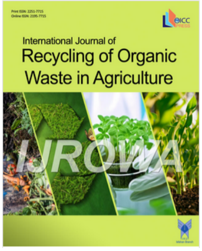

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Quality evaluation and characterization of organic compost suitable for agricultural utilization

Hari Naga Prasad Chenna*, Sandeep Kumar Chouksey

Department of Civil Engineering, National Institute of Technology, Raipur, Chhattisgarh, India.

*Corresponding author: hhariprasad31@gmail.com

Original Research

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Abstract:

Purpose: This study assessed the marketability and suitability of compost produced from municipal solid waste (MSW) in Raipur, Chhattisgarh, India.

Method: Atomic absorption spectroscopy (AAS) was used to assess the heavy metal analysis of the compost material, such as Zn, Cd, Cr, Ni, Cu, and Pb. X-ray Diffraction (XRD), Scanning Electron Microscope (SEM), and Energy Dispersive Spectroscopy (EDS) methods were used to estimate the compost's spectral properties. The study also aimed to evaluate the qualitative nature of the compost by using Fertilizer control order (FCO) standards.

Results: On the 60th day of sampling, the Raipur city compost sample had a Fertility Index (FI) of 3.6 and a Clean Index (CI) of 4.0, respectively. Compost is categorized as *class* C, which means it represents good quality, has a high potential for fertility, and has medium-heavy metals. From the comparison, the Delhi compost sample was unsuitable for its intended purpose. Ahmadabad and Bangalore compost samples were suitable for use as green compost. Due to their low fertilising potential, Solan region compost samples cannot be used as fertilizer. Mandi region produced high-quality compost samples with low concentrations of heavy metals and moderate potential for fertilizer.

Conclusions: Compost from Raipur MSW is a good choice for fertilizer because of its high potential for fertilization; heavy metal concentrations are moderate compared with FCO guidelines. The study finds that aerobic composting is a successful waste management technique that can lower the amount of organic waste dumped in landfills.

Keywords: Compost; X-ray diffraction; Scanning electron microscopy; Heavy metal; Fertility index; Clean index

1. Introduction

Municipal solid waste (MSW) is a significant source of pollution and presents environmental challenges globally (Sharholy et al., 2008; Mamo et al., 2021). The amount and variety of MSW have increased due to urbanization, rising per capita income, and population growth (Khandelwal et al., 2019). In 2016, more than 2.0 billion tons (BT) of solid waste were generated worldwide, with an average production rate of 0.74 kg per person per day, and it will increase to 3.8 BT by 2050 (Khandelwal et al., 2019; Mahapatra et al., 2022). As per the Central Pollution Control Board (CPCB, 2020-21) report, In India, 1,60,038.9 tons of solid waste is produced daily (TPD). 1,52,749.5 TPD of waste has been collected overall. 95.4% of the data was efficiently collected overall. Daily, 50% of the waste is processed, 18% is dumped in landfills, and 31.7% is unaccounted. Cities all over the world, including India, have seen substantial demographic growth as a result of the rising rate of migration from rural to urban areas. A significant portion of the Indian population has swiftly migrated from rural to urban areas in today's expanding economy due to rapid industrialization. MSW production in urban areas has significantly increased due to this movement (Sharma et al., 2018). The variation in the waste fraction is mainly influenced by the city's economic situation (Sarkar and Chourasia, 2017). The amount of MSW generated in India varies from 0.2 to 0.87 kg per person per day depending on whether the area is rural or urban, and it is anticipated that the rate in urban areas will rise even more (Kumar and Goel, 2009; Rana et al., 2018; Sharma et al., 2018). As reported by the (MoUD, 2016) collection efficiencies are less than 50% in tier-II and tier-III cities and range from 70% to 90% in metropolitan and tier-I cities. 90% of the waste is collected and disposed in an open dump in India (Hazra and Goel, 2009). Dumping waste is often considered the most cost-effective and efficient approach. Fig. 1 compares the MSW that should be dumped in a landfill and the MSW composting.

MSW open dumping results in emissions (gas and leachate) from landfills that may impact global warming (Tan et al., 2014; Pandyaswargo and Premakumara, 2014), and hence, it is essential to dispose of MSW properly (Kumar et al., 2009; Nash, 2009; Shekdar, 2009; Greene and Tonjes, 2014). MSW produced in India typically contains a large percentage of paper $(3-6\%)$, inert materials $(30-60\%)$, and biodegradables $(40-60\%)$, with additional materials like plastics and metals making up the remaining 1%. Properly managing landfill gas emissions from open dumps is essential (Rawat et al., 2013; Rana and Gupta, 2015; Joshi and Ahmed, 2016).

In this context, effectively managing generated MSW is vital for maintaining public health and provides a sustainable solution for resource recovery (MoUD, 2016). However, proper scientific waste disposal remains a significant concern in our rapidly growing world (Sudharmaidevi et al., 2017). In addition, the increasing rates of population growth, which impact the characteristics and production patterns of MSW in conjunction with the heightened levels of urbanization and industrialization in developing nations, underscore the imperative need for the implementation of efficient municipal solid waste management systems (Srivastava and Krishna, 2014).

Characterizing MSW is essential to determining the best waste management techniques for these studies. In this context, several studies have been conducted from an Indian perspective on various topics such as the characterization of solid waste, predictions of future solid waste generation based on population growth, current waste generation, collection and disposal methods, properties of leachate generated from solid waste, design of engineered landfill sites, and life cycle assessment studies (Sang et al., 2010; Rawat et al., 2013; Das and Bhattacharyya, 2014; Rana and Gupta, 2015; Rana et al., 2017).

Raipur is the largest city and capital of Chhattisgarh state. It is divided into eight zones. It generates 750 tons of MSW daily. Initially, 150 kgs of fresh waste sample was taken, and all types of composition were manually segregated. In segregation, the highest amount was noticed as organic matter at 44%, and the lowest was jute at 0.2%. The physical characterization of MSW, considering the current study region of Raipur city, is shown in Fig. 2. The results showed that biodegradable materials accounted for over half of Raipur city solid waste, with paper waste constituting the second-largest portion of the city's overall solid waste. Sharma et al. (2019) reported that the chemical characterization of MSW revealed that it has enough moisture and organic matter to be suitable for composting. A high organic waste content was found in the physical characterization of MSW in the study area of Raipur (Chhattisgarh). Therefore, composting is one of the best ways to process this waste and lessen the load on landfills.

Composting is a biological waste transformation process that entails the breakdown and stabilization of organic matter in the presence of oxygen. The end product is stable and pathogen-free, making it helpful in amending soil (Levis et al., 2010; Mhindu et al., 2013; Ywih et al., 2013; Pandey et al., 2016; Manohara and Belagali, 2017; Malakahmad et al., 2017; Ayilara et al., 2020). Composting also saves money on transportation, produces renewable energy, and preserves land by prolonging the life of landfills (Hoornweg et al., 1999; Larney et al., 2006; Mandal et al., 2014). Additionally, less landfill gases and leachates are produced when organic waste is composted rather than dumped in a landfill (Lou and Nair, 2009; Varma and Kalamdhad, 2014).

Manohara et al. (2017) reported that anaerobic composting occurs without oxygen, whereas aerobic composting uses oxygen under controlled conditions to break down residual materials biologically. Moreover, waste breaks down faster in aerobic composting than in anaerobic composting, which releases fewer offensive odours (Rawat et al., 2013). Maximizing recycling, optimizing resource recovery, and minimizing waste generation are all effective ways to improve the municipal solid waste management system (Mbuligwe et al., 2002). Composting organic MSW can be achieved through various methods, such as windrow composting, aerated static pile composting, and in-vessel composting techniques. The current study opted for windrow composting. The main advantages of windrow composting are its low equipment needs, low cost, and ability to handle large amounts of organic waste effectively. Moreover, compared to other techniques, it facilitates aerobic decomposition,

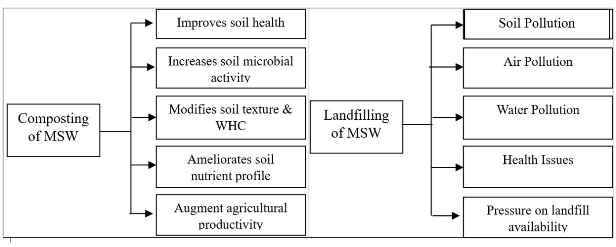

Figure 1. Comparison between the MSW landfill and the MSW composting.

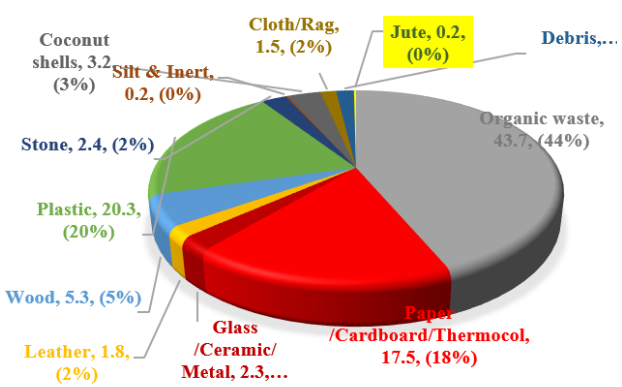

Figure 2. Composition of Raipur city municipal solid waste.

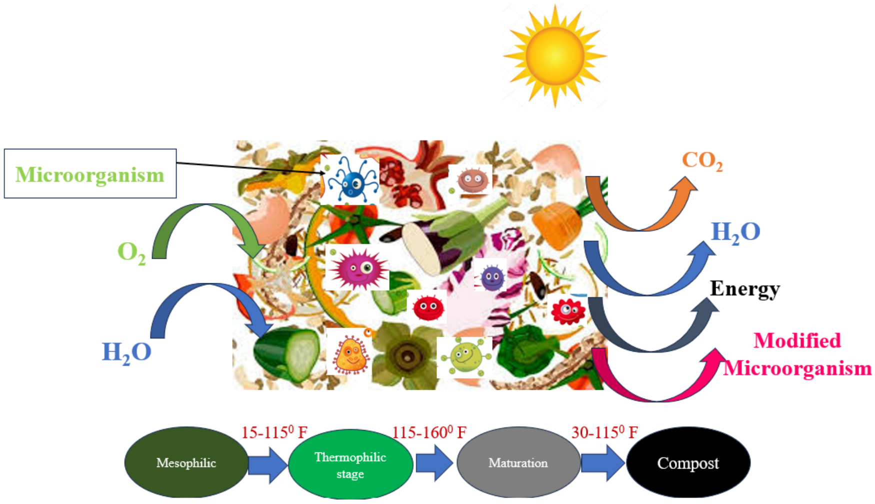

Figure 3. Composting process in its various stages.

speeding up composting and improving odour control.
The composting process can be separated into three distinct phases. Fig. 3 represents the different phases of the composting process. In the first step, dry bulking agents are mixed with organic matter to provide adequate space for microorganisms to help break down the organic material (Abdullah et al., 2013). Microorganisms with natural aeration break down organic matter into smaller particles in mesophilic conditions at moderate temperatures (15–115 °F). The degradation process accelerates in the thermophilic stage (115 – 160 °F) because these particles have a larger surface area, leading to more water-holding capacity (Samal and Dash, 2021). Regular particle mixing is necessary because low aeration rates prevent moisture from evaporating, slowing down the decomposition rate. Microorganisms assist in keeping the compost's porous structure, which further aids in distributing nutrients and water (Jouhara et al., 2017). Compost remains for a few days to approximately a month in this state. Excess water (known as leachate), which is highly rich in nutrients are produced during the process of composting (Frankenberger and Dick, 1983; Faverial and Sierra, 2014). Compost leachate is typically dark brown to yellowish-brown in colour. The concentrations of organic matter, nutrients, and contaminants are highest in the initial leachate, and they significantly decrease as more rain or runoff water percolates through the compost. Compost leachate's dissolved and particulate organic matter are vital sources of C, H, N, O, and P (Chatterjee et al., 2013). Nitrogen and organic matter are typically considered the two primary contaminants in composting leachate.
The maturation process occurs at an ambient temperature, and mesophilic microorganisms, such as fungi and bacteria, are important spectators (Makan et al., 2013). Microorganisms and larger creatures like macrofauna start to appear during this phase. They interact in a predatory and antagonistic manner. Heat release and weight loss are negligible, but significant antibiotics are synthesized (Voběrková et al., 2017; Azim et al., 2018). The compost material matures when: i) temperature is in the range of 30 – 115 °F after turning, ii) avoid anaerobic conditions during maturation, iii) after soil amendment, avoid adding nitrogen to the soil. At this point, some of the nitrogen from proteins are converted into humic acids, which makes it less vulnerable to microbial degradation (Romam et al., 2015). In this stage, the degree of maturation is more important. During this phase, maintain the composting parameters such as temperature, humidity, N, H, C, O, etc. Compost will not reach the maturation stage if these parameters are not properly maintained or monitored during the process. Fig. 4 represents the degree of maturity in various stages.

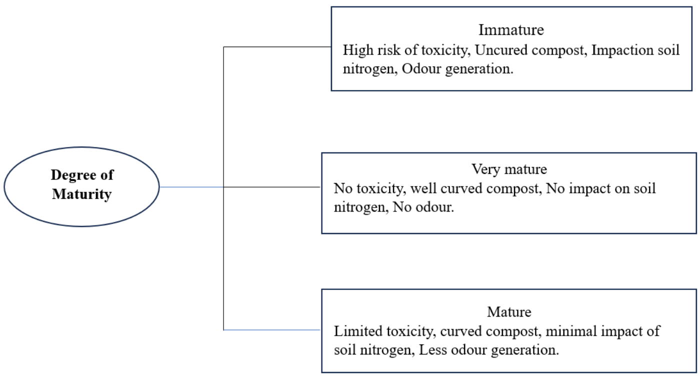

Figure 4. Degree of maturity in various stages.

MSW is a mixed waste. It should be segregated before being processed. Without segregation of waste often results in poor-quality compost that is not marketable, leading to financial losses. Poor-quality MSW compost can poses a significant health risk to humans due to its accumulation of heavy metals. These heavy metals can lead to a range of health complications, including blood-related issues, bone disorders, kidney damage, and neurological problems (Bruun et al., 2006). Because of this, it is essential to control the amount of compost applied in accordance with the concentrations of heavy metals found in compost samples. Saha et al. (2010) reported that different people opt for various types of composting methods and feedstocks, making compost of several grades. Additionally, the kind of composting facility, the process, and the duration of maturation all significantly impact the composition of compost (Hargreaves et al., 2008). In this context, the Indian government has given certain standards and grades for composting. The Indian government established the Fertilizer Control Order (FCO) standards in 1985. Moreover, the original FCO standards needed to be revised to evaluate the overall quality of compost. Saha et al. (2010) proposed a novel method for compost classification that depends on digital clean and fertility indices. This approach aims to maximize compost utilization, avoid soil pollution, and help end users choose the right uses for their compost. Fig. 5 represents the step-by-step procedure for the composting process.
Several nations in Europe, North America, and India have implemented particular regulations to control the sale of premium composts (Brinton, 2000; Mandal et al., 2014; Sharma et al., 2019). However, these quality control guidelines do not show any difference between various grades of marketable compost. This uneven composition of feedstock and the different composting methods make grading necessary. In order to grow high-value crops, food crops, non-food fiber/flowering crops, established lawns and gardens, and reclaim or rehabilitate degraded lands and mining areas, end users will find it easier to select suitable composts with this classification.
The current study aims to determine: 1) The compost's spectral and physicochemical properties in Raipur, Chhattisgarh, India. 2) To examine changes in structure and nutrient concentrations during the composting process. 3) The updated methodology was also used to determine the compost's "Fertility Index" and "Clean Index" to assess its potential use. 4) The compost's physicochemical characteristics and heavy metal concentrations were compared with other Indian cities, such as Bangalore (Karnataka), Delhi, Ahmedabad (Gujarat), Solan, and Mandi (Himachal Pradesh).

Study area

Raipur City lies at 21.25140 N, 81.62960 E and has a population of 16,05,232 as per 2011 senses. The Raipur municipal corporation is divided into eight zones and has 70 wards. Only 217 of the 211 vehicles planned to collect MSW are in use. They are stationed at the Gokul nagar and Daldal seoni parking lots. The waste was collected from door-to-door and transported to several transfer stations such as Tarun talab transfer station, Dharnasthal transfer station, Purena transfer station, Kalimata transfer station, and Narayana transfer station. After that, the waste was transferred to the

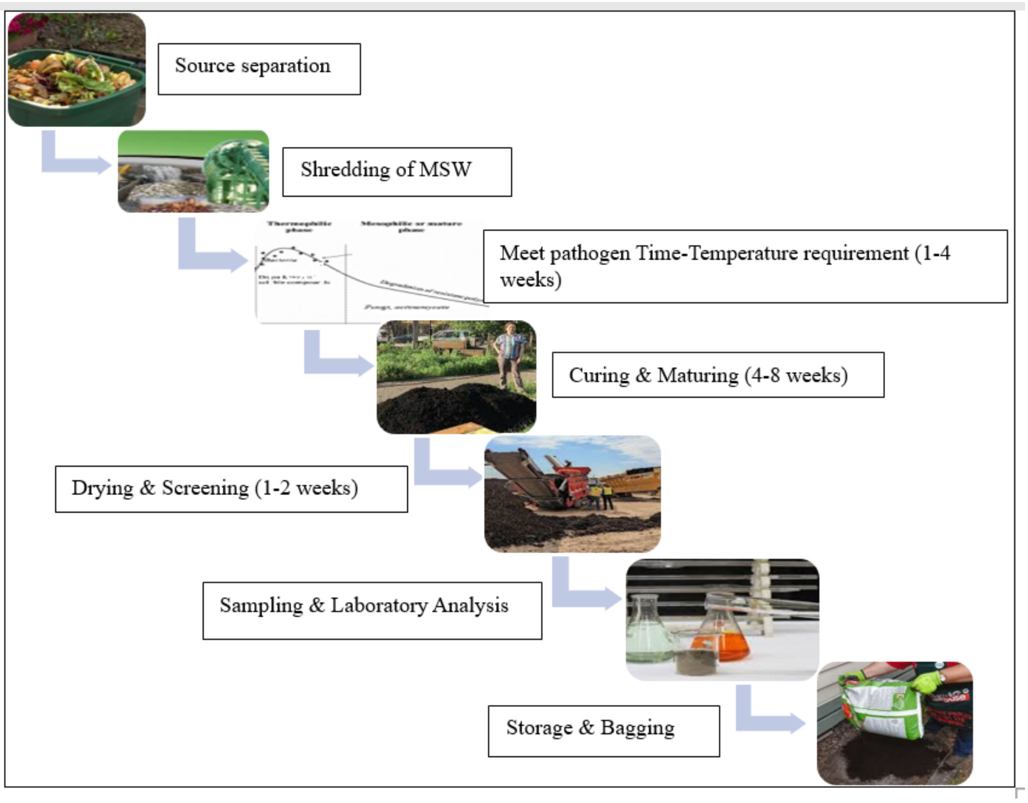

Figure 5. Step-by-step procedure for the composting process.

main station (Sankari village). The plant was operated by Delhi MSW Solutions Ltd. (DMSWSL), a subsidiary of Hyderabad-based Ramky Enviro Engineers Ltd. Fig. 6 represents the different transfer stations for segregating waste. Fig. 7 indicates the location of the composting plant in Sankari village, Raipur district, Chhattisgarh, India.

2. Materials and methods

Processing of MSW in Raipur City

Door-to-door waste was collected by Raipur Municipal Corporation (RMC) and then transferred to the primary and secondary transfer stations using RMC's assigned vehicles. Initially, they weigh the waste with a weighbridge and then shred it. After shredding the waste, they send it into the trommel. This trommel has two screens. These screens separate the waste into two fractions: <75 mm and >75 mm of organic material. <75 mm of the organic fraction is sent into the windrows (for aerobic decomposition). In this process, they are using the decomposer for degradation purposes. After 45 days, they again do the coarse segregation using a 25-mm sieve. 25 mm of material is sent into the curing $(7-10$ day) period for fine segregation, and >25 mm of material is sent into the RDF (Refuse Derived Fuel) for cement industries. After curing the material, send it through fine segregation with a particle size of 4 mm. Because >4 mm fine material is considered inert, it is disposed of in a landfill. <4 mm of fine material is considered compost and is therefore sold. >75 mm of organic fraction and place it

Figure 6. Different transfer stations in Raipur city. (a) Shukyaari Bazar, (b) Purena, (c) Haat Bazaar, (d) Devpuri, (e) Ram nagar, and (f) Khamtarai transfer stations in Raipur

Figure 7. Study area and compost samples collected from the Sankari village MSW processing plant, Raipur.

in the RDF. Based on that, waste, compost, and RDF will be produced daily in Raipur city. The remaining material is being sent to the landfill. Fig. 8 represents the processing of waste can be easily understood as a step-by-step process.

Method for composting at the study location

Compost generation in the study area of Raipur city, Chhattisgarh, usually uses the aerobic windrow composting method, in which organic waste is piled in long rows. Typically, the heaps are kept between $1-3$ m in height and $4-5$ m wide (Mazumdar, 2007). However, compared to standard conditions, the compost heaps in the study area were smaller, primarily due to the minimum amount of waste generated. However, to improve aeration, proper mixing, and remove excess moisture in the study locations, the windrows are usually turned by hand following a 20 days stabilization period. After $5-7$ days of curing, the stabilized material is screened. Finally, it is left for another two weeks to cure. Small bits of paper, plastic, and other leftover materials are removed from the cured compost by sifting after composting. Handling mixed waste is one major drawback of the current composting process; segregation happens after compost is generated, whereas the ideal order is for segregation to come before compost production. Fig. 9 represents the final compost (60^{th} day) sample from Raipur city, Chhattisgarh state, India.

Different composting methods under practice

Composting is a sustainable method of getting free of organic waste and is an essential part of waste management and soil enrichment. Several composting techniques have been developed, each with unique qualities and uses. Compostable materials are layered, and water is added to start the microbial breakdown process in the heat process of composting. Karikari (2010), stated that it quickly raises the temperature to $60-70$ °C in 96 hours, which speeds up the decomposition process. Furthermore, adding earthworms improves microbial activity, which produces high-quality compost (Barthod et al., 2018). Unfortunately, this method is labour-intensive and complex, requiring careful layering and manual labour. The process of windrow composting involves placing materials in long, narrow piles that need to be turned regularly to guarantee adequate aeration. This process is commended for producing high-quality compost

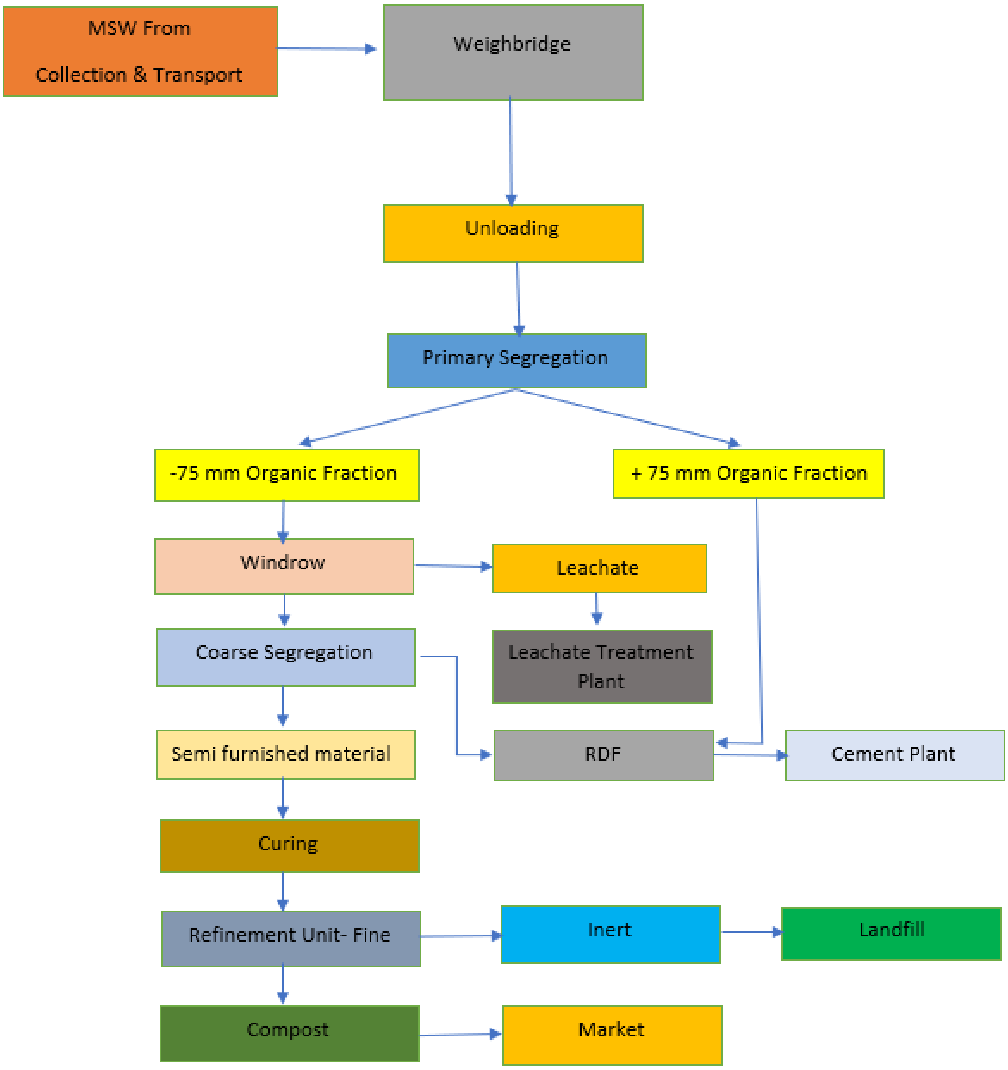

Figure 8. Flow chart for processing the waste in a step-by-step procedure.

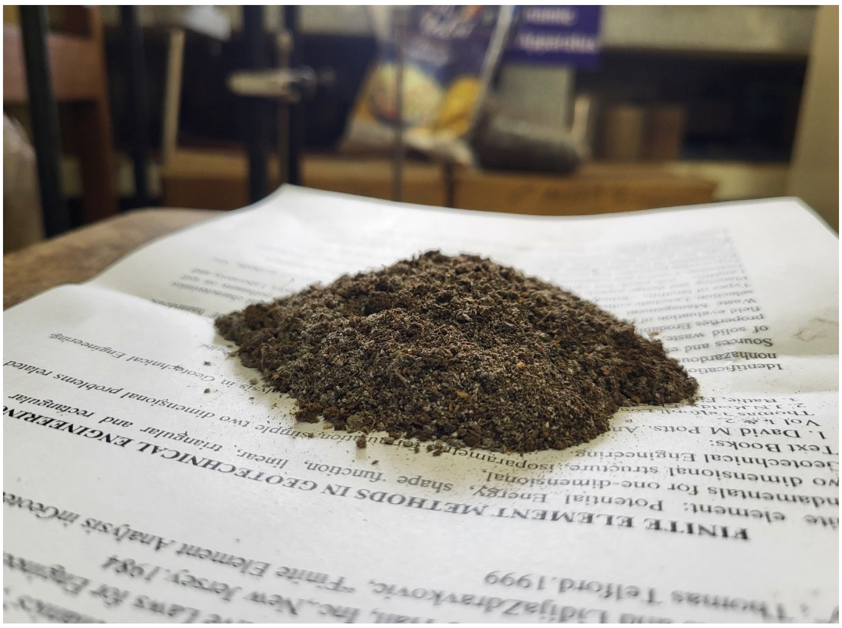

Figure 9. Final MSW compost sample.

with little work, cheap running costs, a slight smell, and ease of turning. Nevertheless, poor turning techniques can result in problems with land requirements and odour. Vermicomposting effectively produces nutrient-rich compost using worms to break down organic waste (Barthod et al., 2018). It increases microbial activity and soil aeration but also presents problems with weed growth, leachate management, and worm health. Vermicomposting, on the other hand, provides environment-friendly waste management when done correctly. In-vessel composting uses closed containers to regulate moisture and temperature, speeding up decomposition (Ahmed et al., 2007). Leachate generation and odour are reduced, but maintenance costs are very high. Furthermore, it is not very applicable in cold climates. Composting on a small scale can be achieved by using a rotation tube and sheet composting, which involves turning compostable materials to provide air. It is simple and inexpensive, but it takes work and time. The technique of Indian Indore composting was created in Indore, India, and entails layering organic materials with irregular moistening of the heap (Karikari, 2010). Although effective, it takes a lot of time and work and could result in insect and pest breeding grounds. Composting in large windrows requires turning piles regularly to promote decomposition (Misra et al., 2003). Although it yields excellent compost, it is labour-intensive and may produce leachate and odour.

Sampling and analysis procedure

Samples were collected on the 65th day of composting in accordance with the USEPA Part 503 Rule (USEPA 1995). The temperature (°C) of the compost samples was noted after they were taken from the study area's composting heaps. Initially, the moisture content of the compost sample was calculated. The gravimetric method was used to determine this by drying the samples in an oven at 70 °C and measuring the resulting weight loss (Saha et al., 2010; Mandal et al., 2014). pH and electrical conductivity were measured using a pH and electrical conductivity meter. TOC was determined by using a TOC analyzer. As per IS code procedures, calculate the compost sample's pH, EC, and TOC. The heavy metals (Lead, zinc, chromium, cadmium, copper, and nickel) were calculated through Atomic Absorption Spectroscopy (AAS). Sodium was estimated using flame photometry (Manohara et al., 2017). Calcium and magnesium were measured using the titration method. As described in (ASTM, 2003) Three grams of the sample were digested with 25 milliliters of triacid (a mixture of nitric acid, sulfuric acid, and perchloric acid in a 9:2:1 ratio) at 120 °C in a digester fitted with a microprocessor controller.

SEM-EDX analysis procedure for compost

Analytical methods for examining different material microstructural and elemental compositions have been enhanced by combining Energy-Dispersive X-ray Spectroscopy and Scanning Electron Microscopy (SEM-EDX). When describing the physical and chemical characteristics of compost samples, SEM-EDX analysis is an essential tool in the field. Because of its nutrient-rich makeup and ability to condition soil, compost, a byproduct of the decomposition of organic waste, is frequently used as a soil amendment in farming operations. To evaluate compost quality and optimize its use in agriculture, one must thoroughly understand its microstructure and elemental composition.

SEM-EDX analysis offers several benefits when examining compost samples. First, SEM offers high-resolution imaging resolution that enables researchers to see the structure and surface morphology of compost particles at a minuscule size. This makes it possible to identify essential characteristics like porosity, shape, size, and the presence of organic and inorganic constituents. The current study examined the structural changes of compost samples at different phases of MSW degradation in Raipur city using (SEM-EDX). The 200 mg MSW compost sample was oven-dried and then heated for 35 minutes at 550 °C. The material was then finely crushed, and a tiny amount was placed on double-sided carbon tape so that the FEG Quanta instrument could analyze it. This process made it possible to see the morphology of the compost material. The samples were evaluated for fifteen minutes at a wavelength of 0.01 Nm, using the methodology outlined by (Sharma et al., 2019).

XRD analysis procedure for compost

Analyzing the atomic and molecular structure of crystalline compounds requires the use of X-ray diffraction. A three-dimensional diagram of the electron density inside the crystal is created by measuring the angles and intensities of diffracted beams, which aids in identifying the locations of atoms and chemical bonds (Manohara et al., 2017). The compost samples used in this investigation were ground into a fine powder and examined with a Philips X-ray diffractometer. For 20 minutes, the 200 mg samples were subjected to a wavelength of 1.54 Nm. The gonio scan axis used a copper anode, fixed divergence slit type, K alpha at 1.54, spinning and maintaining a temperature of 25 °C with a specimen length of 10 mm. The goniometer radius was 240 mm.

Atomic absorption spectroscopy (AAS) procedure for compost

Atomic absorption spectroscopy (AAS) was used to analyze the heavy metals. An acetylene flame was used as the fuel for higher concentrations, and argon was used as the carrier gas for electrothermal atomization in a graphite furnace to analyze lower concentrations (Mandal et al., 2014).

Compost quality Indices

The quality of the compost samples of the current study is characterized by the Fertility Index (FI) and Clean Index (CI). Saha et al. (2010) and Mandal et al. (2014) explain how to calculate the weighing factor. In summary, the weighing factor for each parameter is assigned based on a five-point scale $(1-5)$, considering its importance in enhancing soil productivity (Saha et al., 2010). The compost samples fertility index (FI) values are then calculated using equation (1).

$$\text{FI} = \frac{\sum_{n}^{i=1} S_i W_i}{\sum_{n}^{i=1} W_i} \qquad (1)$$

where W_i is the analytical data weighing factor for the ith fertility parameter, and S_i is the score value.
Additionally, based on the degree of toxicity of different parameters, the weighing factor varies from 1 to 5. Saha et al. (2010) gave the formula for determining compost's clean index (CI) values. A higher CI value indicated less heavy metal contamination and vice versa (Mandal et al., 2014). The following equation (2) is used to calculate the CI value:

$$\text{CI} = \frac{\sum_{n}^{j=1} S_j W_j}{\sum_{n}^{j=1} W_j} \qquad (2)$$

where W_j is the weighing factor for the jth heavy metal parameter in the analytical data, and S_j is the score value.

3. Results and discussion

Compost must be evaluated for quality, maturity, and nutrient content to determine its suitability for various applications (Mandal et al., 2014). The number of compost samples was tested in the laboratory. The tables summarise the primary elements used to assess compost quality. The compost was dark brown in colour and was noticed to have a foul smell (NEERI, 2009). In contrast to an FCO value of at least 90%, the sample particle size was less than 4 mm. Table 1 represents the Physico-chemical characterization of compost in Raipur city.

pH

Based on the experimental results, the average pH of the compost samples was 6.86 ± 0.22, which is in neutral condition. Initially, it is alkaline in nature; during the process, it can be changed to a neutral condition. Previous research has observed that the compost produced by the Okhla compost plant (Delhi) from MSW has pH values ranging from neutral to alkaline (Mandal et al., 2014). Because of its alkalinity, the compost may not have reached the appropriate nutrient levels or reached full maturity for fertilizer use. Moreover, ammonium gas emissions into the atmosphere due to alkaline pH levels can potentially promote the growth of dangerous pathogenic bacteria (Omrani et al., 2004; Mandal et al., 2014). Compost samples from the Himachal Pradesh regions of Solan and Mandi change pH throughout degradation. The pH ranged in Solan from 7.84 on the 20th day to 7.08 on the 60th and in Mandi from 8.24 to 7.48 during the same period. Especially during degradation, both regions displayed a shift in pH ranges from alkaline to neutral, indicating the decomposition of organic matter (Sharma et al., 2019). Table 2 represents the pH ranges in the composting process in different Indian cities.

Temperature

Based on the experimental results, the compost samples consistently had a temperature of 55 ± 2.67 °C. These temperature fluctuations most likely originate from the exothermic process set by the microbial breakdown of organic matter (Mandal et al., 2014). It was also noted that the degradation of organic waste recorded by various researchers varies depending on various factors such as composition, humidity, temperature, and environmental conditions. Table 3 indicates the variation in the temperature of compost from different cities in India.

Table 1. Physico-chemical characterization of compost in Raipur city.

S. NO	Parameters	Range	Average	FCO standards
1	pH	6.86 – 7.82	7.34 ± 0.48	6.5 – 7.5
2	Moisture content (%)	31.00 – 34.17	32.58 ± 1.5	15 – 25
3	Electrical conductivity (dS/m)	5.02 – 5.89	5.45 ± 0.43	< 4
4	Temperature (°C)	55 – 61	58 ± 3	-
5	Total Organic Carbon (%)	13.36 – 17.86	16.11 ± 1.75	16 (min)
6	Total Nitrogen (mg/kg)	0.65 – 0.88	0.76 ± 0.11	0.5 (min)
7	Total Phosphorous (mg/kg)	0.89 – 2.56	1.72 ± 0.83	0.5 (min)
8	Total Potassium (mg/kg)	4.56 – 8.36	6.46 ± 1.9	1 (min)
9	Calcium (mg/L)	9.63 – 13.46	11.54 ± 1.91	-
10	Magnesium (mg/L)	5.20 – 8.16	6.68 ± 1.48	-
11	C/N ratio (%)	19.25 – 20.55	19.9 ± 0.65	20 (max)

Table 2. pH ranges in the composting process in different Indian cities.

S.NO	Plant Name	pH value	Reference
1	Ahmadabad	8.06 (±0.37)	
2	Bangalore	8.19 (±0.29)	Rawat et al. (2013)
3	Delhi	7.82 (±0.42)	
4	Okhla (Delhi)	8.4 – 8.5	Mandal et al. (2014)
5	Mysore city	7.20	Manohara et al. (2017)
6	Solan (Himachal Pradesh)	7.08 – 7.84	Sharma et al. (2019)
7	Mandi (Himachal Pradesh)	7.48 – 8.24	Sharma et al. (2019)
8	Raipur city	6.86 – 7.82	Current study

Table 3. Temperature ranges in the composting process in different Indian cities.

S.NO	Plant Name	Temperature (°C)	Reference
1	Okhla (Delhi)	-	(Mandal et al., 2014)
2	Mysore city	43	(Manohara et al., 2017)
3	Solan (Himachal Pradesh)	54 – 60	(Sharma et al., 2019)
4	Mandi (Himachal Pradesh)	59 – 64	(Sharma et al., 2019)
5	Raipur city	55 – 61	Current study

Electrical conductivity (EC)

Manohara and Belagali (2017) highlighted the significance of electrical conductivity (EC) in assessing soil or compost chemical characteristics and nutrient period. The value of EC was observed to be 5.45 ± 0.43 dS/m for the compost period. As per the FCO standards, the EC range was $<$ 4.0. In the current study, the EC value slightly exceeded the FCO standards because when the organic matter is broken down by microbial activity during the composting process, soluble salts are released, which raises conductivity levels. Inadequate moisture management can make this deficient by allowing salts in the composting materials to dissolve and become more mobilized, which increases electrical conductivity readings. Mandal et al. (2014) reported that the EC ranges were within the prescribed range, whereas the remaining cities reported slightly higher values. Table 4 indicates the Electrical conductivity ranges in the composting process in different Indian cities.

Moisture content

Based on the experimental results, the average moisture content of the sample was $32.58 \pm 1.5\%$ on the 60th day of degradation, which slightly exceeded the permissible limit. As per the FCO standards, the optimum range was $15 - 25\%$. High moisture represents several potential causes for increased moisture content when composting outside, such as poor mixing, insufficient aeration, or heavy rainfall. Also, too-moist compost tends to lump together because less air pockets are available. This lumping effect may raise storage and transportation costs because of the increased weight and decreased bulk density. Table 5 represents moisture content ranges in the composting process for different cities. Mandal et al. (2014) reported that the Okhla, Delhi compost plant shows the moisture content (%) range was within the permissible limit, and the remaining cities show the moisture content range was within the permissible limit, whereas other cities showed slightly higher values.

When calculating compost quality as a fertilizer, the presence and concentrations of important macronutrients like potassium, phosphorus, and nitrogen (N-P-K) are important parameters (Manohara et al., 2017). As per FCO standards, the nitrogen and phosphorus content ranges were 0.50 (minimum), and the potassium content range was 1.0 (minimum). In the current study, the concentration of (N-P-K) was found to be 0.76 ± 0.11 mg/kg, 1.72 ± 0.83 mg/kg, and 6.46 ± 1.9 mg/kg on the 60th day of the composting process, which

Table 4. Electrical conductivity ranges in the composting process in different Indian cities.

S.NO	Plant Name	EC ranges (dS/m)	Reference
1	Ahmadabad	0.71 (±0.07)	
2	Bangalore	0.58 (±0.11)	(Rawat et al., 2013)
3	Delhi	0.83 (±0.078)	
4	Okhla (Delhi)	0.32 – 0.43	(Mandal et al., 2014)
5	Mysore city	7.6	(Manohara et al., 2017)
6	Solan (Himachal Pradesh)	5.8 – 6.7	(Sharma et al., 2019)
7	Mandi (Himachal Pradesh)	5.23 – 6.0	(Sharma et al., 2019)
8	Raipur city	5.45 ± 0.43	Current study

Table 5. Moisture content (%) ranges in the composting process in different Indian cities.

S.NO	Plant Name	Moisture content (%)	Reference
1	Ahmadabad	29.32 (±5.00)	
2	Bangalore	31.61 (±7.02)	(Rawat et al., 2013)
3	Delhi	23.83 (±5.07)	
4	Okhla (Delhi)	19.3 ± 1.4	(Mandal et al., 2014)
5	Mysore city	53 ± 2	(Manohara et al., 2017)
6	Solan (Himachal Pradesh)	33 – 45	(Sharma et al., 2019)
7	Mandi (Himachal Pradesh)	31 – 42	(Sharma et al., 2019)
8	Raipur city	32.58 ± 1.5	Current study

satisfies the FCO guidelines. The study observed that the potassium range in the Mandi region had slightly lower values than the FCO standards. Joshi and Ahmed (2016) reported that the ranges of Indian waste had a nitrogen content of $0.64 \pm 0.8\%$, phosphorus of $0.67 \pm 0.15\%$, potassium of $0.68 \pm 0.15\%$, and carbon-to-nitrogen (C/N) ratio of $26 \pm 5\%$. Based on the experimental results, the average value of the C/N ratio is $19.9 \pm 0.65\%$. The C/N ratio was similar to the FCO standards. As per the FCO standards, the range was 20 (maximum). Table 6 represents the C/N ratio ranges in the composting process in different Indian cities.

The total organic carbon (TOC) was $16.11 \pm 1.75\%$ in the 60^{th} day of the composting process. As per the FCO standards, the TOC range was 16 (minimum). In the current study, the TOC value is within the permissible range. Table 7 represents the TOC ranges in the composting process in different Indian cities.

In the study of the Mandi region, the TOC ranges slightly decreased from FCO standards. There was a decrease in parameters like total organic carbon and magnesium during the 60^{th} day of composting. Methane and carbon dioxide emissions were the cause of this decrease. On the other hand, calcium levels kept rising during the degradation process, which is advantageous for compost production. Concentrations of calcium and magnesium are important because they affect microbial activity and compost quality during the composting process. These components are essential nutrients for the microorganisms in compost to break down organic matter (Manohara et al., 2017). Cultivating microbial activity and growth in an ideal environment accelerates decomposition and produces stable compost. In the current study, the calcium content was observed at 11.54 ± 1.91 mg/L on the 60^{th} day of the composting process. The magnesium content was observed at 6.68 ± 1.48 mg/L on the 60^{th} day of the composting process. Sharma et al. (2019) reported that the maturation stage concentrations of calcium and magnesium in the Solan and Mandi regions were $12.08 - 16.24$ mg/L, $15.24 - 17.89$ mg/L and $9.72 - 5.59$ mg/L and $10.02 - 7.24$ mg/L. Manohara et al. (2017) reported that the maturation stage concentrations of calcium and magnesium in Mysore city compost pits were 18.02 mg/L and 6.79 mg/L, respectively.

Heavy metal analysis

The concentration of heavy metals greatly impacts the composting process, which also affects compost quality and environmental safety. The average concentration of some selected heavy metals in compost, such as Zn, Cd, Cr, Ni, Cu, and Pb, were 4.04 ± 0.81 mg/kg, 1.33 ± 0.23 mg/kg, 0.42 ± 0.24 mg/kg, 4.02 ± 0.16 mg/kg, 1.94 ± 0.92 mg/kg, and 2.48 ± 0.47 mg/kg, respectively observed in the current study. Table 8 represents the concentration of heavy metals in compost samples in Raipur city and the permissible limit given by FCO. Fig. 10 represents the heavy metal concentration present in the compost of different Indian cities. The current study results are similar to the Mandi (Himachal Pradesh) results. Delhi compost samples have a high heavy metal concentration, which is unsuitable for agriculture (Mandal et al., 2014).

Fertility index and Clean index

The Fertility index (FI) and Clean index (CI) are calculated by using the criteria for weighing factors to fertility parameters and score value to compost (Saha et al., 2010). Based on the above results, the compost FI range was 3.6, and

Table 6. C/N ratio ranges in the composting process in different Indian cities.

S.NO	Plant Name	C/N Ratio (%)	Reference
1	Ahmadabad	25.36	
2	Bangalore	23.55	(Rawat et al., 2013)
3	Delhi	18.99	
4	Okhla Composting plant	9.46 ± 0.91	(Mandal et al., 2014)
5	Mysore city	12.09	(Manohara et al., 2017)
6	Solan (Himachal Pradesh)	16.25	(Sharma et al., 2019)
7	Mandi (Himachal Pradesh)	14.93	(Sharma et al., 2019)
8	Raipur city	19.9 ± 0.65	Current study

Table 7. TOC ranges in the composting process in different Indian cities.

S.NO	Plant Name	TOC (%)	Reference
1	Ahmadabad	21.56 ($\pm$4.04)	
2	Bangalore	26.61 ($\pm$5.18)	(Rawat et al., 2013)
3	Delhi	19.56 ($\pm$6.68)	
4	Okhla compost plant (Delhi)	16.13 ± 0.69	(Mandal et al., 2014)
5	Mysore city	12.09	(Mandal et al., 2014)
6	Solan (Himachal Pradesh)	14.93 ($\pm$2.47)	(Sharma et al., 2019)
7	Mandi (Himachal Pradesh)	16.25 ($\pm$2.03)	(Sharma et al., 2019)
8	Raipur city	16.11 ± 1.75	Current study

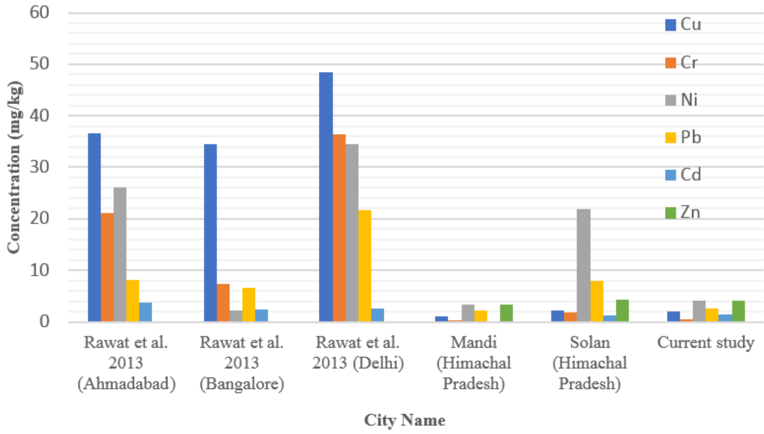

Figure 10. Heavy metal concentrations of different Indian cities.

Table 8. Heavy metal analysis in the composting process in Raipur city.

S.NO	Parameters	Range	Average	FCO standards
1	Zinc (Zn) (mg/kg)	3.23 – 4.86	4.04 ± 0.81	1000
2	Cadmium (Cd) (mg/kg)	1.10 – 1.56	1.33 ± 0.23	5
3	Chromium (Cr) (mg/kg)	0.18 – 0.67	0.42 ± 0.24	50
4	Nickel (Ni) (mg/kg)	3.86 – 4.18	4.02 ± 0.16	50
5	Copper (Cu) (mg/kg)	1.02 – 2.86	1.94 ± 0.92	300
6	Lead (Pb) (mg/kg)	2.02 – 2.96	2.48 ± 0.47	100

the CI range was 4.0. Saha et al. (2010) reported the classification of MSW compost for its marketability and use in different areas. Table 9 presents the categorization of MSW compost based on its marketability and application in different places. It was noted that the Raipur city MSW compost falls in *class C* on the 60th day of the composting process. This type of compost has high fertilizing potential and medium-heavy metal content. Mandal et al. (2014) re-

Table 9. Categorization of MSW compost based on its marketability and application in different areas (Saha et al., 2010; Mandal et al., 2014; Sharma et al., 2019).

S. NO	Class	FI	CI	Quality control compliance	Remarks
1	A	> 3.5	> 4.0	Complying for heavy parameters	Best quality, low-heavy metal, used for high-value crops
2	B	3.1 – 3.5	> 4.0	Complying for heavy parameters	Very good quality, medium fertilizing potential, low heavy metal
3	C	> 3.5	3.1 – 4.0	Complying for heavy parameters	Good quality, high fertilizing potential, medium heavy metal
4	D	3.1 – 3.5	3.1 – 4.0	Complying for heavy parameters	Medium quality, medium fertilizing potential, medium heavy metals
5	RU-1	< 3.1	-	Complying for heavy parameters	Low fertilizing potential; should not be allowed to market, only used as a soil conditioner
6	RU-2	> 3.5	> 4.0	Not Complying for heavy parameters	Restricted use; should not be allowed to market, used only for growing non-food crops
7	RU-3	> 3.5	-	Not Complying for heavy parameters	Restricted use; should not be allowed to market, used only for growing lawns/gardens

ported that the Okhla compost plant (Delhi) demonstrated that the compost samples were categorized as *Restricted Use* (RU-3) because of high levels of heavy metals, making them low-quality. The Solan region is considered medium quality *Class D*, with moderate fertilization and pollution potential, making it appropriate for compost production for livestock and non-food crop cultivation. However, compost from the Mandi region is categorized as *Class A*, because it has a very high potential for fertilization and a low concentration of heavy metals, which makes it ideal for growing food crops (Sharma et al., 2019). Fig. 11 represents the FI and CI values for different compost samples in India.

SEM-EDX of compost material

The presence of toxic and non-biodegradable materials during compost pile processing creates high temperatures and pressures that impede worm growth and activity. The micrographs obtained through scanning electron microscopy (SEM) in this study show the physical changes that happen on the 60th day of the microbial degradation of MSW compost. Larger solid materials with smaller surface voids were present during the 60th day of composting, according to an analysis of the SEM-EDX images. The progressive reduction of particle size during the degradation process led to the eventual development of smaller solid particles with increased surface voids, which is a sign of mature compost. This transformational pattern was held for the duration of the study. Fig. 12 indicates that due to the degradation process, the larger particles split into the smaller particles.
MSW contains 40 – 60% organic matter, which makes up composting. As the 40 – 60% organic matter decomposes, it undergoes aerobic degradation. In comparison to other elements, there is comparatively more carbon and oxygen present in this process. After the compost sample was analyzed using EDX, Fourteen natural elements were found to be present: Chlorine (Cl), Aluminium (Al), Iron (Fe), Silicon (Si), Nitrogen (N), Titanium (Ti), Phosphorus (P), Calcium (Ca), Magnesium (Mg), Potassium (K), Oxygen (O), Sodium (Na), Sulfur (S), and Carbon (C) is shown in Table 10. Fig. 12 represents the SEM images of compost sample structure in different degradation rates.

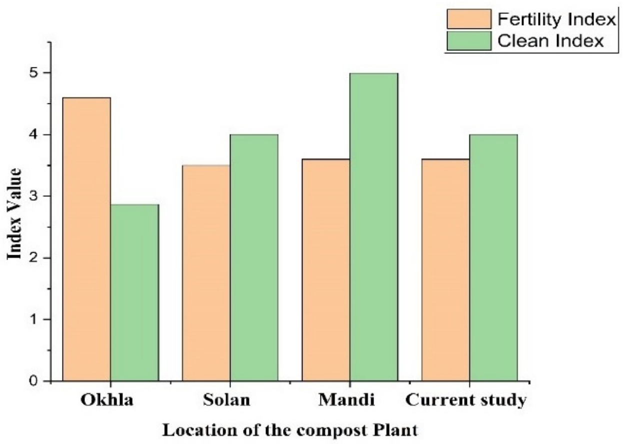

Figure 11. FI and CI values for different compost samples in India.

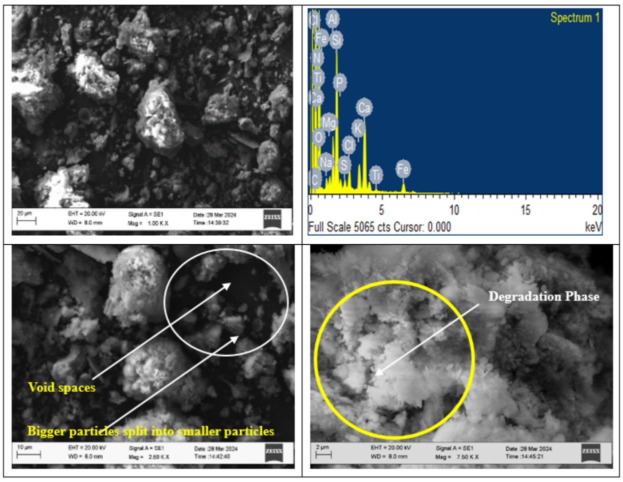

Figure 12. Compost sample structure in different degradation rates.

Table 10. Various elements present in the compost sample using EDX analysis.

S. NO	Element	Weight (%)	Atomic (%)	Net intensity
1	Carbon (C)	8.97	13.88	4.91
2	Nitrogen (N)	0.70	0.93	0.23
3	Oxygen (O)	56.94	66.16	9.22
4	Sodium (Na)	1.30	1.05	0.25
5	Magnesium (Mg)	0.93	0.71	0.22
6	Aluminium (Al)	3.55	2.44	1.11
7	Silicon (Si)	10.58	7.00	3.58
8	Phosphorus (P)	0.78	0.47	0.31
9	Sulfur (S)	0.78	0.45	0.33
10	Chlorine (Cl)	1.72	0.90	0.82
11	Potassium (K)	2.59	1.23	1.36
12	Calcium (Ca)	7.86	3.65	4.21
13	Titanium (Ti)	0.36	0.14	0.22
14	Iron (Fe)	2.95	0.98	1.97

Compared to the other elements, oxygen was determined to be a relatively higher concentration (66.16%). The carbon fraction was determined to be (13.88%) in samples taken on the 60th day of the composting process when analyzed through EDX, whereas the total organic carbon (TOC) content was found to be 16.11% by the TOC analyzer. In this case, the organic carbon fraction accounts for most of the total carbon percentage in the compost samples made from MSW.

XRD analysis of compost material

Compost samples taken in Raipur city on the 60th day of decomposition were subjected to XRD analysis, which sheds light on the structural alterations during composting. The XRD is crucial in helping a compound crystal structure. The composting pile XRD spectra in this study show clear peaks at both time points, and as time passes, the number of peaks decreases, signifying compost maturation (Mbuligwe et al., 2002). The prominent peaks in the XRD spectra indicate significant compounds, as shown in Table 11. Fig. 13 shows an X-ray diffraction image of the compost sample on the 60th day of maturation.

The compost also contains minerals like quartz, calcite, and dolomite. The presence of minerals was attributed to the disposal of mixed waste at the dumping site. The presence of inert materials such as sand, gravel, eggshells, and green waste was identified as the cause of the minerals found in the MSW compost samples (Sharma et al., 2019). Silica-accumulating plants such as grass and rice can be the source of silicon dioxide (SiO_2). During the composting, soil particles are mixed with compost. As a result, silica content is increased. The decomposition of organic matter can increase the compost's porosity, releasing silicon dioxide and improving air circulation. Conditions with sufficient oxygen support the growth of aerobic microorganisms, which are necessary for effective decomposition. By preventing the formation of anaerobic zones, improved aeration lowers the possibility of unpleasant odours and incomplete decomposition. Aerobic microbes are necessary for breaking down organic matter into simpler compounds, and their growth is encouraged by SiO_2 improved aeration. This produces more stable, nutrient-rich compost and speeds up the composting process. SiO_2 keeps enough water for microbial activity while letting extra water drain, which helps the compost's moisture levels balance. This keeps the area from becoming too wet and fosters the growth of microorganisms. Plant cell walls are strengthened by silicon, which increases their resistance to pests and diseases. This encourages healthier plant growth by lowering the frequency of illnesses and pest attacks.

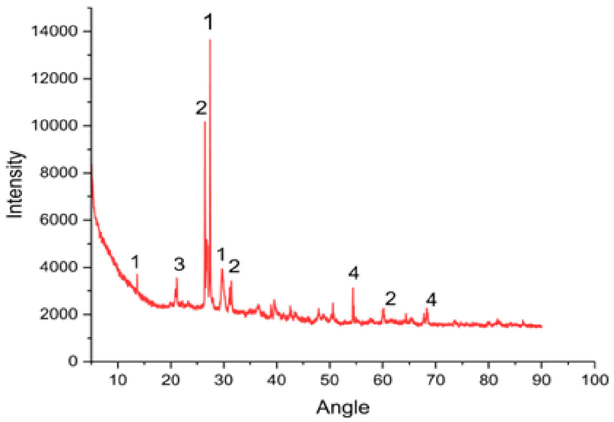

Figure 13. X-ray diffraction image of the compost sample on the 60th day of maturation.

Calcium carbonate ($CaCO_3$) is naturally present in compost of organic matter (shells, bones, and some plant materials) containing calcium. The organic matter produces organic acids, which can lower the pH of the compost. Calcium carbonate reacts with these acids, neutralizing them and maintaining a stable pH.

$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^-$

When these calcium ions neutralize acids, the calcium ions (Ca^{2+}) are released into the compost. After that, the plant can absorb these ions, which are essential for the plant processes, including the stability and information contained in cell walls. The pH $(6-8)$ is more favourable for microbial activity when it is stable, which $CaCO_3$ maintains. Microbes are essential to the decomposition process to break down organic matter and increase the fertility of the compost overall and the cycling of nutrients.

Dolomite ($CaMg(CO_3)_2$) is a multifaceted material that is very helpful in composting processes and improving soil fertility. By releasing calcium carbonate ($CaCO_3$), dolomite regulates pH during the composting process. In order to maintain a stable pH environment favourable to microbial activity and nutrient availability, this compound neutralizes organic acids produced during the breakdown of organic matter. Dolomite releases the ions calcium (Ca^{2+}) and magnesium (Mg^{2+}) into the compost at the same time. The formation of chlorophyll (green colouring matter of plants) and photosynthesis depend on magnesium, while calcium maintains cell structure and is crucial for plant growth. The compost's microbial activity is increased by the dolomite's calcium and magnesium content. These nutrients are essential for microbial metabolism because they support various

Table 11. Significant compounds in compost analysis by using XRD.

S. NO	Compounds	Chemical formula
1	Calcium Carbonate	$CaCO_3$
2	Silicon Oxide	SiO_2
3	Zinc Sulfide	ZnS
4	Niobium Sulfide	NbS_2

microbial communities that accelerate the conversion of organic matter into humus, which is rich in nutrients.

In this study, the SEM analysis of compost samples showed that the compost matured during the 60^{th} day of degradation, going from larger to smaller particles. Simultaneously, early degradation stages and up to the 60^{th} day showed distinct mineral peaks in the XRD spectra; the peaks decreased once particle breakdown and mature compost formation occurred. Compost evolution can be logically understood from these XRD results, which align with the observations made from the SEM analysis of compost samples. The most substantial peaks of calcium carbonate were noticed at 27.41°, 13.67°, and 29.72°. Similarly, peaks of silicon oxide were noticed at 26.41°, 31.45°, and 60.18°. zinc sulfide was noticed at 21.18°. niobium sulfides were noticed at 54.35° and 68.3°.

4. Conclusion

A study on municipal solid waste (MSW) in Raipur, Chhattisgarh, found a high organic content, making composting a cost-effective way to manage this waste and reduce the burden on dumpsites. Most physico-chemical parameters of the MSW compost samples were within FCO standards, except for moisture content ($32.58 \pm 1.5\%$) and electrical conductivity (5.45 ± 0.43 dS/m), both of which were higher than recommended. High moisture content likely results from the presence of food and green waste, while elevated electrical conductivity may be due to soluble salts in organic matter. Heavy metal levels were initially high but decreased as composting progressed. Fertility and clean indices indicated good compost quality, suitable for high-value crops. SEM and XRD analyses showed that by the 60^{th} day, the compost had matured into small particles with expanded cavities. The study concludes that aerobic composting is effective for processing MSW but emphasizes the need for proper waste segregation and treatment to ensure the compost's agricultural value.

It was observed that the moisture content range is above the permissible limits as per FCO standards. Maintaining the moisture content ($50 - 60\%$) ensures optimal microbial activity, effective decomposition, and uniform composting. This helps to achieve high-quality compost with the desired nutrient content and reduces the risk of odour and pathogen issues. Further studies can be done by using parameters such as moisture content, temperature, and odour control to increase microbial activity and achieve high-quality compost.

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Authors contributions
Literature review, experimental and analytical work by Hari Naga Prasad. Concept and critical review by Dr. Sandeep Kumar Chouksey.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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