Composting for a Cleaner India: Comparing Technologies for Sustainable Waste Management

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Abstract

India, as one of the most populous countries, faces an ever-growing challenge in managing its municipal solid waste (MSW). With over 40-50% of Indian MSW being biodegradable organic matter, composting has emerged as a viable solution for sustainable waste management. This article, based on the study "Assessment of the Quality of IMC Composting Produced from Municipal Solid Waste," explores the comparative efficacy of different composting techniques Windrow Composting (WC), Vermicomposting (VC), and Inoculated Microbial Composting (IMC). The analysis is grounded in laboratory testing of compost samples collected from various municipal corporations and assessed based on Fertilizing Index (FI) and Clean Index (CI) parameters. The findings offer a deeper understanding of compost quality, environmental safety, and potential for marketability, thereby shaping India's journey towards a cleaner and more sustainable future.

1. Introduction

Rapid urbanization and population growth have resulted in increased generation of municipal solid waste across India. Urban areas alone generate about 1.43 lakh metric tonnes of waste daily, a significant portion of which is organic and biodegradable. While landfilling has traditionally been the go-to solution for waste disposal, it has led to severe environmental degradation, groundwater contamination, and public health risks. Composting, therefore, is being positioned as a more sustainable, eco-friendly alternative, aligning with global and national waste management strategies such as the Swachh Bharat Abhiyan and the Municipal Solid Waste Management Rules, 2016.

Solid waste management remains a critical environmental challenge in urban and semi-urban regions across India. Rapid urbanization and rising population densities have led to a substantial increase in municipal solid waste (MSW) generation, placing significant strain on local authorities to implement sustainable waste management practices [1],[6]. Notably,

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biodegradable organic matter constitutes approximately 40–50% of the MSW generated in Indian cities [4], presenting a considerable opportunity for composting initiatives, provided effective segregation and processing systems are established [3].

However, the composting process attains environmental significance only when the final product is utilized safely and productively, such as in horticultural and agricultural applications [9]. To ensure the safety and efficacy of compost for such uses, certification grounded in standardized quality parameters is essential [2]. Traditionally, compost quality assessments have relied on parameters such as the carbon-to-nitrogen (C/N) ratio [8]. However, the integration of comprehensive indices, including the Fertility Index (FI) and the Clean Index (CI), can enhance the robustness of compost quality certification, offering a more holistic evaluation framework [5].

This study aims to conduct a comparative analysis of compost quality using these advanced indices, providing in-depth insights into quality assurance practices for compost derived from municipal solid waste in India. Such an approach is crucial for safeguarding soil health and ensuring the sustainable application of compost within the broader municipal waste management ecosystem [7].

Vermicomposting utilizes earthworms to accelerate the decomposition of organic waste, producing nutrient-rich compost with improved microbial activity and structure suitable for soil application [5]. Windrow composting, a widely used aerobic method, involves placing organic waste in long heaps or windrows that are periodically turned to maintain aeration and moisture levels, facilitating efficient microbial breakdown of waste materials [9]. Microbial composting, on the other hand, involves the deliberate inoculation of effective microbial consortia to enhance the biodegradation of organic matter, significantly reducing composting time while improving pathogen reduction and nutrient content in the final compost [8]. These composting methods provide scalable and sustainable pathways for managing the high organic fraction in municipal solid waste in India while producing valuable soil conditioners [7].

Composting technologies not only reduce the volume of waste sent to landfills but also contribute to soil health, agricultural productivity, and climate change mitigation through carbon sequestration. This study focuses on evaluating three major composting methods - Windrow, Vermi, and Inoculated Microbial Composting - through a rigorous scientific assessment of their physical, chemical, and heavy metal properties. [10]

2. Composting Techniques: Overview

1. **Windrow Composting (WC)**

Windrow composting involves piling organic waste in long rows (windrows), which are aerated regularly through mechanical turning. It is relatively cost-effective and widely used in India but may require more space and longer processing time. [12]

2. Vermicomposting (VC)

This method employs earthworms to enhance the decomposition of organic material. Vermicomposting is effective in producing nutrient-rich compost with improved microbial activity. However, it is more sensitive to climatic variations and operational disturbances.[11]

3. Inoculated Microbial Composting (IMC)

IMC involves introducing specialized microbial cultures (bio-activators) to accelerate the composting process. In this study, BIOCULUM was used as an inoculum in the composting of MSW. IMC has shown promise in improving compost quality and reducing heavy metal content.[13]

3. Study Design and Methodology

Samples were collected from multiple municipal corporations across India using grab sampling methods. A total of 15 samples 5 each from WC, VC, and IMC techniques were analyzed. This article focuses on two large-scale IMC samples (M1 and M2) sourced from Ahmedabad, Gujarat.

The samples underwent laboratory tests to assess parameters such as:

- Moisture content
- Volatile solids
- pH and Electrical Conductivity (EC)
- Total Organic Carbon (TOC)
- Macronutrients (N, P, K)
- C:N ratio
- Carbon respiration
- Heavy metal concentration (Zn, Cu, Cd, Pb, Ni, Cr) [15]

4. Quality Control Indices:

The composts were graded using two indices:

- **Fertilizing Index (FI)** – assesses soil fertility-enhancing properties.
- **Clean Index (CI)** – evaluates environmental safety based on heavy metal content. [15]

The values were then benchmarked against international standards, including FCO 1985 (India), MSW 2016 rules, and compost regulations from the USA, EU, and Finland.

1. Fertilizing Index:

According to the categories listed in Table 1, each analytical parameter that influences the fertilizing value (which is in charge of enhancing soil productivity) of compost, such as the total C, N, P, and K contents as well as the C:N ratio and respiration activity, is given a "score" value. Analytical values of these fertilizing parameters acquired for source-separated biogenos waste composts are taken into account for determining score values. For these composts, the lowest values of the aforementioned fertilizing parameter were assigned a score of "3." Higher scores were given to fertilizer parameters with higher values. A "weighing factor" was assigned to each of these fertility characteristics based on scientific understanding regarding their contribution to increasing soil production. Adding organic C through compost increases biomass output from land area because it regulates a number of soil productivity factors, including water holding capacity, porosity type, soil structure, plant nutrient reserve pool, and soil biological activity. Additionally, the residence duration of C introduced into soil through compost is longer than that in the landfill region because of the creation of the clay-humus complex. As a result, less greenhouse gas is produced, which helps to mitigate climate change and sequester atmospheric carbon. Therefore, the compost's TOC content was given the highest weighing factor. Since composts with high respiration activity and a high C:N ratio are likely to immobilize nitrogen and other nutrients, these compost maturity criteria were also given larger weighting factors. Based on their functional significance and the frequency of deficiencies in soils, the three main nutrients N, P, and K were given distinct weighing factors, despite the fact that they are all necessary for increased crop output. [18][20]

Equation 1 Fertilizer Index

$$\text{Fertilizing index} = \sum W_i S_i / \sum W_i$$

The 'Fertilizing index' of the MSW composts is computed using the formula

'Si' is score value of analytical data and 'Wi' is weighing factor.

2. **Clean Index:**

Following the guideline set forth in Table 2, the analytical values for each heavy metal were assigned score values. In determining score values, the defined quality control limits of Saha et al (2009) for India as well as the limits defined by Indian counterparts were considered. In fact, most European countries have legal limits on the concentration of heavy metals which corresponds to a score value of 3. Each heavy metal was assigned a "weighting factor." This was done based on the cadmium's toxicity to mammals, its phytotoxic potential, as well as its biological role, if any, in the body. Due to its extremely high toxicity to mammals and a medium to high potential to be phytotoxic, cadmium was assigned the highest "weighting factor." In contrast, Ni and Zn exhibit a low to medium toxicity to mammals, a potential to be phytotoxic, and were involved in several biological functions. Therefore, they were assigned the lowest "weighting factor." The "clean index" value was assessed for each participant using the formula shown. Composts that are low in heavy metals are scored higher, and as a result, the "Clean index" values are higher.

Equation 2 Clean Index

$$\text{Clean index} = \sum W_j S_j / \sum W_j$$

'Sj' is scoring value of analytical data and 'Wj' is weighing factor of the 'j'th heavy metal. Saha et al (2009)

3. **Classification of compost based on fertilizing index and clean index:**

Following a critical analysis of the fertilizing index and clean index values of MSW composts, various classes of compost have been proposed for their use in various application areas as well as for their suitability as marketable products. Fertilizing index scores can be used as a measure of nutrient-supplying potential, while the Clean Index value can be used by regulatory authorities to restrict the entry of heavy metals into sensitive components of the environment (such as agricultural land and water bodies).

4. Only MSW composts classified as A, B, C, and D should be permitted to be sold. Regarding all of the heavy metal levels, these composts have to adhere to the national statutory decree or regulatory limit. While classes A and B present the least amount of pollution hazard to the environment (Clean index > 4.0), classes A and C have the greatest potential for fertilization (Fertilizing index > 3.5).

5. Compost samples classified as restricted use (RU) are unfit for marketing if they either do not meet regulatory limitations for heavy metal concentrations or have insufficient fertilizing value (fertilizing index < 3.1). Despite meeting regulatory limitations for heavy metal levels, MSW compost samples graded under class RU-1 (FCO-QC standards) should not be permitted for sale because of their poorer fertilizing potential. They can, however, be applied freely as a soil conditioner.

6. MSW compost samples classified under class RU-2 have high "Clean index" values (>4.0), but because at least one heavy metal is present in excess of the allowable limit, they do not fulfil regulatory limitations for heavy metal levels. When applied regularly, composts with a high "Fertilizing index" value (>3.5) can be used to grow non-food crops, such as fodder crops, provided that the soil quality is periodically monitored.

7. Composts (class RU-3) with sufficient fertilizing limitations for fertilizing parameters should be used as a guide when the "fertilizing index" is greater than 3.0; nevertheless, composts with high heavy metal content may be permitted for a single application under The classification (a first recommendation for discus-restricted conditions like establishing lawns/gardens, afforestation, recovering damaged land, etc.) is a step in this direction. Samples of compost that don't fit into any of the aforementioned categories might be sent to the landfill.

5. Key Findings and Analysis

1. Physical and Chemical Properties

The C:N ratios for both M1 and M2 exceeded optimal thresholds, indicating a need for better raw material balance. Despite this, the carbon respiration rate was low, pointing to mature and stable composts.

Table 1 Physical and Chemical properties of samples

Physical and Chemical Properties			
Parameter	**M1**	**M2**	**Indian Standard (FCO/MSW 2016)**
Moisture Content (%)	21.32	19.9	20–30
Volatile Solids (%)	79.61	76.6	NA

pH	8.08	8.09	6.5–7.5
EC (dS/m)	3.01	2.96	<3.14
TOC (% dm)	44.21	42.59	>16
Total N (% dm)	0.77	0.88	>0.5
Total P (% dm)	0.011	0.001	>0.22
Total K (% dm)	0.2	0.2	>0.83
C:N Ratio	55.31	47.28	10:1–25:1
Carbon Respiration	0.4	0.4	2–8

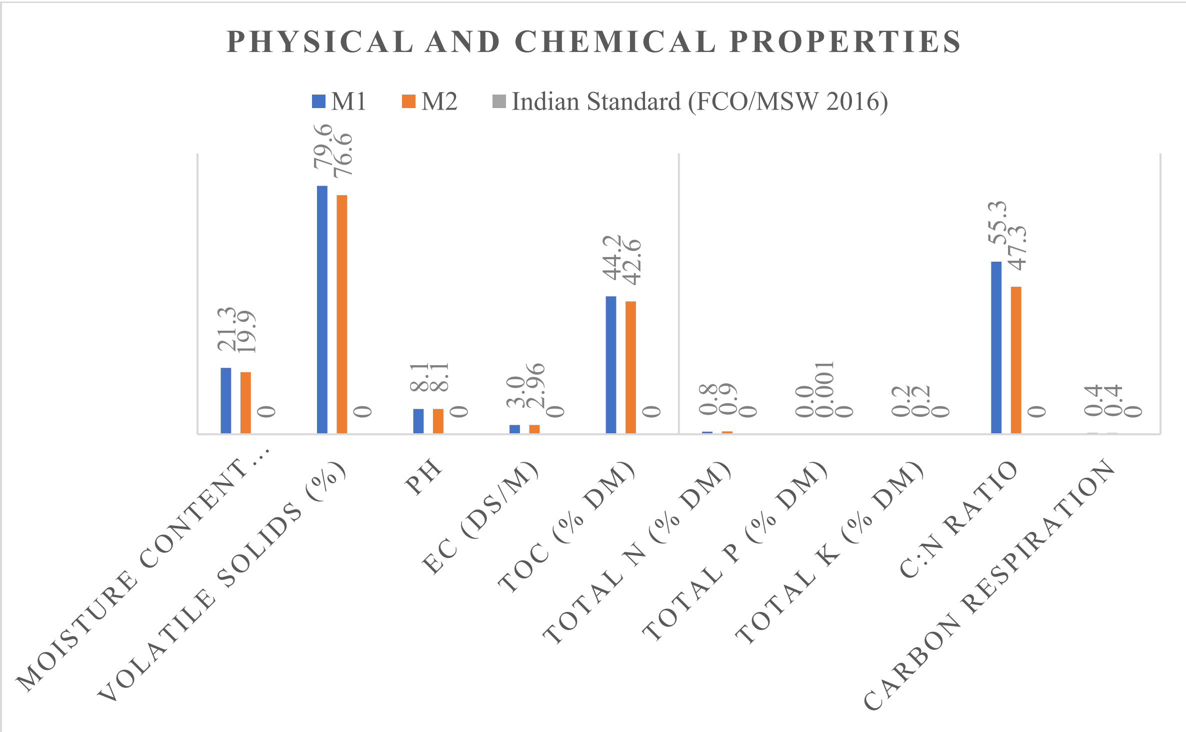

Figure 1 Graph showing physical and chemical properties compared with standard values

2. Heavy Metal Content

Figure 2 Table showing the comparison of ranges of heavy metal components as per different standards

All heavy metals tested within safe limits, reflecting the efficacy of IMC in preventing environmental contamination.

Table 2 Heavy metal content of tested samples

Heavy Metal Content

Metal	M1 (mg/kg)	M2 (mg/kg)	Indian Standard	USA Standard	EU Range
Zn	266	234	<1000	2800	210–4000
Cu	228	260	<300	1500	70–600
Cd	0.1	0.1	<5	39	0.7–10
Pb	54.5	59.1	<100	300	70–1000
Ni	0.1	4.1	<50	420	20–200
Cr	18.3	39.3	<50	1200	70–200

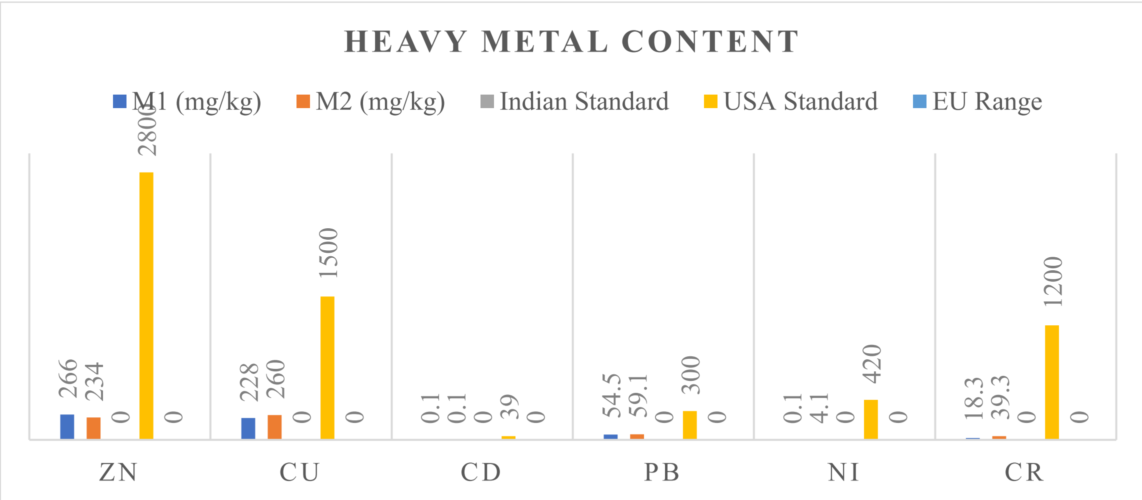

Figure 2 Graph showing heavy metal content of the samples compared to standard values

3. Fertilizing Index (FI) and Clean Index (CI)

Table 3 Fertilizing index calculation

Fertilizing Index Calculation		
Parameter	**Score (M1 & M2)**	**Weight (Wi)**
TOC	5	5
Total N	3	3
Total P	1	3
Total K	1	1
C:N Ratio	1	3
Respiration Activity	5	4

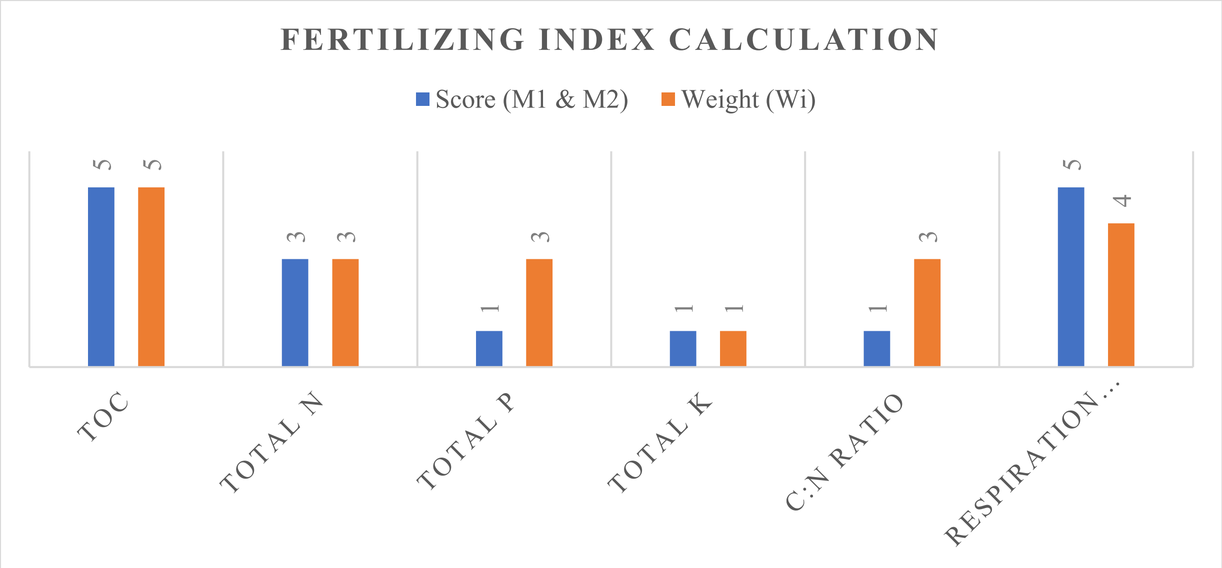

Figure 3 Graph showing fertilizer index calculation of both samples

Table 4 Clean Index Calculation

Clean Index Calculation		
Metal	**Score (Sj)**	**Weight (Wj)**
Zn	4	1
Cu	2	2
Cd	5	5
Pb	4	3
Ni	5	1
Cr	5	3

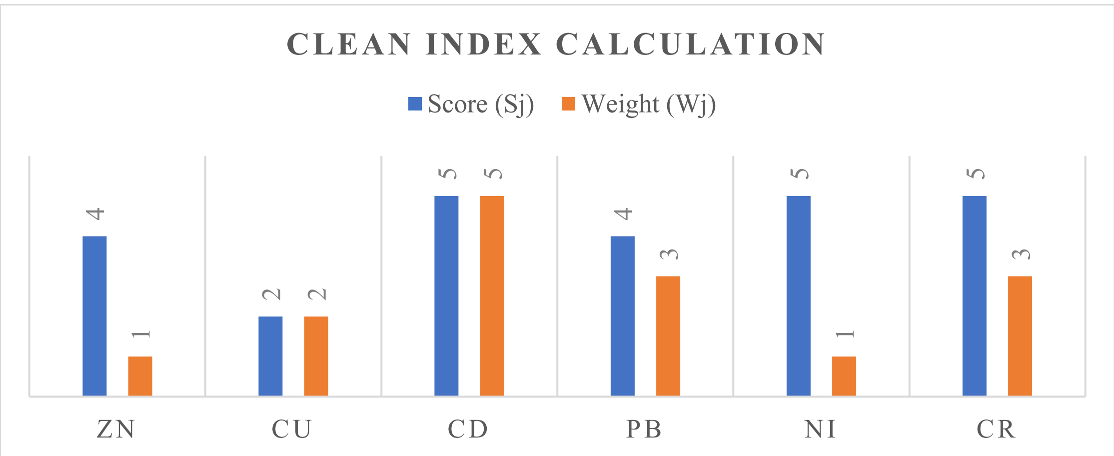

Figure 4 Graph showing Clean Index calculation of both samples

4. **Compost Classification and Marketability**

Based on the computed indices, the composts were classified according to the grading system provided by Saha et al. (2009):

Table 5 Results of both samples and their remarks

Sample	FI	CI	Class	Remarks
M1	3.21	4.32	B	Very Good Quality; suitable for marketing
M2	3.22	4.32	B	Very Good Quality; medium fertilizing value

Composts with Class B classification can be marketed for agricultural and horticultural use, contributing to a circular economy by converting waste to wealth.

5. **Comparative Perspective**

When comparing the three methods of composting:

- **Windrow Composting (WC)** – Simple but space and time-intensive. [14]
- **Vermicomposting (VC)** – High nutrient quality but requires controlled conditions. [17]
- **Inoculated Microbial Composting (IMC)** – Offers a balance between nutrient quality and heavy metal safety. [10]

IMC, when executed with acclimatized inoculums like BIOCULUM, stands out for its environmental safety (CI > 4.0) and good nutrient composition (FI > 3.0), making it a scalable and efficient solution for large urban centres.

6. **Policy Implications and Recommendations:**

1. **Standardization of Compost Quality:** Establishing universal benchmarks for FI and CI across India will ensure consistent product quality.[16]
2. **Training and Capacity Building:** Municipal staff and compost producers should be trained in microbial inoculation techniques to optimize compost yield and quality.
3. **Public-Private Partnerships (PPPs):** Encouraging collaboration between municipal corporations and private composting firms can enhance scalability.
4. **Integration with Agricultural Policies:** Promoting the use of high-quality compost in organic and sustainable farming can reduce dependence on chemical fertilizers.
5. **Awareness Campaigns:** Educating citizens on waste segregation and composting benefits is crucial for effective implementation.

6. Conclusion

Composting stands as a pillar of India's sustainable waste management strategy. This study underscores the superior performance of Inoculated Microbial Composting (IMC) in producing environmentally safe and agriculturally viable compost. With FI and CI as robust evaluative tools, compost quality can be effectively standardized and monitored. As India strides toward its goal of a cleaner, greener future, composting technologies, particularly IMC, offer a promising pathway to transform municipal waste into a valuable resource. [19]

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