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Review Article

Composting of Municipal Solid Waste (MSW) — A State-of-the-Art Review

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Abstract

The rapid pace of urbanization and increase in population have resulted in an unprecedented increase in the generation of municipal solid waste (MSW), highlighting the urgent need for sustainable and effective waste management approaches. Composting stands out as an environmentally friendly approach for the valorization of organic waste among the diverse techniques available. This paper provides a critical analysis of the essential phases involved in MSW composting, starting with preprocessing methods and highlighting the significance of source separation in improving the quality of compost. This paper presents a comparative analysis of major composting methods, specifically windrow, aerated static pile, and in-vessel systems, focusing on their efficiency and operational control. Furthermore, the significant process variables, including temperature, pH, C/N ratio, particle size, moisture content, aeration rate, and the shape of windrows, were discussed. This review encompasses a range of maturity and stability indices utilized to determine compost quality and its readiness for its application. The integration of process control is highlighted as a crucial factor for optimizing composting outcomes. This paper also synthesizes recent advances and challenges in MSW composting, providing a thorough understanding that offers insights for enhancing current practices and directing future research efforts. Important results from research on various kinds of composting processes, particularly aerobic composting, since it is a feasible technique for the composting of MSW; monitoring parameters; the Indian context; and compost utilization are described in this paper.

Keywords

Municipal Solid Waste, Composting, Waste Management, Process Variables, Utilization

1. Introduction

The management of municipal solid waste (MSW) plays a vital role in promoting sustainable development. In developing nations, a considerable fraction of municipal solid waste, frequently surpassing 50% by weight, consists of biodegradable substances, especially food waste [1]. The increasing growth of populations has resulted in increased MSW production, which has caused socioeconomic, ecological, and environmental issues [2]. Aerobic composting is one of the finest technologies for an integrated waste management system since it has the least anthropogenic effect on the environment,

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is economical and practicable, and is in line with the most recent national and international advances [3].

Based on the composition and characterization of MSW, the organic content has a C/N ratio in the range of 20 to 30, making it suitable for composting. Thermal processing and bioprocessing are the two most common methods for treating MSW. Due to its low calorific value (800–1000 kcal kg^{-1}) and environmental consequences, thermal processing is not feasible. The production of a valuable end-product makes bioprocessing, which includes composting, bio methanation, and vermicomposting, a technically and commercially viable alternative for treating MSW [4]. Because of its high biodegradable content, landfilling waste mainly causes methane emissions as well as probably leachate percolation into groundwater, land occupancy, and foul smells. However, incineration of waste may lead to the release of greenhouse gases (CO_2 and NO_2), air pollution (NO_x, SO_2, HCl, particulates, and dioxins), and hazardous wastes (ashes) that must be handled properly [5]. Benefit-cost assessment of composting shows that composting is an appealing and feasible solution to the municipal waste management challenge [6]. Comparing the findings to other existing management approaches, it was found that an estimated 13.62 Gg CO_2 equivalent of GHG emissions were prevented annually by composting MSW [7]. Reportedly, a municipal solid waste landfill with a composting facility saved 136.99 m^3 day^{-1} of capacity and had a 712-day longer service life than a municipal solid waste landfill without a composting facility [8]. Reportedly, microbial inoculation has been proven to improve and optimize the populations of microorganisms deemed essential for the production of enzymes necessary for the degradation of organic matter (OM) [9].

MSW composting is widely practiced across the world as an effective strategy for sustainable waste management and soil enrichment. Therefore, the key objectives of this review paper are as follows: (1) to review existing literature concerning the composting of municipal solid waste, (2) to narrow down essential parameters influencing the composting process of municipal solid waste, and (3) to examine the impacts, utilization, and societal acceptance of compost derived from municipal solid waste.

2. Pre-processing of MSW and Source Separation of Materials

Various kinds of pollutants, including plastic, metal, rubber, and stones, were found to be greatly decreased by source separation of wastes in municipal solid waste (MSW). Even if organic wastes were source separated, it was challenging to remove some pollutants from the waste stream. Before shredding MSW, Brown et al. [10] manually sorted metal, glass, plastic, large paper, and cardboard. Avnimelech et al. [11] separated small organic material for windrow composting using an 8-cm vibrating sieve. Researchers noticed that waste separation at the source will aid in enhancing its quality and fertilizing potential, as well as ensuring that the MSW compost is uniform and marketable [12]. Singhal et al. [13] observed that unsorted MSW cannot be composted owing to its low C/N ratio (5.52 to 24.13) and carbon content (5.3% to 50%). Source separation may enhance both values to the optimal 25:1 to 30:1 C/N ratio and > 50–60% carbon content. Source separation of biodegradable solid waste from metals, glass, and electronic waste components minimizes the degree of heavy metal contamination in compost [14]. Before beginning composting, waste must usually go through various preprocessing phases. The first step is sorting, which involves eliminating unnecessary elements from waste that cannot be composted. The second step is size reduction, which involves lowering the particle size. The third step entails the processing of the feedstock [15]. The composting operation that received source-separated organic waste also carried out manual sorting to remove inorganic materials before piling [16].

3. Composting Process

Composting can be carried out in two ways, i.e., aerobically and anaerobically. The anaerobic method of composting municipal solid waste (MSW) requires depositing the waste in excavated pits, where decomposition occurs anaerobically. It takes around a 4–6 months period for transformation into compost [17]. As land is scarce in urban areas, such practice is not adopted, and the aerobic method of composting is practiced in the majority of urban centers. Shah et al. [18] used heavy metal concentration, daily intake of metals (DIM), health risk index (HRI), hazard index (HI), and total hazard quotient (THQ) to assess the health risks of MSW composting in loamy soil with spinach and carrots. The lowest health risk index and goal hazard quotient were found in anaerobically composted material, showing that consuming these vegetables has no noncarcinogenic health concerns. The major products of aerobic decomposition are carbon dioxide, water, and heat, while the main products of anaerobic decomposition are methane, carbon dioxide, and various intermediates such as low-molecular-weight organic acids. Almost all designed compost systems are aerobic due to the low energy per unit weight of organics digested and the increased odor potential of anaerobic composting. Enzymes that play a role in composting include dehydrogenase, which is a reflection of microbial activity; B-glucosidases, which hydrolyze glucosides; urease, which is involved in N-mineralization; and phosphatases, which remove phosphate and sulfate groups from organic waste [19]. Li et al. [20] found that *Bacillus* was the most common species, and it was more common in the composts where there was a lot of decomposition of organic matter (OM). When carbon is oxidized to carbon dioxide, exothermic energy is released. Under sufficient insulation, organic materials in compost heaps or piles create a large quantity of heat, which raises the temperature to 65–70°C. Nevertheless, if the temperature surpasses 65–70°C, the thermal death of microbes reduces microbial activity and slows the stabilization of organic components. Microorganisms are responsible for the degradation of organic pollutants during composting of mechanically separated OFMSW [21]. During the composting process, bulking agents may provide adequate airflow to enhance the structural and functional qualities. The biodegradation kinetics and overall composting performance are influenced by bulking agents [22]. Figure 1 shows the flow diagram of the composting process in the landfill of Kaduwela, Sri Lanka. As illustrated in the Figure 1, after the waste has been transported to the composting site, windrows are constructed, mixing equipment is used to turn the large-sized windrow, and huller machines are used to screen compost once it has decomposed.

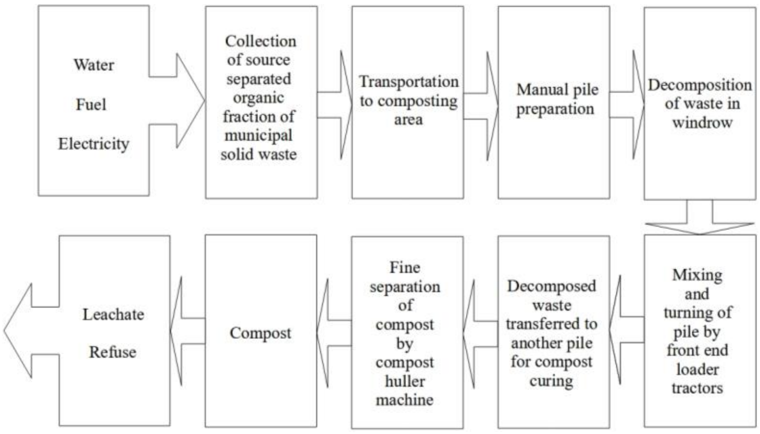

Figure 1. *Flow diagram of the composting process in Kaduwela, Sri Lanka [23].*

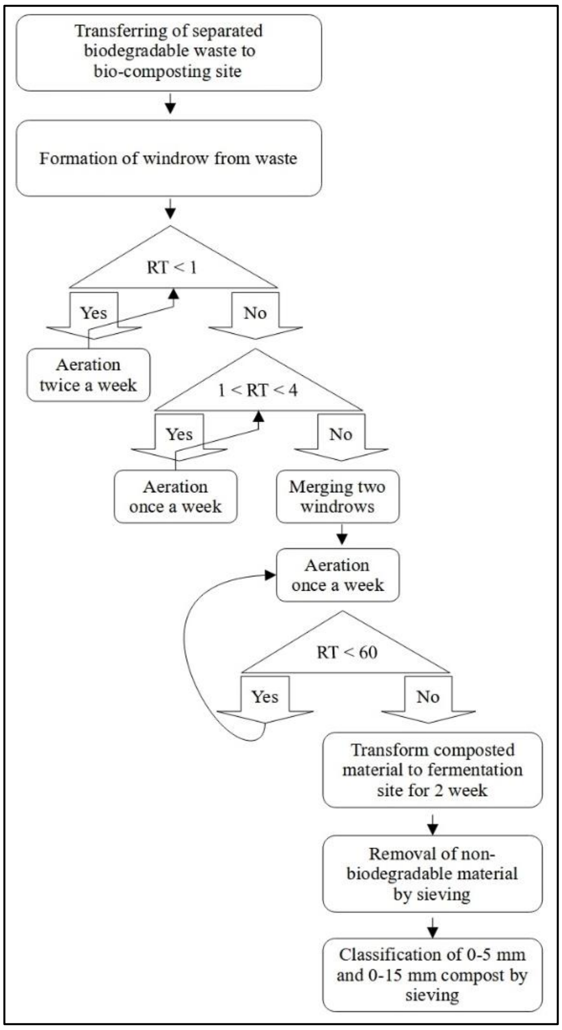

Figure 2. *Industrial composting of commingled MSW in Shiraz City, Iran [24].*

Figure 2 depicts the industrial composting of MSW in Shiraz City, Iran. Every day, the composting facility receives between 220 and 300 tonnes of segregated putrescible waste. A 200 m long, 4.5 m wide, 1.3 m high windrow accumulates this waste daily. After aeration, the temperature and humidity of the windrow were also tested. Aeration depends on the moisture and temperature of the windrow. Aeration is done twice the first week, then weekly. Due to the arid climate of Shiraz City, moisture restricts windrow aeration. After four weeks, windrows are combined to preserve moisture and complete the thermophilic stage. After 60 days of retention time (RT), transformed wastes are sent to a secondary fermentation site for two weeks. Sieving removes non-putrescible items, including glass, metals, sand, stone, and fabrics, after fermentation. Lastly, compost is screened into two sizes: 0–5 mm and 0–15 mm.

3.1. Composting Methods

There are three main centralized composting methods, namely aerated static pile composting, in-vessel composting, and windrow composting. The typical composting systems are shown in Figure 3.

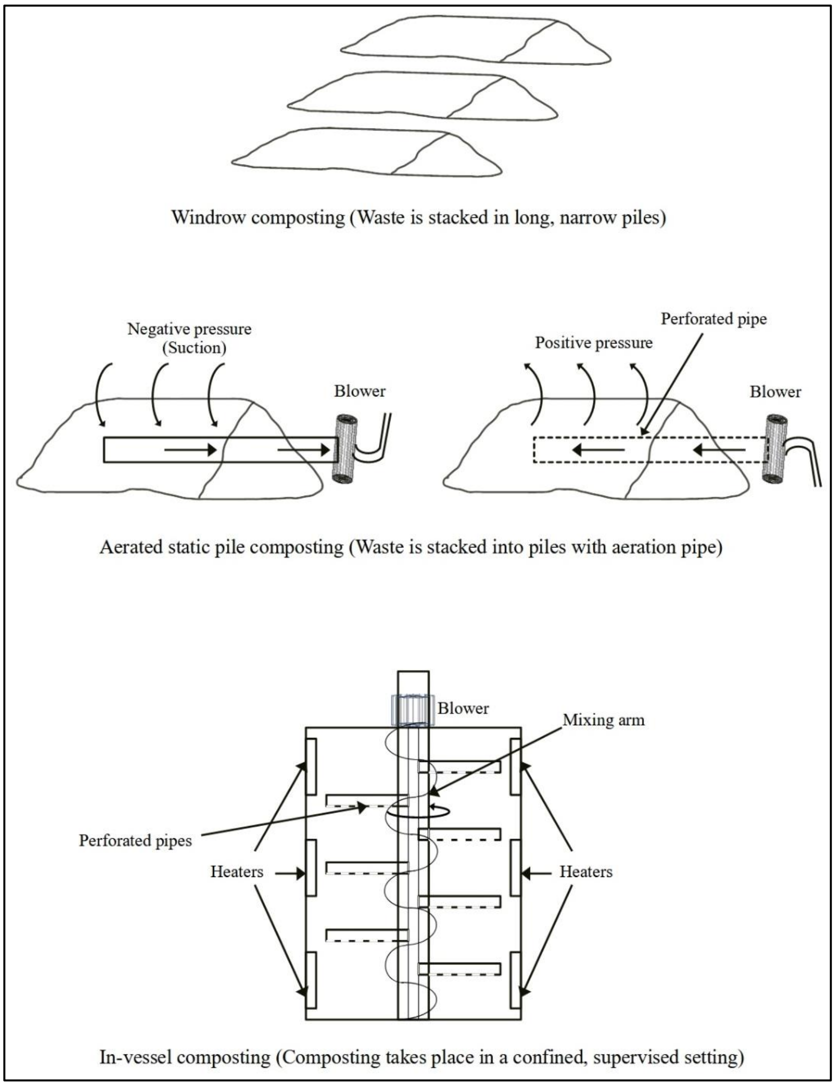

Figure 3. *Typical composting systems.*

3.2. Windrow Composting

Windrow composting is the most common type of composting in India. Aerobic breakdown stabilizes organic waste. Windrow composting can manage more garbage than vermicomposting. Fast composting may shorten processing time from 4–8 months to 3 weeks [17]. A windrow is just a heap of waste that has undergone the decomposition process. Depending on the composting material and turning machinery used, the windrow's cross-section may range from rectangular to trapezoidal to triangular. The composting material is aerated by frequent turning. Large systems use machinery for rotating and aerating the windrows at regular intervals. When a certain temperature (usually 55°C–60°C) is reached, the temperature of the composting mass is used as a turning indicator, and the windrows are turned. The nature of the feed material and the kind of turning machinery used define the height, width, and length of windrows. In windrow systems, an extreme temperature gradient from the outside to the inside, known as the "wall effect," prevents the uniform deterioration of the material. Thus, the material must be turned frequently to bring the outermost material to the center of the pile [25]. The windrow composting of MSW can be effectively enhanced by biochar inoculated with bacteria and bacterial/fungal consortia [1]. Gautam et al. [26] found that source separated organic waste of MSW can be composted by windrow composting with manual turning. Aerobic windrow composting, in which source-segregated MSW and coffee husks are decomposed, yields mature compost in 3 months. To reduce heat loss and drying, perforated HDPE sheeting was used to protect the compost piles [27]. Compared to composting in static piles, windrows may hold more moisture [28]. De Silva & Yatawara [29] discovered that the horizontal arrangement of PVC pipes worked better in the windrow composting process than its vertical arrangement and configuration without pipes. The horizontal pipe arrangement of windrows works best and takes the least time, with lesser heat loss, and labor costs might be reduced by one-third. Figure 4 depicts a schematic illustration of windrow composting in Chandigarh, India.

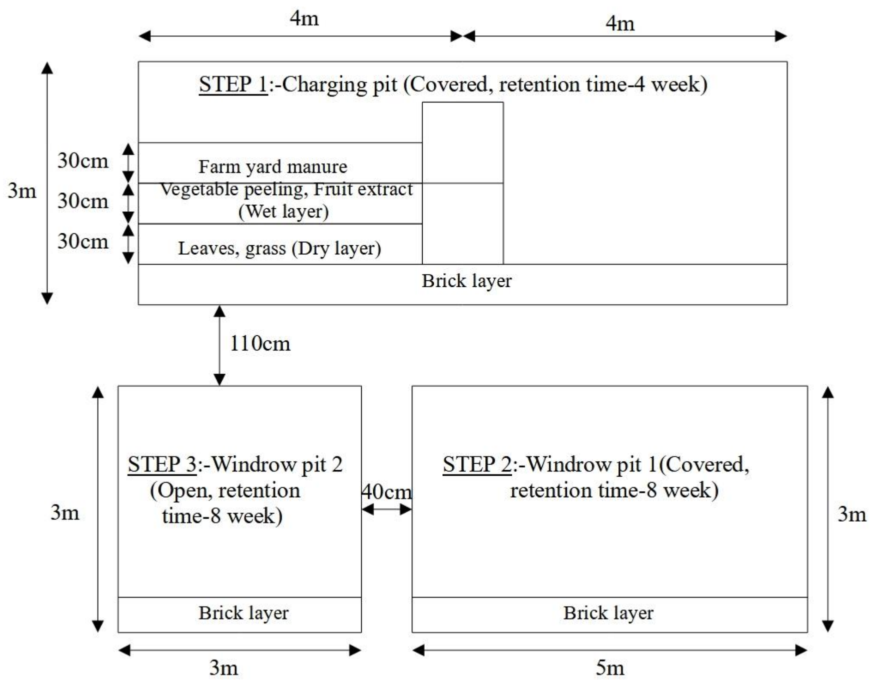

Figure 4. *Schematic representation of windrow composting, Chandigarh, India [30].*

3.3. Aerated Static Pile Composting

The aerated static pile approach aerates composting materials by adding a blower to the piped aeration system. The blower provides direct process control and enables the construction of larger piles. There is no further mixing or turning of the elements once the pile has been formed. The active composting period should last 3–5 weeks if the pile is well formed and the air supply and distribution are stable [17]. In this method, the pile is occasionally covered with screened compost to minimize unpleasant odors and keep the pile warm. The use of blowers and air diffusers ensures adequate ventilation. This sort of pile is often used for homogenous materials like sludge and is not suitable for heterogeneous materials like MSW. In a pilot-scale experience, two 4–6 m^3 aerated static heaps were used to decompose MSW. The piles were supplied with air via three floor-mounted pipes and water through a drip system until the relative humidity reached 40%. To assist in preserving humidity, covers were put over the heaps. Findings indicate that the finished compost is safe for agricultural use [31]. According to research, aeration by the pile-turning method can be replaced by a combination of pile-turning and natural ventilation to reduce nitrogen losses and agricultural energy consumption per unit area [32]. Waste does not need to be mixed in this method, so this is less expensive. But it takes a year and requires more space. In the absence of physical turning, pile surface and core temperatures must be monitored frequently.

3.4. In-vessel Composting

The enclosed system is a silo or agitated-bed-type enclosed vessel. The enclosed space allows for the regulation of environmental factors like temperature, oxygen content, and odor. The container might be a silo or a concrete-lined trench. Silo systems use gravity to transport compost through the vessel, while other systems (such as agitated beds) combine the best features of windrows and aerated static piles. It is a group of methods that keep the materials being composted inside a container or a vessel. To speed up the process, in-vessel methods use different types of forced aeration and mechanical turning [17]. Petric et al. [33] found that poultry manure can be added to composting feedstocks to increase the C/N ratio, and sawdust can be added to promote aeration and mixing during in-vessel composting of MSW. Composts derived from trials using 0.4 and 0.8 bar initial pressure during in-vessel composting were shown to have good maturity levels and may also be utilized for agricultural purposes [34]. According to Makan & Mountadar [35], an in-vessel composting system offers several benefits over the windrow method, including a smaller area, increased process efficiency, and better control. They found that a C/N ratio of 32.2 with 0.6×10^5 Pa initial air pressure showed good levels of maturity and could also be used in agriculture. Boonyaroj et al. [36] reported that a bioreactor with a 10 L working volume, run with different combinations of pressed air and municipal organic waste components, could produce compost in only 20 days. Rich & Bharti [37] reported that the static mechanically air-blown reactor (ABR) outperformed the rotating drum reactor (RDR) by maintaining 45% moisture content, ensuring better temperature control, and achieving compost maturity in 20 days. Though it requires a higher initial investment, its lower operational cost and high efficiency make it suitable for large-scale composting.

4. Process Control Variables

4.1. Temperature

Temperature is an important indicator of microbial activity throughout the composting process. It influences the rate of reaction and aids in the elimination of harmful pathogens throughout the composting process, hence maintaining the process's sanitation capability [22]. The temperature is one of the crucial aspects since the majority of microorganisms are killed when the temperature is higher than 55°C, but some of them can survive high temperatures and even drying. Microorganisms are categorized into mesophiles, psychrophiles, and thermophiles based on their temperature ranges. The optimal temperatures for psychrophiles are below 20°C, those for mesophiles are between 20 and 40°C, and those for thermophiles are above 40°C. Hence, the composting procedure is simply segmented according to the temperature regulation [3]. Xi et al. [38] observed that multi-stage inoculation composting increased the length of the high-temperature phase and secondary fermentation temperature.

4.2. pH

The pH is a crucial factor influencing the decomposition process. The concentration of hydrogen ions in the composting material impacts the composting process because bacteria flourish at relatively moderate or high pH levels. Throughout the composting process, the pH exhibited an upward trend. During the initial rise in temperature, the pH rose quickly from 6.8 to 7.1 in the thermophilic phase. After that, a rise in pH was seen throughout the composting process that lasted for 20 days. It was determined that the pH of the finished compost was 7.6 [22]. During the early stages of composting, the rise in pH is caused by the breakdown of accumulated organic acids and the production of NH^{4+}, which comes from the breakdown of proteins. In particular, the formation of alkaline substances like ammonium ions is needed for the pH to rise [20]. Additives such as cow manure are often added to the composting mixture. Through these additions, diverse microflora (bacilli, lactobacilli, fungi, and yeasts) enter the compost matrix. It causes a sequence of microbial oxidation processes and an increase in process temperature. This intensified the composting process and increased the rate of waste decomposition [39]. Generally, pH is not employed to regulate composting processes. Nonetheless, it may be helpful to identify uncommon compounds by observing variations from normal operations.

4.3. C/N Ratio

One of the most significant indicators used to measure the composting process and compost maturity is the C/N ratio. It helps to maintain nutritional balance in compost by showing the quantity of available carbon relative to nitrogen, which is important for plant growth [40]. Microorganisms require nitrogen for protein synthesis and carbon for growth. Several studies recommend a C/N ratio of 30 for optimal composting, while many also recommend 26–35. Under suitable circumstances, ammonia may be converted to nitrite and nitrate from a low C/N ratio. Organic materials deficient in nitrogen, including cereal residues of wheat, rice, jawar, bajra, cotton, jute, and sawdust, generate high C/N ratios. Agricultural and urban wastes range in C/N ratio from 30 to 80. Materials with a higher C/N ratio take longer to compost. This time can be reduced by adding a nitrogen source or mixing them with organic wastes that are relatively high in nitrogen. Brown et al. [10] found that phosphorus is also necessary for composting of municipal solid waste (MSW). If MSW with high paper content lacks P, the C/P ratio and C/N ratios must be adjusted. It was determined that optimum composting requires a C/P ratio between 120:1 and 240:1 when the C/N ratio is 30:1. Kalamdhad et al. [41] used a rotating drum composter to evaluate the effects of the initial C/N ratio on compost quality and duration for urban MSW mixed with bovine manure and tree leaves. The results showed that an initial C/N ratio of 22 is best for waste breakdown because it promotes a longer thermophilic phase and a high initial composting temperature. Changes in the C/N ratio reveal how composting degrades and stabilizes organic materials. When the compost contains excessive carbon and not enough nitrogen, the extra carbon will pull nitrogen from the soil to make cell protoplasm. This leads to soil nitrogen loss, sometimes referred to as "robbing of nitrogen in the soil." If the C/N ratio is too low, the compost that results does not help in improving soil structure. Makan & Mountadar [35] reported that the rate of degradation was greater at lower C/N ratios (22.2 and 26.0) than at higher C/N ratios (38.4, 44.6, and 50.8).

4.4. Shredding

The process of composting can be speed up if raw materials are shredded into smaller pieces before composting [42]. After the investigation of the temperature and oxygen profiles in windrow composting, Joshua et al. [43] reported that proper aeration could be maintained by efficient particle size of feedstocks. During the aerobic, in-vessel composting of MSW, Rich & Bharti [37] manually shredded waste into pieces smaller than 2 mm in size. When the particle size is too large, there is a risk that the compost materials could collapse, leading to a reduction in the water-holding capacity of the compost throughout the process. A larger particle size may contribute to an increase in the scale of voids, leading to excessive ventilation and inadequate self-heating [44].

4.5. Moisture Content

One of the indicators often used to monitor the composting process is the level of moisture in the waste. An optimum moisture content for fast aerobic and thermophilic composting of organic wastes or waste mixtures is between 40 and 60%. If the moisture level is below 40%, decomposition will be slow. If it exceeds 60%, there may not be enough air space to support aerobic decomposition, and anaerobic conditions may dominate. During composting, the initial moisture content of the substrate drops due to the increase in temperature induced by the development of biological degradation processes, which are more stronger during the active phase and tend to slow down during the curing stage [45]. If the moisture content is below 45%, there is not enough water around the particles for the microorganisms to live. If the moisture content is above 65%, the pores between the particles are filled with water, and the microorganisms cannot get enough oxygen [4]. During the rotation of a windrow, Sinha & Herat [46] sprayed an inoculant slurry to maintain a moisture level between 45 and 55%. Moisture supports nutrient transfer to microorganisms and should have a water content of 25–70%. Traditionally, feed conditioning and manual water addition have been used to establish and maintain a target moisture content. To optimize the composting parameter during windrow composting of source-separated MSW, the surface of the composting mixture is adjusted by sprinkling water over the feedstock with a moisture level of 50–60% [27]. Due to decreased oxygen availability, Ermolaev et al. [47] discovered that the moisture level of the substrate impacts CH_4, and N_2O emissions during composting.

4.6. Aeration

Often, the temperature of a process is regulated through evaporative heat loss caused by aeration. Oxygen levels may be maintained by agitation or forced aeration, but only forced aeration can provide adequate aeration to avoid oxygen restriction. Temperature, oxygen, and moisture are the most important components in sustaining microorganism-friendly circumstances. According to research, larger compost heaps or piles with a lower ratio of surface area to volume need more frequent turning to guarantee aeration and heat dispersion [48]. Aeration is mostly controlled by the type of composting system used, which determines whether air is incorporated through agitation, forced aeration, or a combination of the two. Ideally, the air requirements of the microbes would vary according to the type of waste, temperature, composting stage, and process parameters. The aeration will provide oxygen to the microorganisms, extract heat, and remove moisture from the substrate. Apart from sufficient aeration volume, high aeration pressure is also required to guarantee an aerobic process to produce good compost [49]. As compared to passive aeration, the total coliform count drops more rapidly during the forced aeration technique [50]. The maximum sustained temperatures for aerobic composting are achieved at oxygen levels between 5 and 15%. Oxygen levels below 5% induce anaerobic conditions, while levels above 15% indicate excessive aeration that cools the static pile. Natural convection and the applied turning program were unable to supply enough oxygen to the pile core to keep oxygen levels over 5%. Results reveal that forced aeration is more significant than turning for high interstitial oxygen content [51]. Delgado-Rodríguez et al. [52] discovered that high aeration rates of 0.300 $L_{air}\ kg^{-1}\ min^{-1}$ resulted in normally high emissions of volatile organic compounds, whereas low aeration rates of 0.05 $L_{air}\ kg^{-1}\ min^{-1}$ could cause anaerobiosis problems and the generation of organic sulfur compounds. Bacteria and fungi, which break down OM, live in a layer of water around the OM.

4.7. Shape of Windrow

Heat distribution is affected by the condition and composition of the MSW, while heat loss is affected by the size and form of the windrow. Heat is generally accumulated in the middle zone and is influenced by the size and form of the windrow. According to the results of the dimensional study of the compost pile, the big size of the windrow should be avoided since there is a danger of anaerobic zone creation. A windrow height of up to 1.5 m is generally recommended for maintaining optimal composting conditions and preventing excessive compaction. Heat loss is related to the surface area of the compost mass, whereas heat production is proportional to its volume. As a result, the larger the pile, the less heat is lost, and the higher the temperature rises. For larger heaps, care must be given to ensure that oxygen transport to the inner zones is not obstructed, resulting in anaerobic conditions and lower heat output. According to research, the ideal pile dimensions for optimum heat generation in windrow composting were 1 cm height, 1.5 cm width, 3 cm length, 13.5 m^2 pile surface area, 4.5 m^3 pile volume, and a surface area to volume ratio of 3 [48]. An aerobic composting yard (about 3405 m^2) with concrete floors and sloping double-pitched roofs can make compost in 6 to 8 weeks when organic waste is piled and turned in long rows [12]. Ermolaev et al. [47] examined the composting process carried out in covered, trapezoid-prism shaped windrows that featured forced aeration pipes positioned beneath a semipermeable membrane. The windrows were structured to achieve an ideal configuration, approximately trapezoidal prism-shaped, 3.8 m wide, and 1.7 m high. The findings indicated that the regulated ventilation system markedly reduced methane (CH_4) and nitrous oxide (N_2O) emissions in comparison to uncovered windrows, all the while ensuring effective organic matter (OM) decomposition and consistent compost quality. Furthermore, the study highlighted that enhancing windrow geometry and aeration design is essential for reducing GHGs and increasing composting efficiency.

5. Maturity and Stability Indices for MSW Composting

Maturity and stability parameters have been utilized by researchers to determine composting completeness. Compost stability is a key attribute that allows for the avoidance of odor issues and changes in compost quality during storage. The optimal composting period and compost suitability depend on compost stability. Compost maturity affects microbial activity and stability. Less microbial activity means the compost is more stable. Mature compost should not be phytotoxic or immobilize nutrients when applied [53]. Tahsini et al. [1] reported that the germination index (GI) serves as an effective maturity indicator for municipal solid waste (MSW) compost. A GI > 100 indicates a significant level of maturity in MSW compost. During an investigation of three industrial composting facilities that compost food waste, MSW, and sewage sludge, Siles-Castellano et al. [54] reported that good sanitation did not guarantee that the products were mature and stable. Rastogi et al. [39] observed that adding cellulolytic bacteria and cow dung to MSW composting increased the percentage of nitrogen, the C/H ratio, and the Humification Index (HI), which improved the overall stability of the compost. Cation exchange capacity (CEC) is a key chemical indicator of compost quality. Mature, high-quality compost contains high CEC, according to the literature [55]. Adamcová et al. [56] used white mustard seed phytotoxicity (*Sinapis alba*) to evaluate MSW compost for ecotoxicity and landfill reclamation. They found that the compost was not toxic to plants because the germination index was above 90%. Aeration rates less than 0.2 L/min kg organic matter (OM) were observed to result in a low degradation rate, moisture, and heat loss; a reduction in NH_3 formation, and a considerable temperature drop. Aeration was the key element affecting compost stability because these circumstances altered microbial diversity. The humic acid-to-fulvic acid ratio (HA/FA) is often used to describe how fast HA and FA change and how mature the final compost is. A compost that is ready to use has an HA/FA ratio between 3.6 and 6.2 [45]. Table 1 presents a summary of the literature on MSW composting. The table highlights input conditions and variables studied by various research workers, along with their salient findings.

Table 1. *Summary of literature on MSW composting.*

Year	Variables/ Components studied	Salient findings	Ref.
2002	Use of slurry culture containing active decomposer bacteria and enzymes for enhancement of decomposition. Parameters studied were moisture content, temperature, and turning interval.	For the bioconversion process, the moisture content was 45–55%; the optimum turning frequency was 7–10 days.	[46]
2005	Windrow and pit composting of chicken manure, leaves, and MSW were compared in this research.	It was discovered that the pit method was superior at maintaining temperature, nitrogen, organic carbon, and OM.	[57]
2010	The study investigated the effectiveness of composting source-separated OM from MSW generated in low, middle, and high-income zones of Jabalpur city.	Nitrogen levels were low in MSW. The MSW is compostable due to its high biodegradable OM, moisture content, and C/N ratio.	[26]
2012	This research monitored process parameters and kinetics in the composting organic fraction of municipal solid waste (OFMSW) and poultry manure.	The optimum composting mixture was 60% OFMSW, 20% poultry manure, 10% mature compost, and 10% sawdust.	[33]

Year	Variables/ Components studied	Salient findings	Ref.
2012	Using a 250 L rotational drum composter, compost dynamics and stability were studied.	MSW combined with cattle manure and tree leaves impacts rotary drum composter compost quality and process dynamics. Has a higher initial composting temperature and a longer thermophilic phase.	[41]
2012	To reduce heavy metal toxicity during MSW composting, researchers used citric and oxalic acids.	The particle size was 80 mm. Lowers Cu, Pb, and Zn by 60–80%, although Cr and Ni levels barely alter.	[58]
2013	For compost maturation, pH, moisture, temperature, C/N ratio, and volume decrease were studied for 42 days.	A 47% volume reduction was observed in 42 days of composting. Solar aeration improved process efficiency. Due to the addition of bacteria culture, the composting process was accelerated.	[17]
2013	Polyvinylpyrrolidone (PVP) coated silver nanoparticles (PVP-AgNPs) are tested for their effect on MSW composting.	The leachate, gas, solid, and composting performance of the AgNPs, Ag^+, and negative control treatments were not significantly different. Due to compost samples' bacterial functional redundancy, the bacteria's functional performance was unaffected.	[59]
2013	Composting of biodegradable diapers with the organic component of MSW was tested.	No technical issues in the biological process in terms of the stability, quality, and cleanliness of the resultant compost. No harmful bacteria were found in the compost.	[5]
2013	This study assessed the ideal pile size and turning frequency for MSW thermophilic composting.	Composting is quicker with smaller surface area-to-volume ratios. Moisture content is not a significant decomposition rate indicator. Piles with a lower surface area-to-volume ratio require more turning for aeration and heat transfer.	[48]
2016	This research examines the variables influencing the composting of MSW in Sri Lanka.	Most local authorities lack the expertise and implementation abilities to manage composting facilities and sell compost products that fulfill regulations.	[60]
2018	Landfilling and composting-landfilling energy utilization and exergy demand were compared in this research.	Composting-landfilling is more environmentally friendly in terms of lesser emissions and toxicity. Composting-landfilling needs 29% more energy to process MSW than landfilling.	[61]
2018	Polyvinyl alcohol and polyvinyl alcohol + cellulose nanofiber nanocomposites were investigated for compostability in this study.	Pure polyvinyl alcohol films degraded more rapidly than polyvinyl alcohol + cellulose nanofiber nanocomposites.	[62]
2019	12 physicochemical and 2 microbiological parameters were assessed throughout the 7 weeks of composting 1300 kg of organic waste from MSW.	The best monitoring variables for the economy and technical simplicity are respirometry, water retention capacity, ash content, and moisture.	[63]
2019	This study examined the health risks and fertilizer value of aerobically, anaerobically, and aerobic-anaerobically composted MSW. Carrots and spinach were grown for 85 and 90 days in sandy loam soil in pots with all the compost elements.	Plant absorption of lead and cadmium was lowest in anaerobic composting, whereas dry matter yielding and vegetable N uptake were highest. Anaerobic composting is superior to the other composting methods.	[54]
2019	Cow dung and cellulolytic bacteria of the Bacillus species were tested for their effects on MSW composting humic characteristics.	Showed 82.4% humification improved MSW compost stability.	[39]
2019	This research examined coffee husk, pulp, and source-separated municipal solid waste's composting and co-composting efficiency.	Compost samples made from coffee husks and pulp were found to be particularly rich in iron, potassium, and micronutrients.	[27]
2019	In this research Black soldier fly larvae were used to compost municipal organic solid waste into organic fertilizer.	The experimental groups showed significant NPK increases. Heavy metal content is reduced by larval decomposition.	[64]
2020	This study investigated the optimal ratio of khat straw biochar and organic MSW mixtures for increasing co-compost quality.	The optimum khat-derived biochar rates were 5% and 15% (w/w). Khat straw has a high lignin content, as its charcoal output is 29.4%.	[55]

Year	Variables/ Components studied	Salient findings	Ref.
2021	This study examined six industrial composting plants that sanitize and compost MSW and sewage sludge.	Municipal solid waste compost exceeds regulatory faecal and phytotoxicity standards.	[54]
2022	Life cycle assessment was used to examine the environmental implications of a full-scale composting operation in Sri Lanka.	Gaseous emissions and diesel usage during composting pose environmental risks.	[65]
2023	In-vessel composting for composting vegetable and food waste with coco peat additions and biochar from coco peat was examined.	5% biochar in C/N 22 had the greatest germination index of 93.55%.	[66]
2023	A temperature-controlled lab-scale reactor was used to assess how storage duration on an enhanced microbial population affected the efficiency of OM breakdown.	Enriched microbial communities kept dry for 30 days showed the same impact on OM breakdown as when employed without storage. Enriched microbes are active for a short time after being stored. Yet, extended storage reduces their OM breakdown efficacy as an inoculum.	[20]
2024	The study determined the impact of aeration, turning mechanisms, bulking agents, degradation rate, and process parameters on compost quality from the OF-MSW.	The provision for aeration via perforated vents, regular turning mechanisms, and addition of bulking agents substantially impacted compost quality.	[67]
2025	This study examined the use of biochar and microbially inoculated biochar to improve and speed up the composting process of MSW.	Biochar inoculated with bacteria and bacterial/fungal consortia increased biological activity, resulting in higher temperatures and a longer thermophilic phase.	[1]
2026	This study developed a rapid composting technique that can successfully transform food waste, a substantial component of MSW, into quality compost within 1-day in-vessel processing and 10-day maturation.	Increasing organic waste generation presents significant difficulties to the global population, emphasizing the need for new and effective waste management techniques. Due to its rapid processing time than conventional composting, in-vessel composting will be utilized widely for full-scale waste treatment.	[68]

6. Utilization of MSW Compost

Utilization of municipal solid waste (MSW) compost improves soil structure, organic matter (OM), and water retention while supplying essential micronutrients; however, MSW compost utilization is often limited by various factors. Kabasiita et al. [69] reported that only around 2% of farmers actually utilize MSW compost. Their findings indicate that increased farm income, previous experience with fertilizers or soil conditioners, and availability of other organic amendments have a positive impact on the adoption of compost. Conversely, factors such as high compost costs, subpar quality, and membership in farmer groups are associated with a negative influence on its use. The limited awareness, absence of technical guidance, and contamination of compost with plastics significantly hindered its utilization. They also stated that enhancing the quality and affordability of compost, increasing farmer awareness, and providing improved extension services and market access are crucial for the effective use of MSW compost in urban agriculture. Bhardwaj et al. [70] reported that applying MSW compost (25%, 50%, 75%, 100%) to amend soil influenced the development and production of brinjal (*Solanum melongena*), tomato (*Solanum lycopersicum*), and okra (*Abelmoschus esculentus*). Results showed that MSW compost significantly boosted crop growth and output and may be utilized as an alternative to chemical fertilizer in a safer ratio (25%). The compost utilization faces various challenges that hinder its widespread adoption, including issues related to compost quality, adherence to regulatory standards, and the competition from chemical fertilizers. Therefore, it is imperative to implement more robust market incentives, educational initiatives, and government policies to promote the widespread use of compost [71]. Tohumcu et al. [72] conducted experiments on applying sewage sludge, farmyard manure, and MSW compost to alkaline soils to improve their physical and chemical qualities. The 2-year field study used a random trial design with 48 plots, 3 controls, and 3 replications. Table 2 gives detail on the physical and chemical changes in alkaline soil after the application of MSW compost.

Table 2. Physical and chemical changes in alkaline soil after the application of MSW compost.

Year	Doses (t/ha)	pH	EC (μS/cm)	OM (%)	CEC [cmol (+)/kg]	Exchangeable Na content [cmol (+)/kg]	Bulk density (g/cm^3)	Soil porosity (%)	Soil field capacity (%)	Soil available moisture capacity (%)
1	0	8.60	337.33	1.10	26.56	4.50	1.35	47.55	29.27	11.79
	25	8.57	399.00	1.77	25.61	3.55	1.34	47.88	29.80	12.00
	50	8.52	387.00	2.07	26.73	3.31	1.32	48.62	30.15	12.14
	75	8.43	458.00	2.57	27.07	3.28	1.26	50.95	30.35	12.22
	100	8.34	475.00	2.79	26.39	3.01	1.25	51.39	30.41	12.25
	125	8.29	509.00	2.90	26.39	2.96	1.23	51.97	30.58	12.32
2	0	8.55	324.50	1.12	26.05	3.53	1.29	49.68	29.55	11.9
	25	8.53	441.83	1.79	25.88	2.38	1.20	53.39	30.69	12.36
	50	8.49	475.17	2.10	25.72	2.12	1.18	54.03	30.93	12.46
	75	8.41	511.00	2.17	26.22	2.04	1.17	54.37	30.99	12.48
	100	8.31	559.00	2.22	26.54	2.04	1.16	55.05	31.07	12.51
	125	8.26	586.00	2.25	26.56	2.02	1.13	55.91	31.11	12.53

Ref. [72]

7. Indian Scenario

The composition of municipal solid waste (MSW) produced in different Delhi zones and localities showed that solid waste with high organic content (38.6% biodegradable waste) and moisture content has the potential for composting and biomethanation [73]. The chemical assessment of Guwahati MSW indicated that the moisture content fluctuates between 43.4% and 58.3% on a seasonal basis, the pH ranges between 5.5 and 6.5, the volatile solid content ranges from 32.9% to 58.9%, and the calorific value ranges between 1203 and 3015 kcal/kg. Due to the high moisture and volatile content of MSW, composting might be a viable waste treatment method if waste is segregated properly [13]. Dantroliya et al. [74] reported that bacteria that were isolated from a landfill site were able to produce enzymes such as cellulase, xylanase, ligninase, and protease that enhance the biodegradation of MSW. Saha et al. [75] examined MSW composts from 29 cities and found that almost all did not meet the quality control guidelines of the Government of India Ministry of Agriculture [76] for total organic C, total P, and total K, including heavy metals Cu, Pb, and Cr. Table 3 gives detail on the classification of MSW composts by marketability and applicability.

Table 3. Classification of MSW composts by marketability and applicability.

Class	Fertilizing index	Clean index	Quality control compliance	Remarks
A	> 3.5	> 4.0	Conforming to the specifications for all heavy metals	Best quality. It has a high manure value and a low level of heavy metals, so it can be used for high-value crops, such as in organic farming.
B	3.1–3.5	> 4.0	Conforming to the specifications for all heavy metals	Very good quality. Moderate fertility and low levels of heavy metals.
C	> 3.5	3.1–4.0	Conforming to the specifications for all heavy metals	Good quality. High fertility and moderate heavy metal content.
D	3.1–3.5	3.1–4.0	Conforming to the specifications for all heavy metals	Moderate quality. Moderate fertility and moderate heavy metal content.

Class	Fertilizing index	Clean index	Quality control compliance	Remarks
RU-1	< 3.1	-	Conforming to the specifications for all heavy metals	Due to its low fertilizing capacity, it should not be allowed on the market. Nonetheless, these can be utilized as soil amendments.
RU-2	> 3.5	> 4.0	Not conforming to all of the requirements for heavy metals	Should not be allowed to enter the market. Restricted usage. Allowing for the cultivation of non-food crops. If applied repeatedly, periodic soil quality monitoring is required.
RU-3	> 3.5	-	Not conforming to all of the requirements for heavy metals	Should not be allowed to enter the market. Restricted usage. Only for use in establishing lawns and gardens (with a single application) and restoring previously unproductive land.

Ref. [75]

1) MSW compost should only be sold if it has been graded as an A, B, C, or D. For all heavy metals, these composts must be below the national regulatory limit or statutory order. Fertilizing potential is highest for categories A and C (Fertilizing index > 3.5), while pollution risk is lowest for categories A and B (Clean index > 4.0).
2) Compost samples with heavy metal levels over allowable limits or insufficient fertilizing value (Fertilizing index 3.1) are not commercially viable, thus being designated as "restricted use" (RU).
3) The samples of MSW compost classified as RU-1 are within the regulation limits for heavy metal levels, but they should not be sold because of their limited fertilizing potential. Nonetheless, these can be used as soil conditioners without restriction.
4) The samples of MSW compost classified as RU-2 have a high 'Clean index' value (> 4.0), but they do not comply with regulatory restrictions for heavy metal concentrations since they contain at least one heavy metal beyond the allowable limit. Repeated use of composts with a high "Fertilizing index" value (> 3.5) is safe for growing non-food crops (including fodder crops), but only if soil quality is checked regularly.
5) In some cases, when establishing new lawns or gardens, reforesting, or rehabilitating damaged land, composts (categorized as RU-3) with sufficient fertilizing value ('Fertilizing index' > 3.0) may be approved for a single application despite their high heavy metal levels. If a compost sample does not fall into one of the aforementioned categories, it may be sent to the landfill.

8. Conclusion

Municipal solid waste (MSW) management assumes great significance and is being recognized as an important facet of overall environmental management. Composting of MSW and other organic waste materials is gaining in popularity and is considered one of the techno-economically viable options. The higher percentage of compostable fraction in the MSW reported in studies makes the composting process suitable for adoption. Preprocessing of MSW through source separation of contaminants such as plastic, metal, rubber, and stones has been reported in the literature. The literature reveals that separation of organic fraction and shredding of MSW before composting with due attention to particle size helps in increasing the efficiency of the composting process as well as reducing the time of composting. Several research workers have studied the process control variables. Research findings have consistently shown that the rate of decomposition in composting is dependent on the initial C/N ratio of waste. The length of composting is inversely correlated with the C/N ratio. For efficient composting without nitrogen loss, a C/N ratio of 30 has been recognized as ideal. Various studies have reported that effective composting occurs within an optimum temperature range exceeding 20°C and reaching approximately 55°C, with a pH maintained between 7 and 8 and moisture content ranging from 40% to 60%, which supports active microbial metabolism and efficient organic matter (OM) degradation while minimizing the loss of volatile nutrients and excessive ammonia emissions during composting of MSW. Reportedly, temperatures > 70°C can hinder the decomposition process by causing thermal kill of active microorganisms. Turning windrows at frequent intervals is a simple and feasible method for providing aeration and enhancing microbial activity. This technique also helps in preventing anaerobic conditions that produce odors. The size and shape of windows need to be selected in such a way as not to create anaerobic conditions resulting from improper oxygen diffusion inside the compost pile. Because of less heat loss from the larger windrows with the resultant increase in temperature, care needs to be exercised in setting up the windrows of appropriate shape and size to ensure oxygen diffusion to inner zones. The permissible height of the windrow has been suggested as 1.5 m. Monitoring the degradation of composting mass is one of the crucial stages during composting. The literature indicates different parameters and their desired values as process monitoring parameters. In developed countries, social problems are related to the quality of MSW compost. In this context, a concern of

MSW compost users about physical and chemical contaminants in compost made from mixed refuse has been reported. Chemical contaminants that pose a relatively greater problem are reported to be toxic organic chemicals and heavy metals. It is necessary to delineate strategies for MSW composting based on techno-economic and social considerations for its adoption in urban areas.

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Author Contributions

Chandani Lakhani: Conceptualization, Writing – original draft

Sandeep Bodkhe: Validation, Writing – review & editing

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, Sandeep Bodkhe, upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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