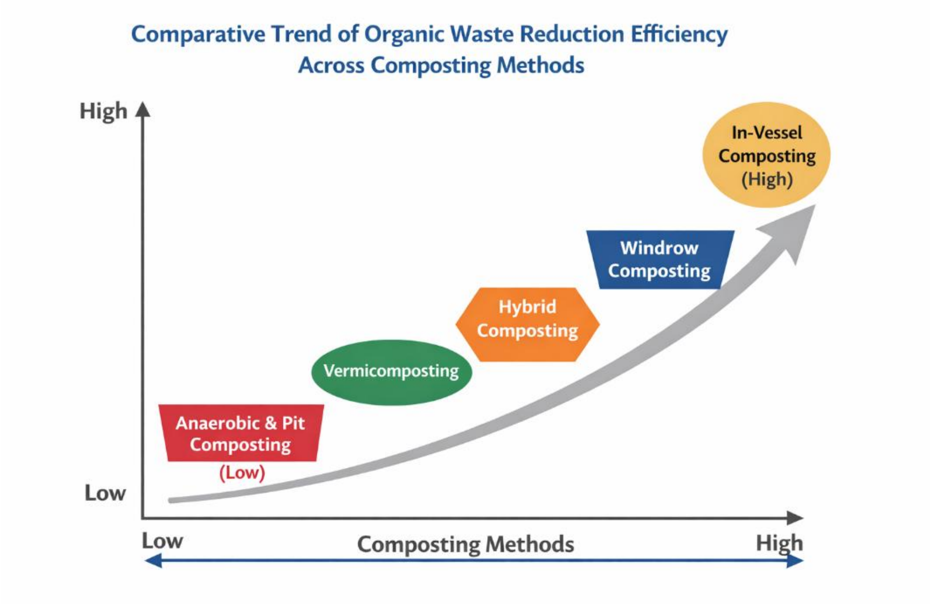
From a sustainability perspective, composting contributes significantly to landfill diversion, greenhouse gas mitigation, and soil health improvement. Multiple studies emphasize that effective composting reduces methane emissions associated with landfill disposal while producing nutrient-rich compost suitable for agricultural applications (Doughmi et al., 2024; Lhaj et al., 2024). Aerobic composting systems, in particular, demonstrate lower environmental risks compared to anaerobic systems when properly managed (Xavier de Melo & Duarte, 2018).

Community-based composting initiatives further strengthen sustainability outcomes by improving waste segregation and public participation. Ramadhani et al. (2025) reported high levels of community understanding and engagement following composter-based training programs, supporting long-term implementation of composting practices.

Integrated Interpretation and Practical Implications

The synthesis of empirical findings confirms that no single composting method is universally optimal, yet aerobic-based systems consistently provide superior organic waste reduction and process reliability. Windrow composting remains suitable for large-scale applications with adequate land availability, while in-vessel systems are more appropriate for urban or institutional contexts requiring tighter process control (Jalalipour et al., 2020; Jihad & Arif, 2024).

Figure 2 presents an empirical comparison of composting methods based on reduction efficiency and operational complexity.



This figure highlights that higher reduction efficiency is generally associated with greater operational control, reinforcing the need to balance technical performance with feasibility and resource availability.

CONCLUSION

This study provides a comprehensive evaluation of composting methods for organic waste reduction based on empirical evidence reported in the existing literature. The findings demonstrate that composting is an effective and sustainable strategy for managing organic waste, with aerobic-based systems consistently showing superior performance compared to anaerobic and pit-based approaches. Windrow composting and in-vessel composting achieve higher waste reduction efficiency and faster stabilization due to enhanced aeration and process control, while vermicomposting and hybrid systems contribute to improved compost maturity and pathogen reduction.

The results also indicate that operational factors, including aeration, moisture control, and temperature regulation, play a critical role in determining composting effectiveness. Methods that allow better control of these parameters tend to produce more stable compost within shorter processing periods. From a sustainability perspective, composting supports landfill diversion, greenhouse gas mitigation, and soil quality improvement, reinforcing its relevance within sustainable waste management and circular economy frameworks.

Although no single composting method is universally optimal, the comparative evidence highlights that method selection should be aligned with local conditions, waste characteristics, land availability, and institutional capacity. This study emphasizes the importance of evidence-based decision-making when implementing composting systems. Future research should focus on standardized reporting of waste reduction outcomes and comparative assessments across diverse contexts to strengthen the scalability and policy relevance of composting practices.

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