ASSESSMENT OF BIOREMEDIATION METHODS TO EFFICIENTLY MANAGE FORESTRY WASTES WHILST CONCURRENTLY EVALUATING THE MATURITY STATUS OF COMPOST

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Abstract. Environmental pollution driven by human activities and urbanization poses significant global challenge in recent decades. Converting organic waste by composting waste in to organic fertilizer is a sustainable environmental protection approach. Compost must reach a stable and mature state to be agriculturally viable. This study assesses compost maturity of conventional and vermicompost methods by employing physico-chemical and spectroscopic analyses of water extracts of different forestry substrates. Initially the effectiveness of humification parameters such as polymerization ratio, humification index and degree of humification determining compost maturity were assessed. Next the impact of the composting techniques related to physico-chemical properties of compost was compared. Finally, the viability of composting as a bioremediation tool for the forestry and agricultural wastes was studied. The findings showed significant variability in humification parameters among compost types, with no single indicator consistently reflecting maturity. The polymerization ratio was higher in Albizia litter, humification ratio was greater in teak litter, and the degree of humification was high in coffee pulp. Physico-chemical analysis revealed an increase in pH towards neutrality, and electrical conductivity during composting. Carbon to nitrogen ratio (C:N) decreased during decomposition. The nitrogen and phosphorus nutrient contents were high in vermicompost than conventional compost. The degree of humification to aromatic carbon (E4/E6) ratio correlates with the composting process. These findings pave the way for improved agricultural and forestry waste management.
Keywords: *humification, albizia, teak litter, coffee pulp, vermicompost*

Introduction

Decomposition of underutilized organic sources such as agriculture and forest waste composed of post-harvest crop residues, fallen leaves, broken branches, old crates, barks, shavings, scraps, wood processing rejects and animal remainings will play significant role in maintaining environmental sustainability and farm productivity (Koul et al., 2022).the extensive use of synthetic fertilizers to maximize crop yields has led to environmental concerns such as soil degradation, water pollution, and greenhouse gas emissions (Jimenez-Lopez et al., 2020; Randive et al., 2021). India ranks second only to china in terms of fertilizer consumption (Randive et al., 2021). Although global estimates of agricultural waste are seldom reported, a significant proportion of total waste in developed countries still originates from agricultural activities (Maji et al., 2020). Replacing synthetic fertilizers with organic manures produced through recycling of organic waste offers a sustainable alternative to prevent soil degradation (Zhao et al., 2024). However, it is to be noted that the organic manure should be well decomposed prior to the field application (Cai et al., 2024). Organic waste predecomposed by microorganisms are preferred by earthworms to make them in to mature compost (Rini et al., 2020). During the composting process, fruit waste requires less additional water because it inherently contains about 80% water, but farm and forest waste demands more water and time to decompose (Parveenparihar and Rakeshchoudhary, 2022). Immature compost can release phytotoxic compounds and reduce the availability of nutrients, underscoring the importance of accurate compost maturity assessment (Cai et

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al., 2024). In this aspect accurate determination of maturity is necessary to ensure the effectiveness of decomposed organic manures when applying to plants.

The complete conversion of organic waste into humus substances is called as compost maturity which is essential for the nutrient uptake by plants (Hou et al., 2024). Organic waste material composition, microbial activity, water content and environmental factors determine the speed rate of composting process, and these parameters directly influence the compost maturity process. Presently several physico-chemical and biological indicators have been available to assess the compost maturity, but selecting a most reliable and universal protocol is challenged by the geographical substrate variations, diversity in microbial profile and variability in composting conditions (Chang et al., 2023). Among several methods, widely acceptable biological indicators provide reliable data of organic decomposition rate and stabilization are humification index (HI), the degree of humification (DH), and the carbon-to-nitrogen (C:N) ratio (Sequi et al., 1986; Ciavatta et al., 1990). HI, DH and C:N ratio parameters precisely assess the changes in structural and biochemical properties reflecting compost quality and compost process (Gastaldi et al., 2024). Spectrophotometric analyses, such as the E4/E6 ratio (the ratio of absorbance at 465 nm to 665 nm), further enhance maturity evaluations by reflecting the degree of aromatic carbon development and humus formation (Chen et al., 1977). The E4/E6 ratio characterize the quality of humic acid and degree of aromatization (Hasan et al., 2012). In general, the E4/E6 is inversely related to degree of maturation (Jiang et al., 2023). The use of different composting methods, such as conventional composting and vermicomposting, significantly influences compost quality (Zhou et al., 2022). Vermicomposting, which incorporates earthworm activity, accelerates the decomposition of organic matter, enhances microbial diversity, and improves nutrient availability (Rini et al., 2020). In forest waste composting process, lignified substrates such as teak, Albizia, and Simarouba shells exhibited slow decomposition rates, and even resistant to microbial decomposition (Liu and Zhang, 2023). The assessment and comparison of different composting methods is necessary to understand the dynamics of humification and the nutrient profiles of the composts.

The compost maturity of forestry and agricultural waste substrates have been studied using a comprehensive set of indicators, including hi, dh, and the C:N ratio, alongside spectrophotometric measurements such as the e4/e6 ratio in this report. Comparison of conventional composting method with vermicomposting technique was made to elucidate the role of composting methods in humification dynamics and nutrient enrichment. It also investigates the limitations of using individual humification parameters as sole indicators of maturity and advocates for a multi-parameter approach. Vermicomposting method showed higher value for humification indices and better nutrient profiles compared to conventional composting, and substrate composition playsa significant role in determining the outcomes. Taken together the present study provided vital contribution towards the development of reliable, standardized protocols for compost maturity assessment towards the goal of sustainable waste management and the production of high-quality compost in agriculture and forestry.

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Materials and methods

Humification parameters

The compost maturity was estimated by analyzing the humification parameters such as humification index (HI), degree of humification (DH), polymerization ratio (PR) and the humification ratio (HR). In a 500 ml beaker 10g of Compost and 70 mL of 0.5 N sodium hydroxide was added, and it was incubated at room temperature for 24 hours with intermittent stirring. Then the solid and liquid fractions of the extract were separated by centrifugation and transfer of supernatant to another vial. The organic carbon content of the supernatant was determined by following Walkley and Black method (Walkley and Black, 1934; Chen et al., 2015). To estimate the humic acid (HA) and fulvic acid (FA), the remaining supernatant was acidified to pH value around 1 with 2 N HCl, centrifuged at 5000 rpm for 10 minutes, and the resulted precipitate and supernatant were analyzed for organic carbon content. All measurements were performed in triplicates, and the mean values were used for calculations. The humification parameters were calculated as follows:

$$HA(\%) = \frac{C_{ha}}{C_{ex}} \times 100 \quad \text{(Eq.1)}$$

$$FA(\%) = \frac{C_{fa}}{C_{ex}} \times 100 \quad \text{(Eq.2)}$$

$$PR = \frac{C_{fa}}{C_{ha}} \quad \text{(Eq.3)}$$

$$DH(\%) = \frac{(C_{ha} + C_{fa})}{C_{ex}} \times 100 \quad \text{(Eq.4)}$$

$$HR(\%) = \frac{HA + FA}{TOC} \times 100 \quad \text{(Eq.5)}$$

$$HI = \frac{NH}{C_{ha} + C_{fa}} \quad \text{(Eq.6)}$$

where C_{ha} is the organic carbon content in the HA fraction, C_{fa} is the organic carbon content in the FA fraction, C_{ex} is the organic carbon content in the alkali extract, TOC is the total organic carbon, HI is humidification index and NH is the carbon content of the non-humic fraction.

Analyses of compost water extract

Preparation of water extract

In order to evaluate the physico-chemical properties and spectroscopic analysis water extract of the compost was prepared. In brief 10 g of compost and 40 mL of deionized water was added to a 100 mL beaker, gently stirred and incubated at room temperature (~25°C) for 1 hour with gentle mixing once in 15 minutes. At the end of incubation, the

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mix was filtered in a Watmann filterpaper and the water extract was collected in a clean vessel. Three sets of water extract were collected to perform experiment with three replicates. Finally, the collected filtrates were stored at 4°C until further analysis.

Physico-chemical analysis of compost water extract

The water extract was used to analyze the physiochemical parameters. pH was measured with a calibrated digital pH meter, electrical conductivity (EC) was estimated by using a conductivity meter and total organic carbon (TOC) was obtained by following Walkley and Black method. Total nitrogen (N) content was measured by using the Kjeldahl method, phosphorus (P) content was estimated by molybdenum blue colorimetric method and Potassium (K) content was analyzed with a flame photometry. Based on the TOC and TN values carbon-to-nitrogen (C:N) ratio was derived. All the experiments were conducted in triplicate.

Spectrophotometric E4/E6 analysis of humidification

Immediately after the compost water extraction, the light absorbance at optical density 280 nm (E_{280}), 465 nm (E_{465}) and 645 nm (E_{645}) was observed in a UV-Vis spectrophotometer.Deionized sterile distilled water was used as the blank control. E_{280} was used as a reference to compare the presence of protein. The ratio of absorbance value at 465 nm to 665 nm, was calculated and mentioned as E4/E6 value to know the humification level and the development of aromatic carbon. Partially composted (PC) and fully composted (FC) substrates ofteak litter (TL), Albizia litter (AL), Simarouba shell (SS), Pungam shell (PS) and Coffee pulp (CP) were subjected to analysis. The experiment was performed in triplicate, and mean values were recorded for analysis.

Results

Humification parameters

The humification parameters polymerization ratio (PR), degree of humification (DH) humification index (HI) and humification ratio (HR) were assessed in different substrates and composting methods. The highest PR value was observed Albizia splitter substrates with 0.30 in conventional composting and 0.31 in vermicomposting method. Lowest PR was observed in Pungam shell showed 0.10 and 0.06 in conventional composting and vermicomposting methods respectively (*Table 1*). In conventional composting method DH value showed a lowest level of 23.85% in coffee pulp to a highest calue of 87.00% in Simarouba shell. Under vermicomposting method the highest DH value was 1.974% in coffee pulp and lowest value was 0.243% in Simarouba shell. The humification index (HI) showed maximum values in coffee pulp during conventional composting (9.98) and minimum values in teak litter during vermicomposting (0.7). The humification ratio (HR) was greater for teak litter under vermicomposting (0.08) compared to conventional composting (0.06), while Albizia litter showed lower HR values of 0.02 and 0.04, respectively (*Table 1*).

Among the two composting methods, vermicomposting exhibited higher values of DH and HR across most substrates compared to conventional composting. For example, coffee pulp under vermicomposting recorded a DH of 1.974%, compared to 23.85% in conventional composting.

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Table 1. *Humification indices of various composts. The substrates Teak litter (TL), Albizia litter (AL), Simarouba shell (SS), Pungam shell (PS) and Coffee pulp (CP) were subjected to conventional composting or vermicomposting, and humidification indices were taken*

Substrates	Polymerization ratio (PR)		Humification ratio (HR)		Degree of humification (DH)		Humification index (HI)	
	Conventional	Vermicompost	Conventional	Vermicompost	Conventional	Vermicompost	Conventional	Vermicompost
Teak litter (TL)	0.15[d]	0.21[b]	0.06[a]	0.08[a]	40.79[d]	0.594[c]	0.81[e]	2.23[d]
Albizia litter (AL)	0.30[a]	0.31[a]	0.02[d]	0.04[d]	53.50[c]	0.399[d]	5.45[b]	2.48[c]
Simaroubashell(SS)	0.20[c]	0.08[d]	0.05[b]	0.03[e]	87.00[a]	0.243[e]	2.80[c]	3.66[a]
Pungam shell (PS)	0.10[e]	0.06[e]	0.06[a]	0.05[c]	68.30[b]	1.720[b]	1.98[d]	2.65[b]
Coffee pulp (CP)	0.27[b]	0.12[c]	0.03[c]	0.06[b]	23.85[e]	1.974[a]	9.98[a]	0.70[e]

In a column, means followed by a common letter are not significantly different at 5% level by DMRT

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The PR for Albizia litter remained consistent at 0.30 and 0.31 across the two methods. For Pungam shell, PR values were 0.10 for conventional composting and 0.06 for vermicomposting.

Organic carbon content in humic and non humic substances under conventional and vermicomposting conditions

Regarding the carbon content in humic acid, Pungam and Albizia recorded the highest (1.0) and lowest values (0.41), respectively, in conventional composting processes. In vermicomposting, coffee and Simarouba had the highest (0.88) and lowest values (0.45), respectively (*Table 2*). For the carbon content of fulvic acid, compost made from Simarouba shell recorded the maximum value (0.15%), followed by Albizia and coffee (0.13%), which were statistically similar. In vermicompost, teak litter registered the highest value (0.158%), surpassing other conventional and vermicomposts (*Table 2*). The cumulative values of humic acid and fulvic acid content in various composts are presented in *Table 2*. In conventional composting, Pungam shell obtained the highest value (1.1), while Albizia received the lowest value (0.53). In the vermicomposting process, Pungam recorded the highest value (1.86), and Simarouba registered the lowest value (0.49). The results on carbon content in non-humic substances indicated that coffee pulp conventional compost had the maximum content (5.74%). Among the vermicomposts, vermicompostedPungam recorded the highest value (2.28%). Conventional compost of teak and vermicompost of coffee recorded the lowest values (0.67 and 0.69, respectively) for conventional composting and vermicomposting (*Table 2*)

Total organic carbon and humic acid content among the substrates under conventional and vermicomposting conditions

The data for the Cha/Cfa ratio are reported in *Table 3*. The investigation found that Albizia litter had the highest ratio in traditional composting (32.8), but Pungam shell had the highest ratio in vermicomposting (16.2). In contrast, the lowest ratios were observed in the conventional compost of coffee pulp (3.6) and vermicomposted Albizia litter (3.2). *Table 3* also shows the total organic carbon content, with Albizia litter having greater values in both composting procedures (25.2 and 19.5, respectively), whereas teak litter had lower values in both processes (12.7 and 10.6). In terms of carbon content in total alkali extract, *Table 3* shows that coffee pulp and Simarouba shell had the highest values in conventional composting (2.41 and 2.01, respectively). Albizia and Simarouba had lower values in traditional composting (1.0 each), while Pungam shell and coffee pulp had lower values in vermicomposting (0.5 each), with statistically comparable results. The humic acid concentration of several composts is shown in *Table 3*. Simarouba and coffee pulp showed greater values in conventional composting (72.0) and vermicomposting (176.0), respectively. Coffee pulp and Simarouba showed lower values in traditional composting (18.62) and vermicomposting (22.38), respectively.

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Table 2. *Organic carbon content of different fractions of humic substances of various composts*

Substrates	'C' content in humic acid		'C' content in fulvic acid		Humic acid (HA) +Fulvic acid (FA)		'C' content in non-humic substance	
	Conventional	Vermicompost	Conventional	Vermicompost	Conventional	Vermicompost	Conventional	Vermicompost
Teak litter (TL)	0.71[b]	0.74[c]	0.11[c]	0.158[a]	0.82[c]	0.89[c]	0.67[e]	1.99[b]
Albizia litter (AL)	0.41[d]	0.46[d]	0.13[b]	0.143[b]	0.53[e]	0.60[d]	2.89[b]	1.50[d]
Simarubashell (SS)	0.72[b]	0.45[d]	0.15[a]	0.039[e]	0.87[b]	0.49[e]	2.44[c]	1.79[c]
Pungam shell (PS)	1.00[a]	0.81[b]	0.10[d]	0.050[d]	1.10[a]	1.86[a]	2.18[d]	2.28[a]
Coffee pulp (CP)	0.45[c]	0.88[a]	0.13[b]	0.107[c]	0.57[d]	0.98[b]	5.74[a]	0.69[e]

In a column, means followed by a common letter are not significantly different at 5% level by DMRT

Table 3. *Organic carbon content of different fractions of humic substances of various composts*

Substrates	C_{ha} / C_{fa}		Total organic carbon		'C' content in TEC		Humic acid (%)	
	Conventional	Vermicompost	Conventional	Vermicompost	Conventional	Vermicompost	Conventional	Vermicompost
Teak litter (TL)	6.45[c]	4.90[d]	12.70[e]	10.60[e]	2.01[b]	1.51[b]	35.32[d]	49.00[c]
Albizia litter (AL)	32.80[a]	3.20[e]	25.20[a]	19.50[a]	1.00[d]	1.51[b]	41.00[c]	30.46[d]
Simarouba shell (SS)	4.80[d]	15.00[b]	17.08[d]	18.60[b]	1.00[d]	2.01[a]	72.00[a]	22.38[e]
Pungam shell (PS)	10.00[b]	16.20[a]	18.60[c]	16.00[c]	1.61[c]	0.50[c]	62.11[b]	162.00[b]
Coffee pulp (CP)	3.60[e]	8.22[c]	22.60[b]	14.90[d]	2.41[a]	0.50[c]	18.62[e]	176.00[a]

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Bio-chemical analysis of compost water extract

The pH of water extracts increased during composting, with vermicomposts exhibiting values closer to neutrality. *Table 4* shows the pH and electrical conductivity results for water extracts from both conventional and vermicomposting methods. Electrical conductivity (EC) also increased, with the highest values recorded for Pungam shell compost in both methods. The pH of partially degraded substrates was initially near neutral, however it became slightly alkaline after composting. Similarly, electrical conductivity values in water extracts increased during the composting process.

The carbon-to-nitrogen (C:N) ratio decreased during decomposition, with conventional compost showing the lowest values. *Table 5* shows the organic carbon content and carbon-to-nitrogen (C:N) ratios in the water extracts. Albizia litter had the highest organic carbon content (1.66), whereas Pungam shell had the lowest value (0.006) in traditional composts. In the vermicomposting process, teak litter had the highest organic carbon value (0.016), while Albizia and Simarouba had the lowest values (0.006 apiece), which were statistically equivalent. The C:N ratio investigation found that in conventional composting, Simarouba shell had the highest ratio (3.5:1) while teak had the lowest ratio (0.153:1). In vermicomposting, teak had the highest ratio (3.2:1), whereas Albizia had the lowest (0.512:1).

Nitrogen content was highest in teak litter and Albizia litter in both methods, whereas phosphorus content was maximized in Pungam shell compost. Potassium levels were higher in vermicomposts compared to conventional composts, with coffee pulp vermicompost recording the highest value at 1.219%. Teak and Albizia showed higher nitrogen content (0.99 and 0.014, respectively) in both conventional and vermicomposting methods. In contrast, Simarouba shell had lower nitrogen values (0.004 and 0.005) in both composting procedures (*Table 5*). The phosphorus concentration, with Pungam shell having the highest levels (3.83 and 3.85) in both composting methods. Albizia had the lowest phosphorus levels (0.9 and 1.06) in both methods. Teak litter and coffee had greater total potassium content levels in traditional composting and vermicomposting procedures (0.993 and 1.219, respectively). In contrast, Simarouba shell showed lower potassium levels (0.363 and 0.371) in both composting and vermicomposting processes.

Analysis of compost water extracts

Organic wastes are primarily made up of high molecular weight, water-insoluble polymers. During composting, decomposing bacteria primarily attach to surfaces and are most active at the water-solids interface.

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Table 4. *Physico-chemical analysis of partially and fully degraded compost water extract. Partially composted (PC) and fully composted (FC) substrates were analyzed for pH and EC*

Substrates	pH				EC			
	Conventional compost		Vermicompost		Conventional compost		Vermicompost	
	PC	FC	PC	FC	PC	FC	PC	FC
Teak litter (TL)	7.40^{c}	8.70^{a}	7.80^{a}	8.46^{b}	1.78^{b}	2.82^{a}	1.40^{a}	2.10^{b}
Albizia litter (AL)	7.90^{a}	8.35^{c}	7.40^{c}	8.08^{d}	1.92^{a}	2.27^{c}	0.93^{c}	1.67^{c}
Simaruba shell (SS)	6.70^{d}	8.07^{d}	6.50^{e}	7.87^{e}	0.73^{d}	0.89^{e}	0.73^{e}	1.25^{e}
Pungam shell (PS)	7.40^{c}	8.63^{b}	7.30^{d}	8.35^{c}	1.92^{a}	2.73^{b}	0.87^{d}	1.66^{d}
Coffee pulp (CP)	7.70^{b}	8.07^{d}	7.70^{b}	8.56^{a}	1.02^{c}	1.86^{d}	1.33^{b}	2.56^{a}

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Table 5. *Humidification indices of the partially and fully degraded compost water extract. Waste fromdifferent plat sourceswere composted by conventional composting and vermicomposting methods, and Partially composted (PC) and fully composted (FC) substrates were analyzed for humidification indices*

Substrates	Compost method	Compostcondition	Teak litter (TL)	Albizia litter (AL)	Simaruba shell (SS)	Pungam shell (PS)	Coffee pulp (CP)
Organic carbon	Conventional compost	PC	0.010^{b}	0.016^{a}	0.007^{d}	0.003^{e}	0.009^{c}
		FC	0.020^{b}	1.660^{a}	0.015^{d}	0.006^{e}	0.018^{c}
	Vermicompost	PC	0.003^{c}	0.004^{b}	0.002^{d}	0.006^{a}	0.002^{d}
		FC	0.016^{a}	0.006^{d}	0.006^{d}	0.009^{c}	0.015^{b}
Carbon:Nitrogen ratio	Conventional compost	PC	1.25:1^{c}	1.45:1^{b}	3.60:1^{a}	0.38:1^{e}	0.90:1^{d}
		FC	0.153:1^{e}	1.67:1^{b}	3.510:1^{a}	0.370:1^{d}	0.540:1^{c}
	Vermicompost	PC	4.6:1^{a}	3.3:1^{c}	2.0:1^{e}	3.0:1^{d}	4.0:1^{b}
		FC	3.290:1^{a}	0.512:1^{e}	1.304:1^{d}	2.400:1^{c}	3.040:1^{b}
Total nitrogen (%)	Conventional compost	PC	0.008^{c}	0.011^{a}	0.002^{d}	0.008^{c}	0.010^{b}
		FC	0.013^{d}	0.990^{a}	0.004^{e}	0.016^{c}	0.020^{b}
	Vermicompost	PC	0.005^{a}	0.001^{c}	0.001^{c}	0.003^{b}	0.001^{c}
		FC	0.014^{a}	0.012^{b}	0.005^{e}	0.006^{c}	0.006^{d}
Total phosphorus (%)	Conventional compost	PC	0.980^{d}	0.897^{e}	1.320^{c}	3.470^{a}	1.420^{b}
		FC	1.840^{b}	0.900^{d}	1.560^{c}	3.830^{a}	1.870^{b}
	Vermicompost	PC	1.050^{c}	1.020^{d}	1.170^{b}	2.970^{a}	1.170^{b}
		FC	1.120^{d}	1.060^{e}	1.360^{c}	3.850^{a}	1.870^{b}
Total potassium (%)	Conventional compost	PC	0.786^{a}	0.529^{b}	0.218^{e}	0.289^{d}	0.432^{c}
		FC	0.993^{a}	0.789^{c}	0.363^{e}	0.987^{b}	0.576^{d}
	Vermicompost	PC	0.532^{b}	0.376^{d}	0.196^{e}	0.432^{c}	1.056^{a}
		FC	0.719^{b}	0.409^{d}	0.371^{e}	0.667^{c}	1.219^{a}
E280 nm	Conventional compost	PC	2.89^{d}	3.10^{c}	3.50^{b}	3.70^{a}	2.12^{e}
		FC	2.09^{d}	2.57^{a}	2.27^{c}	2.36^{b}	1.99^{e}
	Vermicompost	PC	4.60^{b}	2.12^{e}	3.17^{d}	4.19^{c}	4.92^{a}
		FC	3.25^{b}	2.03^{e}	2.80^{c}	2.61^{d}	3.40^{a}
E4 / E6	Conventional compost	PC	14.80^{c}	13.81^{d}	10.92^{e}	17.00^{a}	16.41^{b}
		FC	3.12^{e}	5.00^{a}	3.99^{c}	4.87^{b}	3.36^{d}
	Vermicompost	PC	34.45^{b}	34.85^{a}	15.71^{c}	11.45^{d}	8.98^{e}
		FC	6.85^{a}	4.19^{c}	3.40^{d}	3.01^{e}	6.00^{b}

In a column, means followed by a common letter are not significantly different at 5% level by DMRT

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Microbial breakdown products are either ingested by microorganisms and used for growth, or they accumulate in the water. These dynamics change as the compost matures. As a result, the examination of water extracts from composts is an important factor in determining compost maturity. The E4/E6 ratio showed a declining trend from partially decomposed to fully decomposed composts across all substrates. Pungam shell recorded the highest absorbance at E280 nm and E665 nm, while Albizia litter exhibited the greatest E4/E6 ratio of 5.6 under conventional composting. The E4/E6 ratio for vermicomposted samples was lower, with the lowest ratio recorded in Pungam shell vermicompost at 3.01 (*Table 5*).

Discussion

Interpretation of composting and humification parameters

Composting evolves through an active phase and a maturation phase. The active phase is characterized by intense microbial activity, ensuring the stability of organic matter and preventing deficiencies such as phytotoxicity due to easily decomposable compounds. Maturation, which begins at the end of the composting process, converts the already digested organic matter into humus-like compounds. Since the value of compost depends on its humification level, quantifying the amount and quality of humic acids is the best way to gather information about the process and quality of the end product (Sequi et al., 1986; Ciavatta et al., 1988). The study highlights significant variability in humification parameters across substrates and composting methods, reflecting differences in decomposition dynamics. The high polymerization ratio (PR) observed in Albizia litter suggests a more advanced structural transformation of organic matter, which aligns with findings by Tomati et al. (2000) that lignin-rich materials undergo slower but more stable humification. In contrast, the lower PR values recorded for Pungam shell indicate limited structural polymerization, likely due to its relatively low microbial decomposition rates. The degree of humification (DH) was markedly higher in Simarouba shell under conventional composting and coffee pulp under vermicomposting, suggesting substrate-specific responses to decomposition methods. This finding corroborates Ciavatta et al. (1990), who noted that humification indices are sensitive to the biochemical composition of the substrate. The humification of organic matter during composting was investigated by determining the levels of humic and fulvic acids, which are routinely used to measure compost maturity using several humification indices (Adani et al., 1995, 1997; Madejon et al., 1998). Humification is the polymerization and recombination of low molecular weight subunits that are transformed by the microbial communities found in composting trash. As a result, the progression of humic acids to higher molecular weights can be viewed as a more accurate diagnostic of humification and a general marker of the structural changes that occur during composting (Tomati et al., 2000). Because of its importance, the evolution of humic acids during the composting process was thoroughly investigated. Despite differences in substrate behavior, vermicompost had greater humification indices (degree of humification, polymerization ratio, and humification ratio). Nonetheless, their values varied according to the type of vermicompost. As a result, the humification maturity characteristics differed depending on the source material or substrate used for composting, highlighting the importance of standardizing these indices for each substrate.

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Comparative analysis of composting methods

Vermicomposting consistently demonstrated enhanced humification indices compared to conventional composting. For example, coffee pulp exhibited a higher degree of humification (1.974%) under vermicomposting than under conventional methods, likely due to the synergistic action of earthworms and microbes. Earthworms facilitate fragmentation and create microenvironments conducive to microbial activity, as documented by Rini et al. (2020). The lower E4/E6 ratio in vermicomposted samples further supports greater humification, as it indicates increased aromatic carbon development and the presence of humus-like compounds (Chen et al., 1977). These findings suggest that vermicomposting is more effective in accelerating the stabilization of organic matter and nutrient cycling.

Implications for compost maturity assessment

The variability observed in humification parameters underscores the limitations of relying on single indices to evaluate compost maturity. While the humification index (HI) and degree of humification (DH) provide valuable insights, their inconsistency across substrates highlights the need for a multi-parameter approach. For instance, the high HI value in coffee pulp during conventional composting did not consistently align with other parameters, such as the PR or C:N ratio. This aligns with studies by Chang et al. (2023), which emphasize the importance of integrating physico-chemical and biological indicators for a comprehensive assessment of compost maturity. The inclusion of spectrophotometric properties, such as the E4/E6 ratio, adds further robustness to the evaluation framework.

Nutrient enrichment in vermicomposting

Vermicomposting showed higher levels of phosphorus and potassium, particularly in substrates like Pungam shell and coffee pulp. This enrichment can be attributed to the enhanced microbial activity and nutrient cycling facilitated by earthworms, as reported by Rini et al. (2020). These improvements make vermicomposting a practical option for producing nutrient-rich compost suitable for agricultural applications, particularly for soils deficient in phosphorus or potassium.

The study demonstrates the complexity of assessing compost maturity, as no single parameter consistently captured the nuances of humification and stabilization across all substrates. Substrate-specific characteristics, such as lignin and cellulose content, significantly influenced the outcomes, making standardization challenging. Additionally, the variability in humification parameters suggests that external factors, such as temperature, moisture, and microbial communities, may have played a role. Future studies should explore advanced spectroscopic techniques, such as fluorescence spectroscopy, to capture molecular-level changes more precisely. Incorporating microbial profiling and enzyme activity measurements could further elucidate the mechanisms underlying humification and nutrient cycling. This study contributes to the understanding of compost maturity by emphasizing the importance of a multi-parameter approach to assessment. By integrating humification indices, spectrophotometric properties, and nutrient profiles, it provides a comprehensive framework for evaluating compost quality. The findings also highlight the potential of vermicomposting as a superior method for managing agricultural and forestry wastes, offering practical solutions for producing high-quality, nutrient-enriched compost.

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Conclusion

This study aimed to evaluate compost maturity by analyzing key humification parameters, physico-chemical properties, and spectrophotometric indices in various forestry and agricultural substrates, comparing conventional composting and vermicomposting methods. The primary objectives were to assess the reliability of humification indices, examine the influence of composting methods on decomposition dynamics, and highlight the limitations of single-parameter evaluations in compost maturity assessment. These objectives were successfully addressed through the study's findings. The results confirmed significant variability in humification parameters, such as the humification index (HI) and degree of humification (DH), across substrates and composting methods. Vermicomposting consistently demonstrated enhanced decomposition and nutrient enrichment, evidenced by lower E4/E6 ratios and higher phosphorus and potassium levels compared to conventional composting. These findings align with the hypothesis that vermicomposting, due to earthworm activity and its facilitation of microbial diversity, would result in higher humification indices and superior compost quality. However, the observed substrate-specific differences in humification parameters indicate that the second hypothesis, positing uniformity in humification trends across substrates, was only partially supported. The study highlights the limitations of relying solely on individual humification indices, as no single parameter consistently captured the complexity of compost maturity across all substrates. For example, while the polymerization ratio (PR) was a strong indicator of structural changes in Albizia litter, it was less effective for substrates like Pungam shell. These findings emphasize the need for a multi-parameter approach, integrating humification indices, C:N ratio, and spectrophotometric properties, to ensure a comprehensive and reliable evaluation of compost quality. The practical implications of this research are significant. Vermicomposting proved particularly effective for substrates with high lignin content, offering a viable strategy for accelerating the composting process and producing nutrient-rich amendments for agricultural and forestry applications. These findings can inform compost management practices, guiding the selection of composting methods and maturity indicators based on substrate type. Future research should refine current indices and explore advanced methodologies to better capture molecular-level changes during composting. Techniques such as fluorescence spectroscopy and microbial community profiling could provide deeper insights into the interactions between substrate properties and composting processes. Additionally, investigating the synergistic effects of microbial inoculants and earthworms may optimize humification and nutrient cycling, contributing further to sustainable waste management practices. In summary, this study advances the understanding of compost maturity by demonstrating the importance of a multi-parameter evaluation framework and highlighting the advantages of vermicomposting for enhancing compost quality. The findings contribute valuable knowledge for improving composting practices and managing organic waste effectively in both agricultural and forestry contexts.

Conflicts of interest. The authors declare that they have no conflict of interest.

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