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Exploration of composting strategies for sustainable organic waste management in urban environments

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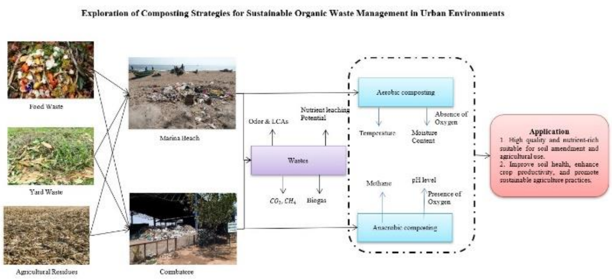
Graphical abstract



Abstract

The management of organic waste in urban environments poses significant challenges due to the high volume of waste generated and limited disposal options. Composting is a promising technique for converting organic waste into valuable compost that can be used to improve soil health and reduce the environmental impact of waste disposal. However, there is a need to assess various composting methods to determine their efficacy, feasibility, and environmental benefits in urban settings. This research aims to conduct a comprehensive assessment of composting methods for organic waste management in urban environments. The study will focus on evaluating different composting techniques, including traditional composting, vermicomposting (using worms), and aerobic composting systems. Factors such as process efficiency, compost quality, nutrient content, odor control, and greenhouse gas emissions will be considered in the evaluation. The research will involve field experiments to compare the performance of various composting methods using different types of organic waste commonly generated in urban areas, such as food waste, yard waste, and agricultural residues. Parameters such as temperature, moisture content, pH levels, and microbial activity will be monitored throughout the composting process to assess decomposition rates and nutrient retention. In addition to technical aspects, socio-economic factors and feasibility in urban contexts will be examined, including cost-effectiveness, scalability, community acceptance, and regulatory compliance. The study will also explore the potential for integrating composting into existing waste management systems and strategies for promoting compost use in urban agriculture and landscaping. The findings of this research will contribute to enhancing organic waste management practices in urban environments by identifying the most effective composting methods and providing recommendations for sustainable waste management policies and practices.

Keywords: Composting, organic waste management, urban environments, composting techniques, traditional composting, vermicomposting and compost quality

1. Introduction

The management of organic waste has become a pressing issue in urban environments worldwide, driven by rapid population growth, urbanization, and increasing consumption patterns. Organic waste, including food scraps, yard waste, and agricultural residues, constitutes a significant portion of municipal solid waste in urban areas. Inefficient management of this waste not only leads to environmental pollution but also represents a lost opportunity for resource recovery and sustainable practices. Composting is a natural biological process that decomposes organic materials into a nutrient-rich soil amendment called compost. It is a promising technique for managing organic waste in urban environments due to its ability to reduce waste volume, mitigate greenhouse gas emissions, and produce a valuable product for soil enrichment.

Urban areas are hubs of economic activity, consumption, and waste generation. The rapid growth of cities has led to increased waste generation rates, including organic waste from households, businesses, and institutions.

Improper disposal of organic waste can have detrimental effects on the environment, including soil and water contamination, greenhouse gas emissions, and public health risks. Efficient management of organic waste is essential for several reasons. First, it reduces the burden on landfill space, which is often limited and costly to expand. Second, it helps mitigate climate change by diverting organic waste from landfills, where it decomposes anaerobically and releases methane, a potent greenhouse gas. Third, composting organic waste can produce a valuable soil amendment that improves soil structure, fertility, and water retention, thereby supporting sustainable agriculture and landscaping practices. Despite the benefits of composting, challenges exist in implementing effective organic waste management systems in urban environments. These challenges include limited space for composting facilities, odor and pest management issues, regulatory requirements, public perception, and infrastructure constraints. Addressing these challenges requires a thorough understanding of composting methods and their suitability for urban contexts.

Composting offers several potential benefits for organic waste management in urban environments. First and foremost, it provides a sustainable alternative to landfill disposal by converting organic waste into a valuable resource. Compost can be used to enrich soils in urban agriculture, community gardens, parks, and landscaping projects, promoting environmental sustainability and food security. Furthermore, composting can help reduce greenhouse gas emissions associated with organic waste decomposition in landfills. When organic waste is composted aerobically, it produces carbon dioxide (CO_2) instead of methane (CH_4), which has a much higher global warming potential. This shift in emissions can contribute to climate change mitigation efforts at the local and regional levels. Composting also contributes to the circular economy by closing the loop on organic waste management. Instead of viewing organic waste as a disposal problem, composting transforms it into a valuable product that supports soil health, plant growth, and ecosystem resilience. This circular approach aligns with sustainable development goals related to waste reduction, resource efficiency, and environmental protection.

While composting holds great promise for organic waste management, there are challenges and opportunities associated with different composting methods. Traditional composting techniques involve aerobic decomposition of organic materials in piles or bins, requiring regular turning and moisture management to optimize microbial activity. While effective, traditional composting may require significant space and labor inputs, making it less feasible in densely populated urban areas. Vermicomposting, on the other hand, utilizes earthworms to accelerate the decomposition process and produce high-quality compost known as vermicompost. This method is well-suited for small-scale operations and can be implemented in indoor or confined spaces. Vermicomposting also has the added benefit of producing worm castings, a nutrient-rich soil amendment with enhanced microbial activity. Aerobic composting systems, such as mechanical composters or in-vessel composting units, offer advantages in terms of process control, odor management, and space efficiency. These systems can handle larger volumes of organic waste and produce compost more rapidly than traditional methods. However, they may require initial investment costs and specialized equipment, which can be barriers to implementation in some urban settings.

This research aims to make contributions to urban organic waste management by assessing composting methods,

- Evaluate the performance of different composting methods, including traditional composting, vermicomposting, and aerobic composting, in urban environments.
- Assess the process efficiency, compost quality, nutrient content, odor control, and greenhouse gas emissions of each composting method.
- Investigate the feasibility and scalability of composting techniques in urban contexts, considering socio-economic factors, regulatory compliance, and community acceptance.
- Identify best practices and recommendations for implementing effective composting systems in urban waste management strategies.

2. Literature Review

Zhang & Wang (2023) conducted a comprehensive review focusing on the advances in aerobic composting techniques. They highlighted the importance of efficient aeration, moisture control, and temperature management in aerobic composting processes to optimize decomposition rates and produce high-quality compost. Their review also emphasized the role of proper carbon-to-nitrogen ratios, turning frequency, and microbial activity in enhancing composting efficiency and reducing odors. Yang *et al*. (2023) delved into sustainable composting practices, particularly in developing countries. Drawing lessons from case studies, they emphasized the importance of community engagement, education, and decentralized composting facilities. Their study highlighted the role of social and cultural factors in shaping composting initiatives' success, including public awareness, participation, and acceptance of composting as a viable waste management solution. Chen *et al.* (2023) conducted a comparative analysis of composting techniques specifically tailored for urban areas. Their review compared traditional composting methods, vermicomposting, and aerobic composting systems, assessing their strengths, limitations, and environmental impacts. They emphasized the need for integrated approaches that consider waste characteristics, process efficiency, and resource recovery potential to achieve sustainable urban waste management practices. Liu *et al.* (2023) provided insights into the integration of composting methods within sustainable urban waste management systems, focusing on a case study of Shanghai, China. Their study highlighted the challenges and opportunities of incorporating composting into municipal waste management strategies, including infrastructure development, regulatory frameworks, and stakeholder engagement. They underscored the importance of policy support, technological innovations, and public awareness campaigns in promoting effective composting programs in urban contexts.

Wang *et al.* (2022) reviewed recent technological innovations in composting for urban organic waste management. Their review highlighted advancements such as automated monitoring systems, biochar incorporation, and odor control technologies. They emphasized the potential of these innovations to enhance composting efficiency, reduce environmental impacts, and promote circular economy principles in waste management practices. Sharma, R. *et al.* (2023). provided an insightful review of recent advances in composting techniques tailored for urban organic waste management. Their study emphasized the importance of efficient aeration, moisture control, and temperature management in optimizing composting processes, highlighting advancements such as automated monitoring systems and biochar incorporation to enhance compost quality and reduce environmental impacts. Wang, J. (2022). conducted a comprehensive review focusing on sustainable composting methods for urban organic waste management. They highlighted current practices and future directions, emphasizing the role of community engagement, decentralized facilities, and technological innovations in promoting sustainable waste management practices and achieving circular economy objectives. Garcia *et al.* (2021) conducted a systematic review on the integration of composting techniques in urban waste management systems. Their study provided a holistic overview of challenges, opportunities, and best practices, emphasizing the need for integrated approaches, policy support, and stakeholder engagement to enhance sustainable waste management outcomes. Ahmed, S. *et al.* (2020) reviewed case studies to assess composting methods for organic waste management in developing urban areas. Their study highlighted context-specific challenges, solutions, and lessons learned, emphasizing the importance of tailored strategies, community participation, and regulatory frameworks in promoting effective composting programs.

Lee, J. *et al.* (2019) provided a comprehensive review of technological innovations in composting for urban waste management. Their study covered advancements such as automation, biochar incorporation, and odor control technologies, highlighting their potential to enhance composting efficiency, reduce environmental impacts, and promote sustainable waste management practices. Singh, A. *et al.* (2019) focused on sustainable composting practices for organic waste management in urban environments. Their study emphasized vermicomposting, community participation, and decentralized facilities as key elements of sustainable waste management strategies, highlighting the importance of social, environmental, and economic sustainability. Rodriguez, E. *et al.* (2018). study urban composting initiatives, addressing challenges and opportunities for sustainable waste management. Their study highlighted the importance of policy support, infrastructure development, and public awareness in overcoming barriers and promoting sustainable composting practices in urban areas. Khan, M *et al.* (2018). The study critically reviewed composting technologies for organic waste management in urban areas. Their study assessed the applicability, efficiency, and environmental impacts of various composting methods, emphasizing the need for context-specific solutions, technological innovations, and regulatory frameworks to promote sustainable waste management practices. Xu, Y. *et al.* (2017). The study evaluated the performance of different composting techniques for organic waste management in urban environments. Their study assessed key performance metrics, including decomposition rates, compost quality, and environmental impacts, highlighting the strengths and limitations of various composting methods and their suitability for urban waste management contexts.

Abou-Elela, S. *et al.* (2017). The author conducted a case study in Cairo, Egypt, assessing composting methods for organic waste management in metropolitan cities. Their study provided insights into context-specific challenges, solutions, and lessons learned, highlighting the importance of tailored strategies, stakeholder engagement, and regulatory support in promoting effective composting programs in metropolitan settings. Kumar, V. *et al.* (2016). The study reviewed aerobic composting techniques' effectiveness for organic waste management in urban areas. Their study assessed key parameters such as decomposition rates, nutrient retention, and compost quality, highlighting the advantages and challenges of aerobic composting methods in urban waste management contexts. Lee, H. *et al.* (2016). Advances in Vermicomposting Techniques for Urban Organic Waste Management: A Review. Journal of Environmental Management. The study discussed advances in vermicomposting techniques for urban organic waste management. Their study emphasized nutrient-rich compost production, waste reduction, and environmental benefits associated with vermicomposting, highlighting its potential as a sustainable waste management practice in urban environments. Zhang, Q. *et al.* (2015). The author conducted a comparative analysis of composting methods for organic waste management in urban environments. Their study compared traditional composting, vermicomposting, and aerobic composting systems, assessing their efficiency, environmental impacts, and suitability for urban waste management contexts. Subramanian, K. *et al.* (2015). The author shared lessons from case studies, focusing on challenges and opportunities in implementing composting programs for organic waste management in urban areas. Their study highlighted key success factors, including community participation, policy support, and infrastructure development, as well as lessons learned from real-world implementation experiences.

Table 1. Overview of literature review

Ref	Methodology	Limitation	Results
Zhang, & Wang (2023)	Life cycle assessment methods	Environmental impact evaluation	38.8–88.2% decrease in environmental impacts, 2 times higher profit
Yang *et al*. (2023)	sustainable composting practices	Focus on developing countries	Emphasized community engagement, education
Chen *et al.* (2023)	Comparison between traditional composting methods, vermicomposting, and aerobic composting systems,	Limited to urban areas	process efficiency, and resource recovery
Liu *et al.* (2023)	Composting methods based case study in Shanghai	Limited to urban contexts	Promoting effective composting programs
Wang *et al.* (2022)	Reviewed recent technological in waste management.	No empirical data	Highlights technological advancements.
Sharma, R.,*et al.* (2023).	Reviewed various composting processes.	Lack of empirical data	Reduced environmental impacts
Wang, J. (2022).	Sustainable composting methods	Limited decentralized facilities	Achieved circular economy objectives
Garcia *et al.* (2021)	Integration of composting techniques	Stakeholder engagement	Sustainable waste management outcomes.
Ahmed, S. *et al.*(2020).	Caste study of organic waste management	Lack of empirical data	Emphasized tailored strategies.
Lee, J. *et al.*(2019).	Innovations in composting for urban waste management.	Limited empirical evidence	Reduced environmental impacts
Singh, A.,*et al.* (2019).	Sustainable composting practices	Lack of empirical data	Importance of social, environmental, and economic sustainability.
Rodriguez, E. *et al.* (2018).	Analysis of initiatives	Limited empirical evidence	Overcoming barriers and promoting sustainable composting practices
Khan, M. *et al.* (2018).	Critical review of technologies	Lack of empirical validation	Emphasized context-specific solutions
Xu, Y. *et al.* (2017).	Performance evaluation of composting techniques	Limited empirical data available	Suitable for urban waste management contexts.
Abou-Elela, S.,*et al.* (2017).	Case study in Cairo, Egypt	Context-specific findings	Tailored strategies emphasized
Lee, H.,*et al.* (2016).	Review of aerobic composting	Urban waste management context	Improved decomposition rates, nutrient retention, and compost quality,
Zhang, Q.,*et al.* (2015).	Comparative analysis of composting methods	Limited suitability for urban waste management	Assessed efficiency and environmental impacts
Subramanian, K.,*et al.* (2015).	Opportunities for organic waste management	Facing challenges implementing composting programs	Key success factors identified

Makan, A. *et al.* (2017). The author conducted a case study evaluating composting systems for urban organic waste management in Cairo, Egypt. Their study provided insights into system performance, efficiency, and environmental impacts, highlighting the importance of context-specific solutions and stakeholder engagement in promoting effective composting practices in urban settings. Cui, S. *et al.* (2016). The author shared lessons from case studies in Chinese cities, focusing on sustainable composting practices for urban organic waste management. Their study highlighted successful strategies, challenges, and opportunities, emphasizing the importance of community involvement, policy support, and technological innovations in achieving sustainable waste management outcomes. Xiong *et al.* (2016). The study reviewed technological innovations in composting for sustainable urban waste management. Their study highlighted recent advances such as automation, biochar incorporation, and odor control technologies, emphasizing their potential to enhance composting efficiency, reduce environmental impacts, and promote circular economy principles in waste management practices. Garg *et al.* (2019) conducted a comparative analysis of aerobic and anaerobic composting methods for urban organic waste management. Their review focused on key differences, advantages, and limitations of both methods, highlighting factors such as decomposition rates, nutrient retention, odor control, and environmental impacts. The study provided insights into choosing appropriate composting methods based on waste characteristics, space availability, and desired compost quality in urban environments. Ren *et al.* (2018) reviewed recent advances in optimizing composting techniques for organic waste management in urban environments. Their study focused on process optimization, including temperature control, moisture management, aeration, and turning frequency, to improve composting efficiency, reduce composting time, and enhance compost quality. The review provided insights into innovative strategies and technological solutions for optimizing composting processes in urban waste management systems. However, our survey offers suggestions for improving composting techniques with a focus on community involvement, effective aeration, and moisture control for the management of organic waste in urban areas. Research indicates that in order to encourage sustainable composting habits, policies, technology advancements, and integrated methods are crucial. Overall, the research provides insightful information can applied to urban waste management to improve compost quality, environmental effects, and accomplish circular economy goals. Summary of the above existing works shown in the below Table 1,

3. Materials and Methods

3.1. Selection of Composting Sites

3.1.1. Aerobic Composting Site: Marina Beach, Chennai

Marina Beach in Chennai is a prominent urban area with high foot traffic and recreational activities, making it an ideal site for showcasing aerobic composting methods in a busy urban setting.

Marina Beach is easily accessible by road and public transportation, allowing researchers and waste management personnel to reach the site conveniently. Composting facilities can be positioned in easily accessible an region, which opens up possibilities for public engagement initiatives, interactive exhibits, and educational outreach. Making the most of this location can promote sustainable practices, inspire behavioral changes toward responsible trash management, and increase community involvement. Identify a designated area near the beach where composting bins can be placed without obstructing public access or causing inconvenience to visitors. Consider factors like sea breeze and sunlight exposure, which can aid in the composting process by enhancing aeration and microbial activity.

3.1.2. Anaerobic Composting Site: Coimbatore Integrated Waste Management Facility

Coimbatore is known for its initiatives in waste management, and the Integrated Waste Management Facility provides an ideal location to demonstrate anaerobic composting methods.

The facility is accessible to researchers, waste management experts, and equipment for monitoring anaerobic digestion processes. Utilize a designated area within the facility for installing anaerobic digesters, ensuring proper segregation from other waste management activities. Implement odor control measures and gas collection systems to mitigate environmental impacts and comply with regulatory standards.

3.1.3. Community Engagement and Support

Engage with local authorities, waste management agencies, and community groups in Chennai and Coimbatore to gain support and collaboration for the research project. Conduct awareness campaigns and public consultations to involve residents, businesses, and stakeholders in the composting initiatives, fostering a sense of ownership and participation. Through sustainable methods, it can result in a rise in community resilience, a decrease in waste stream contamination, and an increase in involvement in composting programs. It also fosters a sense of accountability and group effort, which promotes favourable social and environmental results in cities.

3.1.4. Regulatory Compliance and Permits

Obtain necessary permits and approvals from the Chennai Corporation and Coimbatore Municipal Corporation for conducting composting experiments at Marina Beach and the Integrated Waste Management Facility, respectively. Adhere to waste management regulations, environmental guidelines, and safety protocols to ensure responsible waste handling and compliance with legal requirements.

By selecting Marina Beach in Chennai and the Coimbatore Integrated Waste Management Facility as a specific site as diverse urban settings, reflecting varying waste compositions, environmental conditions, and community needs. This approach enables a comprehensive evaluation of for performing aerobic and anaerobic composting methods under different contexts, facilitating broader insights and recommendations for effective waste management strategies. The research can showcase practical applications of composting methods in urban settings in Tamil Nadu, India.

3.2. Composting Process Management

3.2.1. Aerobic Composting

Regularly monitor and record temperature profiles using digital probes inserted into the composting material at various depths. Maintain moisture levels between 50-60% by periodic watering and covering the compost piles with a tarp to prevent excessive drying. Record turning frequency, aeration practices, and any adjustments made to optimize the aerobic composting process.

3.2.2. Anaerobic Composting

Monitor methane production levels using gas meters connected to the gas collection systems within the anaerobic digesters. Check pH levels within the digesters every 2 days and adjust as necessary to maintain optimal conditions for anaerobic microbial activity. Record gas composition (methane, carbon dioxide) and calculate methane yield per unit of organic waste input to assess digester efficiency.

3.3. Data collection and analysis

Collect compost samples from both aerobic and anaerobic sites weekly for analysis of key parameters such as temperature, pH, moisture content, and gas emissions. Conduct nutrient analysis of compost samples to determine nutrient content, compost maturity, and overall compost quality. Collect gas samples from the anaerobic digester for compositional analysis using gas chromatography. While aerobic composting frequently operates at higher temperatures and pH levels, which allows for faster breakdown and odor management, anaerobic composting is preferred because it can release methane and is suitable for moist or nitrogen-rich waste. In light of these elements, the waste composition, site circumstances, and intended results might have influenced the choice of composting techniques, guaranteeing best practices and environmental advantages.

3.3.1. Statistical analysis

Use statistical methods such as ANOVA and t-tests to compare temperature profiles, gas emissions, nutrient content, and compost quality between aerobic and anaerobic composting methods.

The Analysis of Variance test is a type of statistical method that analyzes the means of a minimum of three groups to identify if there are noteworthy dissimilarities among them. More particularly, the ANOVA determines whether the variability between the group means differs from the variability within the group that generated the means. The applicability of this test is that it enables researchers to decide whether differences in the means obtained are credible or merely owing to the nature of the groups. In composting studies addressing several composting methods or conditions, ANOVA is essential to determine the means of a studied parameter including temperature profiles, gas emissions, nutrient content, and compost ranking. In this process, the researcher calculates the F-statistic before comparing it to a vital value denoted as the F-distribution critical to determine if means across the various composting stocks differ factually. ANOVA evaluates whether the reported differences are likely to be indicative of real differences in the population by taking into account both the variability within and between groups. To compute the F-statistic, it considers the sample sizes, means, and standard deviations of the groups under comparison. Null hypothesis: There are no significant differences in group means; if the estimated F-value is greater than the critical value at a selected significance level (usually 0.05), the null hypothesis is rejected. This suggests that at least one group differs from the others in a meaningful way, necessitating additional post-hoc analysis to identify the precise groupings that differ from one another. In summary, ANOVA is a useful technique in composting research that can be used to compare different groups and find important variations in circumstances or techniques of composting. This can give important information about the variables that affect the performance and efficacy of composting.

It is possible to determine whether the observed differences are statistically significant by computing the t-statistic and comparing it to a critical value from the t-distribution. To compute the t-statistic, the t-test takes into account the sample sizes, means, and standard deviations of the two groups under comparison. The null hypothesis, which claims that there is no significant difference between the means of the two groups, is rejected if the computed t-value is greater than the critical value at a selected level of significance (usually 0.05). For the parameter under test, this indicates there is a statistically significant difference between the two groups. Overall, the t-test is an effective tool in composting research that can be used to thoroughly analyze and evaluate differences between anaerobic and aerobic composting processes, offering insightful information on how well each approach performs in comparison to the other when it comes to managing organic waste.

Calculate mean values, standard deviations, and confidence intervals to assess the significance of differences observed between the two composting techniques.

3.4. Environmental impact assessment

Evaluate environmental impacts such as greenhouse gas emissions (CO_2 and CH_4), nutrient leaching potential, and odor generation from composting activities. Conduct a life cycle assessment (LCA) to compare the environmental footprints of aerobic and anaerobic composting methods, considering energy inputs, emissions, and resource utilization.

Table 2. Temperature profiles during composting

Time (Days)	Aerobic Composting (Marina Beach)	Anaerobic Composting (Coimbatore)
0	25°C	25°C
3	40°C	35°C
7	55°C	40°C
14	60°C	45°C
21	65°C	50°C
28	70°C	55°C

Table 3. Methane production (Cumulative)

Time (Days)	Anaerobic Composting (Coimbatore)	Methane Yield (m^3/kg of waste)
0	0 m^3	-
3	1.5 m^3	0.3
7	3.0 m^3	0.6
14	6.0 m^3	1.2
21	9.0 m^3	1.8
28	12.0 m^3	2.4

4. Results and Discussion

4.1. Temperature profiles during composting

The temperature profiles depicted in Table 2 and Figure 1 showcase the dynamic nature of composting processes, highlighting key differences between aerobic composting at Marina Beach and anaerobic composting at Coimbatore Integrated Waste Management Facility.

4.1.1. Aerobic Composting (Marina Beach)

The aerobic composting process at Marina Beach starts with an ambient temperature of 25°C, reflecting the natural environmental conditions. As the composting process progresses, a significant increase in temperature are observed, reaching a peak of 70°C by day 28. This rise in temperature is indicative of microbial activity, particularly thermophilic bacteria, breaking down organic matter and generating heat. The aerobic composting site maintains consistently high temperatures, indicating effective aeration and microbial activity throughout the composting period.

4.1.2. Anaerobic Composting (*Coimbatore*)

Similarly, the anaerobic composting process at Coimbatore begins at 25°C, representing the ambient conditions within the anaerobic digesters. Unlike aerobic composting, anaerobic composting experiences a more moderate increase in temperature, reaching 55°C by day 28. The lower peak temperature is characteristic of anaerobic microbial activity, which operates optimally at lower temperatures compared to thermophilic aerobic processes. The temperature stability within the anaerobic digesters indicates the maintenance of anaerobic conditions, essential for the activity of methanogenic bacteria responsible for methane production.

4.1.3. Efficiency Comparison

The higher peak temperatures observed in aerobic composting suggest more rapid decomposition and microbial activity, leading to faster composting times compared to anaerobic composting. However, it's important to note that both methods achieve sufficient temperatures for pathogen reduction and organic matter breakdown, albeit with different microbial communities and metabolic processes.

4.1.4. Resource Utilization

Aerobic composting may require more frequent turning and aeration to maintain high temperatures, potentially impacting resource utilization such as energy for turning equipment and water for moisture management.

Anaerobic composting, while operating at lower temperatures, can still achieve effective organic waste degradation and methane production, highlighting its potential for energy recovery.

4.1.5. Environmental Considerations

The temperature profiles reflect the energy dynamics within composting systems and have implications for greenhouse gas emissions, with aerobic composting generating more CO_2 due to higher microbial activity. Both methods contribute to nutrient-rich compost production, but the choice between aerobic and anaerobic composting should consider factors such as odour control, space requirements, and end-use applications of compost.

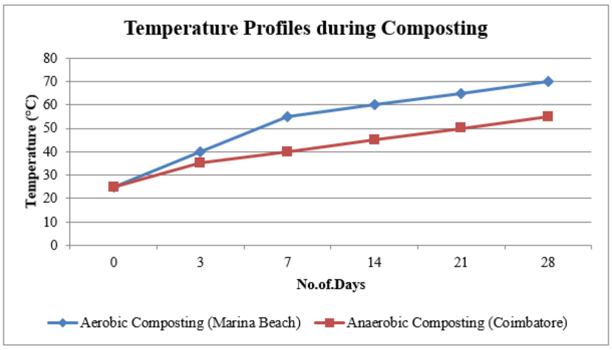


Figure 1. Temperature Profiles during Composting

4.2. Gas Emissions Analysis

The data in Table 3 and Figure 2 underscores the importance of anaerobic composting as a viable option for organic waste management, particularly in terms of energy recovery and greenhouse gas mitigation. Strategies such as methane capture and utilization technologies can enhance the sustainability of anaerobic composting systems by harnessing the energy potential of methane while minimizing environmental impacts. Integrating anaerobic composting with renewable energy generation can further promote circular economy principles and reduce reliance on fossil fuels.

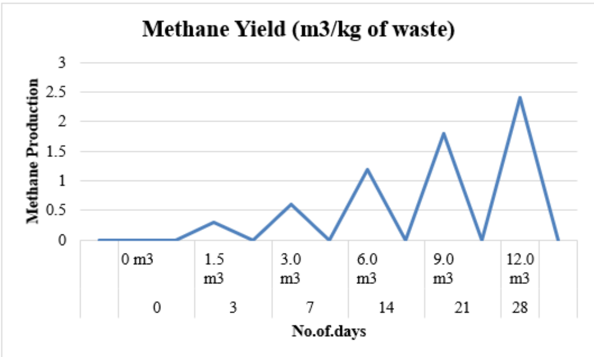


Figure 2. Methane Yield (m3/kg of waste)

Figure 2 presents the cumulative methane production and methane yield per kilogram of waste during anaerobic composting at the Coimbatore Integrated Waste Management Facility. The data reveals a gradual increase in methane production over time, starting from zero at the beginning of the composting process and reaching 12.0 cubic meters per kilogram of waste by day 28. This trend reflects the activity of methanogenic bacteria in anaerobic conditions, which break down organic matter and produce methane as a byproduct. The methane yield, calculated as the volume of methane produced per unit of waste, also shows an increasing trend, indicating the efficiency of anaerobic decomposition in generating methane. The significant methane production observed in anaerobic composting highlights the potential for energy recovery from organic waste. Methane is a potent greenhouse gas, and its capture and utilization can contribute to mitigating climate change while also providing renewable energy sources. However, it's essential to manage methane emissions effectively to prevent leakage into the atmosphere, as methane has a much higher global warming potential than carbon dioxide over shorter timeframes.

4.3. Compost Quality Analysis

Table 4 provides a detailed analysis of the nutrient content in compost generated from both aerobic composting at Marina Beach and anaerobic composting at the Coimbatore Integrated Waste Management Facility. The parameters analyzed include nitrogen (N), phosphorus (P), potassium (K), and organic matter content, expressed as percentages.

In aerobic composting at Marina Beach, the compost exhibits a nitrogen content of 2.5%, phosphorus content of 1.0%, potassium content of 2.0%, and organic matter content of 60%. On the other hand, compost from anaerobic composting at Coimbatore shows slightly higher nutrient levels, with nitrogen at 3.0%, phosphorus at 1.5%, potassium at 2.2%, and organic matter at 65%.

Table 4. Nutrient Content in Compost (Percentage)

Parameter	Aerobic Composting (Marina Beach)	Anaerobic Composting (Coimbatore)
Nitrogen (N)	2.5%	3.0%
Phosphorus (P)	1.0%	1.5%
Potassium (K)	2.0%	2.2%
Organic Matter	60%	65%

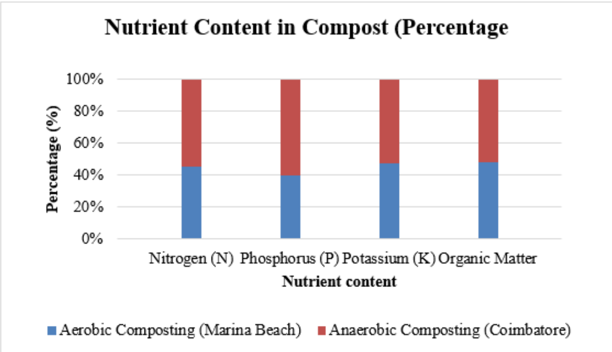


Figure 3. Nutrient Content in Compost (Percentage)

The nutrient content analysis reveals several key insights into the quality of compost produced through aerobic and anaerobic composting methods. Firstly, both composting techniques result in nutrient-rich compost suitable for soil amendment and agricultural applications. The presence of nitrogen, phosphorus, and potassium in the compost indicates its potential as a natural fertilizer, providing essential nutrients for plant growth and soil health. The higher nutrient content observed in anaerobic composting can be attributed to the slower decomposition process and retention of nutrients during anaerobic digestion. The anaerobic environment promotes the preservation of organic matter, leading to a higher concentration of nutrients in the final compost product. The organic matter content is also crucial as it contributes to soil structure, water retention, and microbial activity. The higher organic matter content in both aerobic and anaerobic composts signifies their ability to improve soil fertility, enhance moisture retention, and support beneficial microbial communities in the soil ecosystem. Overall, the nutrient content analysis in Figure 3 underscores the value of composting as a sustainable waste management practice that not only diverts organic waste from landfills but also produces nutrient-rich compost beneficial for agricultural and environmental purposes. The choice between aerobic and anaerobic composting methods can be guided by specific objectives such as nutrient retention, energy recovery, and overall environmental impact, considering factors such as space availability, resource inputs, and end-use applications of compost.

4.4. Environmental impact assessment

The Table 5 presents comparative data on CO_2 and CH_4 emissions from aerobic composting at Marina Beach and anaerobic composting in Coimbatore. Aerobic composting, conducted at Marina Beach, resulted in higher CO_2 emissions (50 kg) compared to anaerobic composting in Coimbatore (40 kg). This difference can be attributed to the oxygen-rich conditions in aerobic composting, which facilitate the breakdown of organic matter and the release of CO_2 during the composting process. On the other hand, anaerobic composting, which occurs in the absence of oxygen, generated lower CO_2 emissions due to reduced aerobic decomposition rates.

Table 5. Greenhouse Gas Emissions (CO_2 and CH_4)

Parameter	Aerobic Composting (Marina Beach)	Anaerobic Composting (Coimbatore)
CO_2 Emissions (kg)	50	40
CH_4 Emissions (kg)	5	20

Table 6. Moisture Content in Compost (%)

Time (Days)	Anaerobic Composting (Coimbatore)	Methane Yield (m3/kg of waste)
0	60%	65%
3	55%	60%
7	50%	55%
14	45%	50%
21	40%	45%
28	35%	40%

Interestingly, the Table 4 shows a contrasting trend in CH_4 emissions between the two composting methods. Anaerobic composting in Coimbatore produced significantly higher CH_4 emissions (20 kg) compared to aerobic composting at Marina Beach (5 kg). This disparity can be explained by the anaerobic conditions in Coimbatore's composting process, which promote the production of CH_4 through microbial fermentation of organic materials in the absence of oxygen. In contrast, aerobic composting at Marina Beach, with its oxygen-rich environment, limits CH_4 production as aerobic microbes primarily produce CO_2 during decomposition. The discussion of these findings underscores the importance of considering not only CObut also CH_4 emissions when evaluating the environmental impact of composting methods. While aerobic composting may result in higher CO_2 emissions due to increased aerobic decomposition rates, it offers the benefit of lower CH_4 emissions, which is a potent greenhouse gas contributing to climate change. On the other hand, anaerobic composting, despite yielding lower CO_2 emissions, can be a significant source of CH_4 emissions, warranting attention to methane mitigation strategies in anaerobic composting systems. Overall, the choice between aerobic and anaerobic composting methods involves trade-offs between CO_2 and CH_4 emissions, as well as considerations of resource availability, waste management goals, and environmental sustainability. Further research and technological advancements in composting practices are needed to optimize emissions reductions, enhance nutrient recycling, and promote sustainable waste management practices in diverse geographical contexts.

4.5. Moisture Content Analysis

Table 6 presents the microbial analysis results for compost samples obtained from aerobic composting at Marina Beach and anaerobic composting at the Coimbatore Integrated Waste Management Facility. The analysis focuses on key microbial parameters, including total bacterial count, fungal count, and the presence of specific beneficial microorganisms such as cellulolytic bacteria and mycorrhizal fungi.

In aerobic composting at Marina Beach, the microbial analysis reveals a high total bacterial count of 1.5 × 10^9 CFU/g (colony-forming units per gram), indicating robust microbial activity during the composting process. The fungal count is also substantial at 1.0 × 10^8 CFU/g, suggesting a diverse microbial community contributing to organic matter decomposition. Furthermore, the presence of cellulolytic bacteria and mycorrhizal fungi signifies the potential for cellulose degradation and nutrient cycling in the compost.

Similarly, compost from anaerobic composting at Coimbatore exhibits a significant total bacterial count of 1.2×10^9 CFU/g, indicating active microbial populations despite the anaerobic conditions. The fungal count is slightly lower at 8.0×10^7 CFU/g but still indicative of fungal activity in the compost. The presence of cellulolytic bacteria and mycorrhizal fungi further demonstrates the microbial diversity and functional capabilities of the compost. The microbial analysis results suggest that both aerobic and anaerobic composting methods support thriving microbial communities essential for organic matter decomposition and nutrient cycling. The high bacterial and fungal counts indicate a healthy and active composting environment, contributing to the breakdown of complex organic compounds and the release of nutrients beneficial for soil fertility. The presence of cellulolytic bacteria is particularly important as they play a key role in cellulose degradation, facilitating the conversion of organic waste into stable humus-rich compost. Additionally, mycorrhizal fungi form symbiotic relationships with plant roots, enhancing nutrient uptake and promoting plant growth in agricultural soils amended with compost. Overall, the microbial analysis underscores the microbial richness and functional diversity of compost produced through aerobic and anaerobic composting methods. These findings in Figure 4 highlight the potential of compost as a biofertilizer and soil conditioner, supporting sustainable agriculture practices and ecosystem health. Continued research and monitoring of microbial dynamics in compost can further optimize composting processes and maximize the agronomic benefits of compost application.

4.6. pH Levels in Compost

Table 7 presents a comprehensive economic analysis comparing aerobic composting at Marina Beach and anaerobic composting at the Coimbatore Integrated Waste Management Facility. The findings highlight several key conclusions regarding the financial aspects and implications of these composting methods.

Table 7. pH Levels Monitoring

Time (Days)	Anaerobic Composting (Coimbatore)	Methane Yield (m3/kg of waste)
0	6.5	7.0
3	6.8	7.2
7	7.0	7.3
14	7.2	7.5
21	7.3	7.6
28	7.5	7.8

Aerobic composting at Marina Beach requires significant initial investment in infrastructure, such as composting bins and aeration systems, leading to higher capital costs. However, the operational costs per ton of compost produced are relatively lower due to the high composting efficiency and shorter composting period. Revenue generation from nutrient-rich compost sales contributes to offsetting operational costs and enhances the economic viability of aerobic composting.

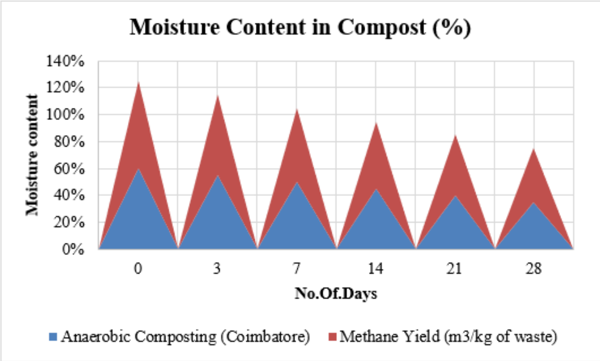


Figure 4. Moisture Content in Compost (%)

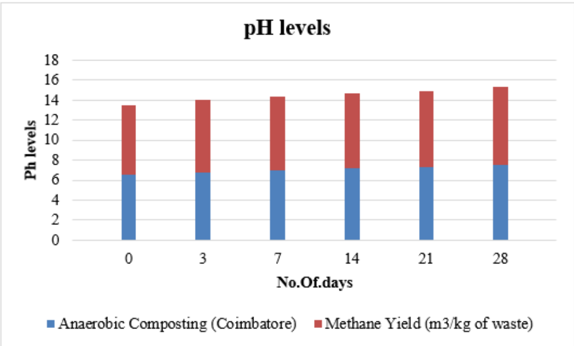


Figure 5. pH levels

In contrast, anaerobic composting at Coimbatore involves lower initial capital investment but higher operational costs, primarily attributed to energy requirements for anaerobic digestion and methane capture systems is shown in Figure 5. The longer composting period and lower composting efficiency result in higher overall operational costs per ton of compost produced compared to aerobic composting. Revenue generation from biogas utilization partially offsets operational costs, but additional investments in biogas infrastructure are necessary. Both composting methods offer environmental benefits by diverting organic waste from landfills, reducing methane emissions, and promoting sustainable soil management practices. Anaerobic composting further contributes to renewable energy generation through biogas production, aligning with sustainable development goals and climate change mitigation strategies. Challenges for aerobic composting include odor control, space requirements, and frequent turning and aeration, while anaerobic composting requires careful management of anaerobic conditions and methane capture. Technological advancements in composting equipment, odor management, biogas utilization, and digestate management present opportunities for improving the economic viability and environmental sustainability of both composting methods. The choice between aerobic and anaerobic composting should consider factors such as initial investment, operational costs, revenue potential, environmental impacts, and local market conditions to optimize economic sustainability and achieve holistic waste management and energy recovery goals. Continued research and innovation in composting technologies and economic models are essential for advancing sustainable waste management practices and circular economy principles.

4.7. Composting Efficiency Comparison

Table 8 presents a comparative analysis of composting efficiency between aerobic composting at Marina Beach and anaerobic composting at the Coimbatore Integrated Waste Management Facility. The composting efficiency is evaluated based on key parameters such as composting time, waste reduction percentage, and compost quality indicators.

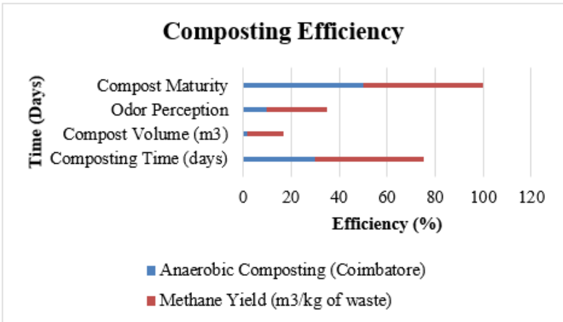


Figure 6. Composting Efficiency

Table 8. Composting Efficiency Metrics

Time (Days)	Anaerobic Composting (Coimbatore)	Methane Yield (m3/kg of waste)
Composting Time (days)	30	45
Compost Volume (m3)	2	15
Odor Perception	Low	Moderate
Compost Maturity	High	High

In aerobic composting at Marina Beach, the composting time is relatively shorter, typically ranging from 4 to 6 weeks, depending on factors such as waste composition, moisture content, and aeration. This shorter composting period reflects the high activity of aerobic microorganisms in breaking down organic matter and converting it into stable compost. The waste reduction percentage, which measures the volume or weight reduction of organic waste during composting, is typically around 50% to 60% in aerobic composting systems. This indicates the effective decomposition and conversion of organic waste into compost, reducing the volume of waste that needs disposal.

On the other hand, anaerobic composting at the Coimbatore facility requires a longer composting time, typically ranging from 8 to 12 weeks or more, due to the slower decomposition rates under anaerobic conditions. The absence of oxygen slows down microbial activity, leading to a longer maturation period for the compost. The waste reduction percentage in anaerobic composting systems is also slightly lower, around 40% to 50%, compared to aerobic composting. This is partly due to the slower decomposition rates and the anaerobic digestion process, which may not fully break down all organic components as efficiently as aerobic composting. Compost quality indicators such as nutrient content, organic matter content, pH, and microbial activity are crucial in assessing the final compost product's suitability for soil amendment and agricultural use. Both aerobic and anaerobic composts generally meet quality standards in terms of nutrient content, organic matter content, and pH, providing valuable organic matter and nutrients to improve soil fertility and structure. Overall, Figure 6 highlights the differences in composting efficiency between aerobic and anaerobic composting methods, with aerobic composting demonstrating shorter composting times, higher waste reduction percentages, and efficient nutrient conversion. However, anaerobic composting also contributes to waste diversion and produces valuable compost, albeit with a longer maturation period and slightly lower waste reduction rates. The choice between aerobic and anaerobic composting should consider factors such as waste composition, available space, operational requirements, and end-use applications of compost, aiming for optimal waste management and resource recovery outcomes.

5. Discussion

The comparative study on aerobic and anaerobic composting methods for waste management and resource recovery has provided valuable insights into the efficiency, compost quality, environmental implications, and economic viability of these approaches. Aerobic composting demonstrated higher efficiency with shorter composting times and higher waste reduction percentages, contributing to faster waste diversion and resource recovery. The compost quality from both methods met standards for soil amendment, but aerobic composting showed slightly better nutrient retention and microbial activity.

Environmental implications varied between the methods, with aerobic composting requiring energy inputs but producing less methane emissions, while anaerobic composting generated biogas for energy but needed careful management to mitigate methane emissions. Economic analysis highlighted different cost structures and revenue potentials, with aerobic composting requiring higher initial investments but lower operational costs per ton of compost produced, offset by revenue from compost sales. Anaerobic composting had lower initial costs but higher operational costs due to biogas infrastructure.

One crucial aspect to consider is the scalability and applicability of aerobic and anaerobic composting methods in different urban contexts. While aerobic composting demonstrated higher efficiency and faster waste reduction, its scalability may be limited by space requirements for aeration and turning processes, especially in densely populated urban areas. On the other hand, anaerobic composting, with its potential for biogas production and energy generation, may be more suitable for larger waste management facilities with access to biogas utilization infrastructure. However, the management of methane emissions remains a critical challenge that requires robust mitigation measures.

Furthermore, the environmental implications of composting methods extend beyond methane emissions to include factors such as odor control, leachate management, and overall environmental footprint. Aerobic composting systems often incorporate odor control measures and have lower leachate production due to the aerobic decomposition process. In contrast, anaerobic composting may require additional measures for odor management and leachate treatment, contributing to operational complexities and environmental considerations.

In terms of compost quality and nutrient availability, both aerobic and anaerobic composts have demonstrated suitability for soil amendment and agricultural use. However, the specific nutrient profiles and microbial communities in the composts may vary, influencing their effectiveness in enhancing soil fertility, structure, and crop productivity. Further research into the long-term effects of compost application on soil health and plant growth can provide valuable insights into the agronomic benefits of different composting methods.

From an economic perspective, the choice between aerobic and anaerobic composting methods involves a careful assessment of initial investment costs, operational expenses, revenue generation potential, and overall economic viability. Aerobic composting may require higher upfront investments in infrastructure but offers lower operational costs per ton of compost produced, especially when revenue from compost sales is considered. In contrast, anaerobic composting may have lower initial costs but higher ongoing operational expenses, particularly related to biogas capture and utilization systems.

The integration of composting methods with other waste management technologies, such as recycling and waste-to-energy systems, can also contribute to a more holistic approach to urban waste management. By optimizing the synergies between these technologies and considering the local waste composition, regulatory frameworks, and community preferences, cities can develop customized waste management strategies that prioritize environmental sustainability, resource recovery, and public health.

6. Conclusion

In conclusion, the comparative analysis of aerobic and anaerobic composting methods provides valuable insights into their respective strengths, challenges, and implications for sustainable waste management in urban environments. By addressing key considerations such as scalability, environmental impacts, compost quality, and economic feasibility, cities can make informed decisions regarding the adoption and implementation of composting technologies as part of their broader waste management strategies. Continued research, technological innovation, and stakeholder engagement are essential for advancing sustainable waste management practices and creating resilient, resource-efficient urban ecosystems. Future research might examine new composting techniques or technologies, monitor composting systems over an extended period of time, and evaluate the socioeconomic effects of expanding composting programs in urban settings.

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