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EVALUATION OF ENGINEERED COMPOSTING TECHNOLOGIES FOR DIVERSE FEEDSTOCKS TO IMPROVE COMPOST QUALITY IN PAKISTAN



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Abstract

Sustainable and climate resilient strategies are indispensable for efficient management of ever depleting soil fertility in sub-tropical dry land areas of Pakistan. For this purpose, integrated addition of organic and inorganic amendment can play a crucial role. The present study aimed to develop and evaluate the influence of three variable composting technologies, (i) Indore method (IM), (ii) Bangalore method (BM), and Effective microorganisms' method (EM) on the decomposition of feed stocks including sugarcane bagasse, wheat straw, and mustard stalks. The composting was done for a period 120 days and the periodical sampling (in triplicate) was done after 20, 30, 60, 90, and 120 days to evaluate the rate of decomposition and release of nutrients. The results of the study revealed showed a periodical decrease in in organic carbon and C:N ratio while the concentrations of nitrogen (N), phosphorus (P), potassium (K), and micronutrients (Zn, Cu, Fe, and Mn) increased consistently with time. We observed that EM composting method compared to other two methods showed a better decomposition of feed stocks and release of nutrients as indicated by the lowest value of C:N ratio of EM-method compared to other two methods at end of 120 days. Similarly, among feed stocks, the mustard stalks generated the compost with the highest N, P, K, Zn, and Fe contents, however, the highest Cu contents were found in wheat straw and Mn contents in sugarcane bagasse. It was concluded that the EM-method is superior method while cotton stalks is the best feedstock to produce high value compost. This study, however, restricted to controlled composting only but did not include the field evaluations. Therefore, the future research should be on field validation and economic feasibility of EM-compost for sustainable crop production under varied agroecological environments.

Keywords: Composting methods, Feedstock variability, Quality, Waste utilization

INTRODUCTION

A rapid increase in crop production has been observed in recent times in Pakistan. However, in attempt to drastic increase in crop soil health and fertility has deteriorated significantly, specifically in sub-tropical dry lands where agricultural production relies heavily on rainfall. The extensive use of chemical fertilizers swept way the soil organic matter due accelerated mineralization. We understand that soil organic matter represents the backbone for soil nutrients and moisture retention. Therefore, the integration of organic soil amendments alongside chemical fertilizers is obligatory to achieve sustainable crop production without compromising soil health and soil fertility (1). The continuous increase in global population has yielded a massive generation of organic waste. It is estimated that Pakistan generates approximately 20 million tons of waste per annu, with 0.612 kg/day per capita (2). These precious resources are yet to be converted into value added products for soil fertility enhancement despite being available in abundance.

Composting of organic wastes is well-known method of organic waste utilization which represent an efficient technique to transform organic wastes into a stable nutrient rich material advantageous for soil health restoration (3). The conventional methods of composting like Indore and Bangalore methods mostly adopted in Pakistan are often labor-intensive and consume a long period of time to achieve desire decomposition (4). The limitations of these methods hinder farmers to adopt on large scale production (5). The enrichment microbial inoculants have been introduced to overcome the limitations and accelerate the decomposition process since microorganisms, such as *Aspergillus oryzae*, has ability to reduce composting time up to 20–45 days (6). The performance of such microorganisms has created a sense of commercial inoculants generation. The use of EM which is a consortium of photosynthetic, nitrogen-fixing bacteria, actinomycetes, yeasts, and fungi has attained notice for its ability to enhance organic matter degradation and nutrient mineralization (7). However, a critical research gap still exists despite off significance of such microorganisms' for their evaluation compared to conventional composting methods for locally available crop residues under Pakistani conditions. There is lack of information regarding how the different composting methods interact with specific feedstock types to influence decomposition rates, nutrient dynamics, and final compost quality. These research and knowledge gaps restrain the development of efficient and resilient composting technologies specifically for sub-tropical dry land conditions.

Keeping in view the present knowledge gaps, present study was hypothesized to evaluate the effectiveness of three composting methods including Indore, Bangalore, and EM methods by exploiting the feed stocks including sugarcane bagasse, wheat straw, and mustard stalks. The objectives of this study were to assess the rate of decomposition under different composting methods, the quality of final compost, and comparison of composts regarding nutrient dynamics.

MATERIALS AND METHODS

EXPERIMENTAL SITE, DESIGN, AND METHOD

The present study was carried out at Soil and Water Testing Laboratory, Attock, Pakistan (2024–2025). The experiment laid in three-factor factorial layout creating total 135 experimental units with three replications under Completely Randomized Design (CRD). The factors were 1). composting method, 2) Feedstocks, and 3) composting time (days). The composting methods were, (i) Indore method, (ii) Bangalore method, and (iii) Effective Microorganisms method. In the Indore method, buffalo dung and crop residues were placed in layers alternately in measured excavated pits (2.0 m × 1.5 m × 1.2 m). Approximately 50% moisture contents were maintained throughout the composting period. A care was made to protect the pits from excessive drying and waterlogging by manual turning of material after 20, 30, 60, and 90 days. Complete compost maturity was obtained after 120 days as previously reported by Bernat *et al.* (8). The similar procedure was adopted for Bangalore method as well except plastering of compost heaps with mud to create semi-anaerobic conditions. While in the EM method, crop residues and buffalo dung were mixed in a 3:1 ratio (v/v) and sprayed with a 5% EM solution (EM:molasses:water at a ratio of 5:5:90) because it is widely used as it represents an optimized balance between microbial activation, nutrient availability, and cost-effectiveness for agricultural and composting applications. The mixture was heaped into a measured pit (2.0 m × 1.5 m × 1.5 m) and covered with a plastic sheet to conserve moisture and heat. The compost was turned periodically similar to previous two treatments while the process continued for 120 days (9).

COMPOSTING MATERIALS

For development of composts, three different types of feedstocks including sugarcane bagasse (SB), wheat straw (WS), and mustard stalks (MS) were used. Prior to initiation of composting process, the collected feedstocks were chopped into 5–8 cm pieces while the buffalo dung was used as an activator and mixed with feedstocks at a ratio of 3:1 (v/v). During the composting process, moisture contents was monitored continuously by observing moisture with moisture-probe and adjusted at each turning to maintain optimal moist conditions for proper microbial activity.

Schematic layout plan of the study

Design: Three factor factorial (3×3×5)		
Factors: 1. Methods (3), 2. Feedstocks (3), 3. Time (5 intervals): Replications 3		
Feedstocks and activator (3:1 v/v ratio)		
Sugarcane Bagasse (SB), Wheat Straw (WS), Mustard stalks (MS)- Chopped 5-8 cm		
Indore Method	Bangalore Method	EM Method
Pit: 2.0×1.5×1.2 m	Pit: 2.0×1.5×1.2 m	Pit: 2.0×1.5×1.2 m
Anaerobic conditions	Semi-anaerobic	5% EM solution sprayed
Alternate layering	Sealed with mud plaster	(EM:Molases:Water=5:5:90)
50% moisture maintained	50% moisture maintained	Covered with plastic
Manual turning	Manual turning	Manual turning
Days: 20, 30, 60, 90	Days: 20, 30, 60, 90	Days: 20, 30, 60, 90
Maturity: 120 days	Maturity: 120 days	Maturity: 120 days

SAMPLING AND LABORATORY ANALYSIS

During the composting process periodical sampling after 20, 30, 60, 90, and 120 days was done to perform chemical and quality tests. The collected samples were from every composting method were air-dried under shade, ground, and passed through 0.5 mm sieve and stored in polythene bags. Organic carbon was determined by the Walkley–Black method (10), total nitrogen (TN) by the Kjeldahl method (11), C:N ratio (calculated from organic carbon and TN), available phosphorus by the Olsen method (12), and potassium contents by flame photometer (13). The concentration of micronutrients including Zn, Cu, Fe, and Mn was determined by di-acid digestion (14) using an atomic absorption spectrophotometer (15).

Table I. Mean value of interaction between different raw materials (A) and different composting methods (B)

Nutrients names	Material	Indore method (IM)	Bangalore method (BM)	E. M method (EM)	Mean (Material)
Carbon (%)	SB	34.10 A	32.46 B	31.61 B	32.72 A*
	WS	30.10 C	28.47 D	27.51 DE	28.69 B
	MS	27.96 DE	27.16 EF	26.35 F	27.16 C
	Mean (Methods)	0.72 A	29.36 B	28.49 C	
Nitrogen (%)	SB	0.52 I	0.53 H	0.55 G	0.53 C
	WS	0.61 F	0.63 E	0.65 D	0.63 B
	MS	0.68 C	0.71 B	0.74 A	0.71 A
	Mean (Methods)	0.60 C	0.63 B	0.77 A	
C: N	SB	78.87 A	72.27 B	69.87 B	73.67 A
	WS	57.33 C	52.93 D	49.47 E	53.24 B
	MS	46.33 F	42.40 G	40.00 G	42.91 C
	Mean (Methods)	60.84 A	55.87 B	53.11 C	
Phosphorus (%)	SB	0.28 F	0.29 E	0.31 D	0.30 C
	WS	0.31 D	0.32 C	0.34 B	0.32 B
	MS	0.32 C	0.34 B	0.35 A	0.34 A
	Mean (Methods)	0.30 C	0.32 B	0.34 A	
Potassium (%)	SB	1.28 I	1.30 H	1.32 G	1.30 C
	WS	1.43 F	1.45 E	1.47 D	1.45 B
	MS	1.55 C	1.57 B	1.59 A	1.57 A
	Mean (Methods)	1.42 C	1.44 B	1.46 A	
Zinc (ppm)	SB	24.24 I	25.51 H	27.17 G	25.64 C
	WS	29.35 F	30.59 E	32.38 D	30.77 B
	MS	38.91 C	40.51 B	42.81 A	40.74 A
	Mean (Methods)	30.83 C	32.20 B	34.12 A	
Copper (ppm)	SB	5.99 H	6.70 H	8.53 G	7.07 C
	WS	21.59 C	22.91 B	24.95 A	23.15 A
	MS	9.54 F	10.43 E	12.22D	10.73 B
	Mean (Methods)	12.37 C	13.34 B	15.23 A	
Iron (ppm)	SB	63.67 H	64.87 H	66.86 G	65.14C
	WS	70.84 F	72.29 E	74.65 D	72.59 B
	MS	83.84 C	85.11 B	87.16 A	85.37 A
	Mean (Methods)	72.78 C	74.09 B	76.22 A	
Manganese (ppm)	SB	147.82C	149.03 B	150.48 A	149.11 A
	WS	36.55 I	37.75 H	39.48 G	37.93 C
	MS	44.22 F	45.46 E	45.93 D	45.54 B
	Mean (Methods)	76.20 C	77.41 B	78.96 A	

*SB=Sugarcane Bagasse, WS=Wheat Straw, MS=Mustard Stalks. Different alphabetical letters show interaction between different raw materials and different composting methods at LSD <0.05%.



STATISTICAL ANALYSIS

The obtained data was subjected to three-way analysis of variance (ANOVA) and a factorial CRD was employed to evaluate the effects of composting method, feedstocks, and composting duration, as well as their interactions (16; 17). The comparisons of means were compared using Duncan's Multiple Range Test (DMRT) at 5% and 1% levels of significance (18).

RESULTS AND DISCUSSION

DYNAMICS OF ORGANIC CARBON

The results (Table I, Fig. 1, 2) showed that organic carbon contents were decreased gradually over time during the composting period. The organic carbon contents were 39.9% at 20th day which were decreased to 16.1% at 120th day. The consistent decrease in organic carbon represent the process mineralization of feedstocks over time. These results confirm the findings of earlier study reported the microbial oxidation and release of CO₂ over time during composting process (3). It was also observed that among feedstocks, sugarcane bagasse showed the highest mean carbon content of 32.7%, followed by wheat straw of 28.7%, and mustard stalks of 27.2%. The comparison of composting methods showed that the Indore method maintained comparatively higher carbon contents of 30.7% compared to Bangalore method of 29.4%, and EM of 28.5%. It is important to describe that the EM method showed the most rapid decrease in organic carbon contents attributed to enhanced microbial activity and enzymatic degradation of labile organic fractions, consistent with earlier findings of Feng *et al.*, (19). Contrarily to that higher organic carbon retention in the Indore method could be due to stable aerobic, while the higher carbon content in sugarcane bagasse is likely due to presence extensive lignocellulosic contents resulting and slower decomposition (20).

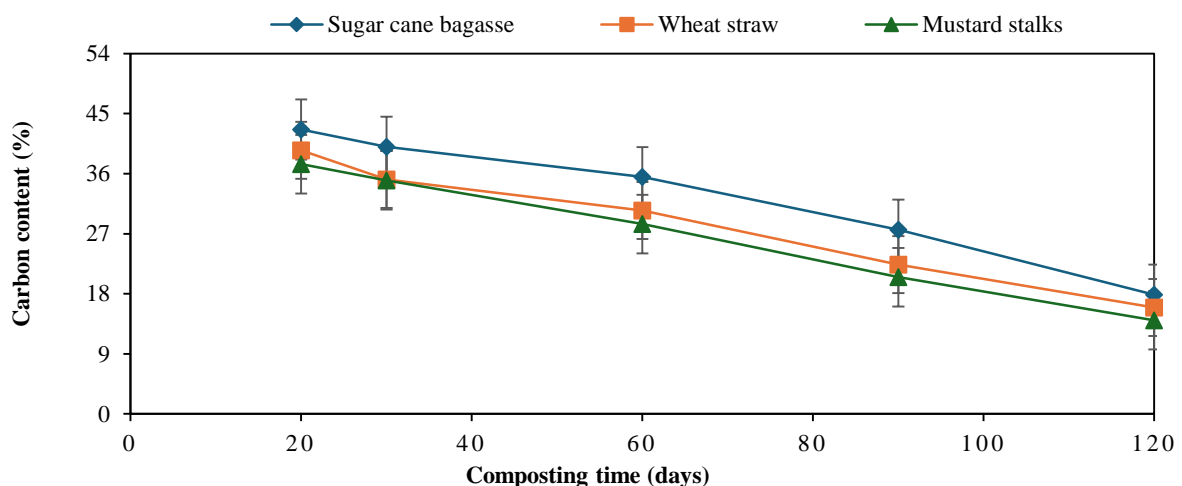


Fig. 1. Effect of composting time on carbon contents for different composting materials. Error bars shows standard error of mean of three replicates (n=3)

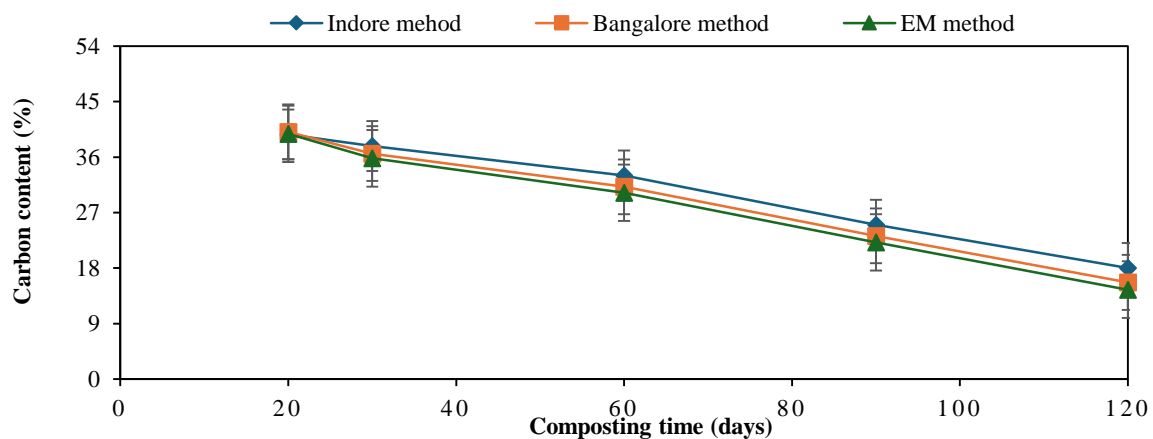


Fig. 2. Effect of composting time on carbon contents (%) for different composting methods. Error bars shows standard error of mean of three replicates (n=3).

DYNAMICS OF NITROGEN

The results (Table I, Fig. 3, 4) showed that the concentration of nitrogen increased gradually during the composting period with a mean increase of 0.40% at 20th day to 0.89% at 120th day. The increase nitrogen concentration was attributed to enrichment due to consistent decomposition organic matter and release of carbon during composting activity. These results are in line with previous studies reporting transformation of nitrogen concentration during composting process (11). It was noted that the highest mean nitrogen contents (0.70%) were recorded in mustard stalks, followed by 0.63% in wheat straw, and 0.53% in sugarcane bagasse. The comparison of different composting methods showed that the EM-method resulted the higher nitrogen contents of 0.77% compared to Bangalore of 0.63%, and Indore of 0.60%. This increment in nitrogen contents under EM-method could be attributed to enhanced microbial immobilization resulting minimized release of nitrogen during composting (19). Similarly, the enhanced nitrogen accumulation in mustard stalks is associated with their relatively higher initial protein contents.

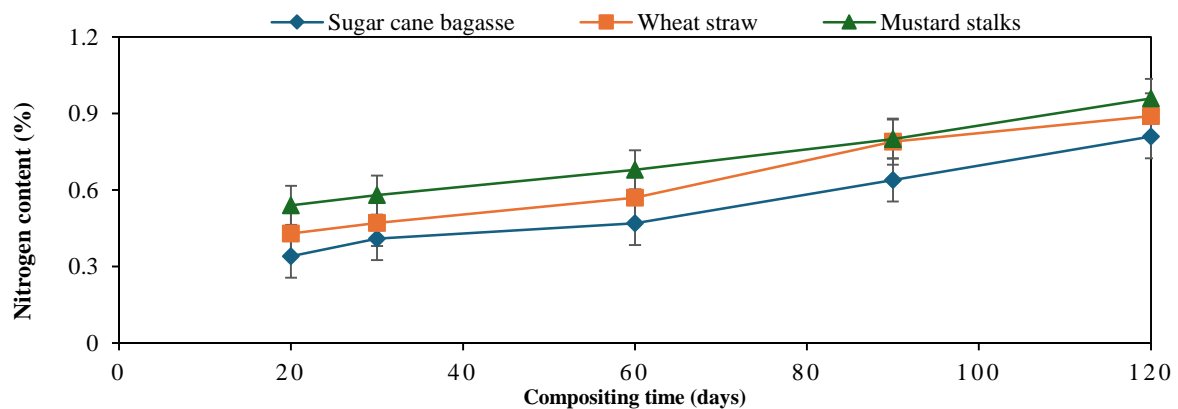


Fig. 3. Effect of composting time on nitrogen contents (%) for different composting materials. Error bars shows standard error of mean of three replicates (n=3)

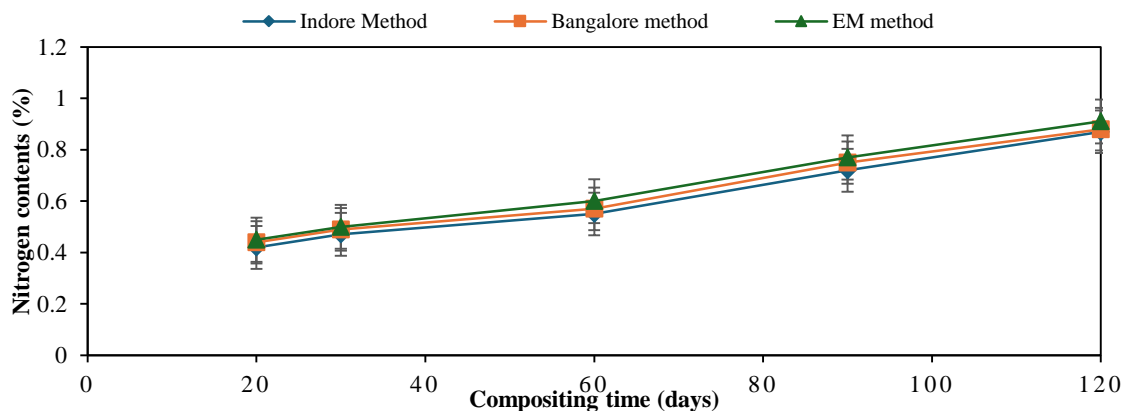


Fig. 4. Effect of composting time on nitrogen contents (%) for different composting methods. Error bars shows standard error of mean of three replicates (n=3)

DYNAMICS OF C:N RATIO

The results (Table I) showed that the C:N ratio significantly decreased over time in all composting methods revealing gradual stabilization of compost over time. At the beginning the C:N ratio of sugarcane bagasse and wheat straw was 90 while in mustard stalks was 72 which ultimately declined to 11–22 at 120th day. These values indicate the maturity of compost and fall well within the acceptable range of stable compost determined by previous studies (3). The lowest value of C:N ratio under EM-method reveal a rapid decomposition of feedstocks in achieving the early mature compost. We found that sugarcane bagasse achieved the highest mean C:N ratio of 73.7 while the mustard stalks achieved the lowest C:N ratio of 42.9. An early narrowing of C:N under EM-method represent the efficiency of this method to promote breakdown of organic matter, confirm the findings of Feng *et al.*, (19).

DYNAMICS OF PHOSPHORUS AND POTASSIUM

The results (Table II) showed that the phosphorus contents of compost gradually increased during composting process in all composting methods. During composting mean total phosphorus contents increased from 0.16% at 20th day to 0.51% at 120th day, respectively. This gradual increase was attributed to gradual release of organically bound phosphorus from feedstocks after mineralization process (12). It was noted that the highest mean total phosphorus contents of 0.34% were recorded in mustard stalk, followed by wheat straw of 0.32%, and sugarcane bagasse of 0.30%, respectively. The comparison of composting methods revealed that the, EM-method yielded the higher phosphorus contents of 0.34% compared to Bangalore method of 0.32%, and Indore method of 0.30%.

The results of the study showed that the potassium contents increased from 1.28% at 20th day to 1.69% at 120th day, attributed to release of soluble potassium contents as result of decomposition of feedstocks during composting (12). It was observed that the highest mean potassium content of 1.57% were recorded in mustard stalks, followed by 1.45% in wheat straw, and 1.30% in sugarcane bagasse. The comparison of composting methods showed that the EM-method generated the higher potassium contents of 1.46% compared to Bangalore of 1.44%) and, Indore of 1.42%.

Table II. Mean values of nutrient concentrations at different time intervals (20, 30, 60, 90, and 120 Days)

Mean	20 days	30 days	60 days	90 days	120 days
Carbon (%)	39.8A	36.73 B	31.48 C	23.49 D	16.10 E
Nitrogen (%)	0.44 E	0.49 D	0.58 C	0.75 B	0.89 A
C:N	96.6A	78.04 B	57.82 C	32.26 D	18.30 E
Phosphorus (%)	0.16 E	0.18 D	0.32 C	0.42 B	0.51 A
Potassium (%)	1.28 E	1.34 D	1.44 C	1.53 B	1.69 A
Zinc (mg kg ⁻¹)	22.62 E	27.36 D	32.34 C	37.90 B	41.69 A
Copper (mg kg ⁻¹)	9.42 E	10.80 D	13.21 C	16.54 B	18.29 A
Iron (mg kg ⁻¹)	65.20 E	67.44 D	74.23 C	79.56 B	85.40A
Manganese (mg kg ⁻¹)	67.99 E	71.34 D	78.33 C	83.43 B	86.53 A

DYNAMICS OF MICRONUTRIENTS

The results (Table II) showed that Zn contents increased from 22.6 mg kg⁻¹ at 20th day to 41.7 mg kg⁻¹ at 120th day. It was observed that the mustard stalk feedstock displayed the highest mean Zn content of 40.7 mg kg⁻¹, followed by 30.8 mg kg⁻¹ in wheat straw, and 25.6 mg kg⁻¹ in sugarcane bagasse, respectively. The comparison of composting methods showed that the EM-method showed the higher Zn contents of 34.1 mg kg⁻¹ compared to 32.2 mg kg⁻¹ in Bangalore method, and 30.8 mg kg⁻¹ in Indore method, respectively. The highest Zn contents under EM-method could be consequence of better microbial solubilization and reduced nutrient loss (14).

The Mn contents increased gradually from 67.99 mg kg⁻¹ to 86.53 mg kg⁻¹ during the composting process. It was observed that the highest mean Mn contents of 149.11 mg kg⁻¹ were recorded in sugarcane bagasse while the lowest Mn contents 37.93 mg kg⁻¹ were recorded in wheat straw, respectively. The comparison of composting methods revealed that the higher Mn contents were recorded in EM-method compared to other methods, respectively. These higher Mn contents in EM-method attributed to the mass reduction and organic matter degradation during composting process as reported earlier by Paul *et al.*, (2017).

The results showed that the Cu contents increased from 9.42 mg kg⁻¹ at 20th day to 18.29 mg kg⁻¹ at 120th day. It was also observed that the highest mean Cu contents of 23.15 mg kg⁻¹ were recorded in wheat straw while the lowest Cu contents of 7.07 mg kg⁻¹ were recorded in sugarcane bagasse. The comparison of composting methods showed that the EM-method produced the higher Cu contents compared to other methods which are indicative of enhanced microbial activity and reduced leaching losses (14).

The results showed that the Fe contents increased from 65.20 mg kg⁻¹ to 85.40 mg kg⁻¹ during composting process. It was observed that the highest mean Fe contents of 85.37 mg kg⁻¹ were recorded in mustard stalks whereas the lowest Fe contents of 65.14 mg kg⁻¹ were recorded in sugarcane bagasse. The comparison of different composting methods showed that the EM-method resulted in greater Fe retention compared to other methods. Some similar findings already reported that these results are due to mineralization and concentration effects (15).

CONCLUSION

The results concluded that the composting method and feedstock type significantly influence the mineralization of wastes and stability of compost. We observed that the EM-composting method proved most efficient in accelerating organic matter mineralization, and improving the nutrient enrichment including macronutrients (N, P, and K), and micronutrients (Zn, Cu, Fe, and Mn) compared to the conventional Indore and Bangalore methods. The superior nutrient retention of EM in composting, despite similar turning frequencies to conventional methods, is largely attributed to a microbial-driven shift from high-heat combustion to low-heat fermentation. The rapid reduction in organic carbon and C:N ratio under EM-method are the responsible mechanisms resulting the short time stability of compost. Further, variability of feedstock played a crucial role in determining nutrient composition of compost. The study determined that mustard stalks produced the compost with highest N, P, K, Zn, and Fe contents while wheat straw and sugarcane bagasse were superior for Cu and Mn enhancement. Therefore, EM-method of composting utilizing mustard stalks emerged as the standout composting option. The results of this research represent viable and efficient composting technology for sustainable management of soil fertility and soil health issues of sub-tropical dry land soils. The validation of this method at field level is required to assess the agronomic performance and long-term impacts on soil health.

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Conflict of interest:

There is no conflict of interest among authors regarding this article.

Authors` contribution:

SUK, MR, SA & AW Writing, review and editing; SA, MR, MTS, SA, SH, SN, MUS, IAS, RK, ZS & GN Review and editing introduction and data analysis. All authors have reviewed and consented to the final version of the manuscript for publication.

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