



Performance Evaluation of a Cost Effective Earthworm-Based Vermicomposting Technology for Integrated Management of Municipal Solid Waste and Sewage Sludge

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Abstract : Municipal solid waste and sewage sludge need safe, economical and sustainable treatment before disposal or reuse. This study developed and evaluated a low-cost earthworm-based vermicomposting system for the integrated treatment of both wastes under six administrative divisions of Maharashtra representing different climatic conditions. A pilot-scale experiment was conducted using three treatment combinations. Physical, chemical and biological parameters were monitored over a 90-day composting period. Treatment performance was evaluated using one-way ANOVA, Tukey's Honest Significant Difference (HSD) test, Pearson correlation and linear regression analysis. The developed system performed well under all climatic conditions and produced stable vermicomposting in every treatment. Treatment T3 gave the best overall performance. It recorded lower total organic carbon (16.28%) and C:N ratio (11.20), together with higher total nitrogen (1.51%) and humification index (5.20). Earthworm biomass and cocoon production increased throughout the study, while coliform counts declined and earthworm mortality remained below 5%. Statistical analysis supported these improvements and confirmed strong relationships among the major compost maturity indicators. Sewage sludge and municipal solid waste can be effectively managed with the cost-effective vermicomposting technology. It is appropriate for local resource recovery and waste management because to its efficacy in a variety of climates.

Keywords: Municipal solid waste; Sewage sludge; Vermicomposting; Earthworms; Performance evaluation; Cost effective technology; Sustainable waste management.

1. INTRODUCTION

The generation of municipal solid waste (MSW) and sewage sludge has increased rapidly over the last few decades. Urbanization, population growth, and changing consumption patterns continue to increase the amount of biodegradable waste produced worldwide. Poor management of these wastes contributes to odor generation, greenhouse gas emissions, soil and groundwater contamination, and public health concerns. Sustainable methods of treatment are thus necessary to restrict impact on the environment while reclaiming valuable resources from organic waste (Alshehrei & Ameen, 2021; Karmakar et al., 2024).

Municipal solid waste contains a large biodegradable fraction that can be converted into useful products instead of being disposed of in landfills. Sewage sludge is another organic waste rich in carbon and plant nutrients. However, its direct disposal or land application is often limited by pathogens and unstable organic matter. Proper stabilization is therefore essential before its safe utilization. Biological treatment offers an effective option because it converts waste into valuable products with lower environmental impacts (Rakkini et al., 2017; Boruah et al., 2020).

Among the available biological methods, vermicomposting has emerged as a simple and cost-effective technology for organic waste recycling. Earthworms physically break down organic materials and increase the surface area available for microbial activity. Their interaction with microorganisms accelerates decomposition and improves nutrient mineralization. As a result, the final vermicomposting becomes more stable and nutrient-rich. Earlier studies have reported a reduction in total organic carbon and C:N ratio together with an increase in nitrogen, phosphorus, and potassium during vermicomposting (Mishra et al., 2014; Wang et al., 2019; Singh et al., 2025).

The efficiency of vermicomposting depends on several factors. Waste composition, moisture content, temperature, and climatic conditions strongly influence earthworm activity and compost quality. Municipal solid waste and sewage sludge differ in their physical and chemical characteristics. Their combined treatment can improve nutrient recovery, but an unsuitable mixing ratio may reduce process efficiency. Previous studies have also shown that climatic conditions influence decomposition rate, microbial activity, and compost stabilization (Ponmani et al., 2014; Pande & Gulhane, 2020; Hemalatha et al., 2024). Although previous studies have evaluated different organic wastes, fewer studies have examined low-cost vermicomposting systems for the combined treatment of municipal solid waste and sewage sludge under different climatic conditions. Most available studies have focused on specific waste streams or controlled experimental conditions. This creates a need for practical and economically viable technologies that can be adopted under field conditions.

Therefore, the present study developed and evaluated a low-cost earthworm-based vermicomposting technology for the integrated management of municipal solid waste and sewage sludge. The developed system was evaluated using different waste combinations under contrasting climatic conditions. Changes in physical, chemical, and biological characteristics were monitored throughout the composting period. The findings provide information on process performance, compost quality, and the practical application of low-cost vermicomposting technology for sustainable organic waste management.

2. MATERIALS AND METHODS

2.1 Study Design

A pilot-scale study was conducted to evaluate the performance of a low-cost vermicomposting system developed for the integrated treatment of municipal solid waste (MSW) and municipal sewage sludge. The system was constructed using locally available materials to provide an economical alternative to conventional vermicomposting units. The study evaluated waste stabilization, nutrient recovery and vermicomposting production using the developed low-cost system.

The experiment was carried out in six administrative divisions of Maharashtra: Konkan, Pune, Nashik, Chhatrapati Sambhajnagar, Amravati, and Nagpur. The selected divisions represent diverse climatic conditions, ranging from humid coastal to semi-arid and tropical regions. Evaluating the system under different climatic conditions helped assess its adaptability and field-scale applicability.

The experimental design included three treatment combinations to evaluate the effect of sewage sludge incorporation on the vermicomposting process. The composition and purpose of each treatment are summarized in Table 1. Treatment T1 consisted of 100% segregated organic municipal solid waste with bulking agents and served as the control. Treatment T2 contained 75% municipal solid waste and 25% sewage sludge with bulking agents. Treatment T3 was composed of 50% municipal solid waste and 50% sewage sludge, with bulking agents and a microbial inoculant (Manea & Bumbac, 2024). These treatment levels were selected based on previous studies reporting that moderate incorporation of sewage sludge improves nutrient recovery while maintaining suitable conditions for *Eisenia fetida* (Yadav & Garg, 2011; Karimi et al., 2016; Suthar, 2009).

Each treatment was maintained in triplicate. The units were arranged randomly under a common shade-net structure to minimize environmental variation during the composting period (Suthar, 2009).

Table 1. Composition of experimental treatments used in the vermicomposting study.

Treatment	Composition	Purpose
T1	100% MSW + Bulking agents	Control
T2	75% MSW + 25% Sewage sludge + Bulking agents	Partial sludge incorporation
T3	50% MSW + 50% Sewage sludge + Bulking agents + Microbial inoculant	Integrated treatment

2.2 FEEDSTOCK MATERIALS AND VERMICOMPOSTING SYSTEM

The organic fraction of municipal solid waste (MSW) was collected from municipal collection points after source segregation. The feedstock mainly consisted of vegetable residues, fruit peels, kitchen waste, garden waste, and leaf litter. Non-biodegradable materials such as plastics, glass, and metals were removed before processing. The collected waste was shredded into small pieces to improve aeration and facilitate earthworm feeding.

Dewatered municipal sewage sludge was used as a nitrogen-rich co-substrate. Bulking agents were added to improve porosity, moisture balance, and aeration of the feed mixture. The selected proportions of municipal solid waste and sewage sludge were prepared according to the experimental design before loading into the vermicomposting units.

A low-cost pilot-scale vermicomposting unit was constructed using brick masonry and locally available materials. A schematic representation of the developed vermicomposting unit is shown in Figure 1. Each unit measured 1.5 m × 1.0 m × 0.75 m and included a drainage layer for leachate collection. A shade-net structure protected the units from direct sunlight and rainfall, while maintaining favorable conditions for earthworm activity. The system was designed for efficient vermicomposting of municipal solid waste and sewage sludge under controlled environmental conditions.

Before earthworm inoculation, the prepared feedstock mixtures were subjected to a short pre-composting period to reduce excess heat and stabilize the substrate. Healthy adult *Eisenia fetida* were then introduced into each vermicomposting unit. The composting process was carried out for 90 days under regular monitoring of moisture and temperature to maintain suitable conditions for earthworm growth and organic matter decomposition.

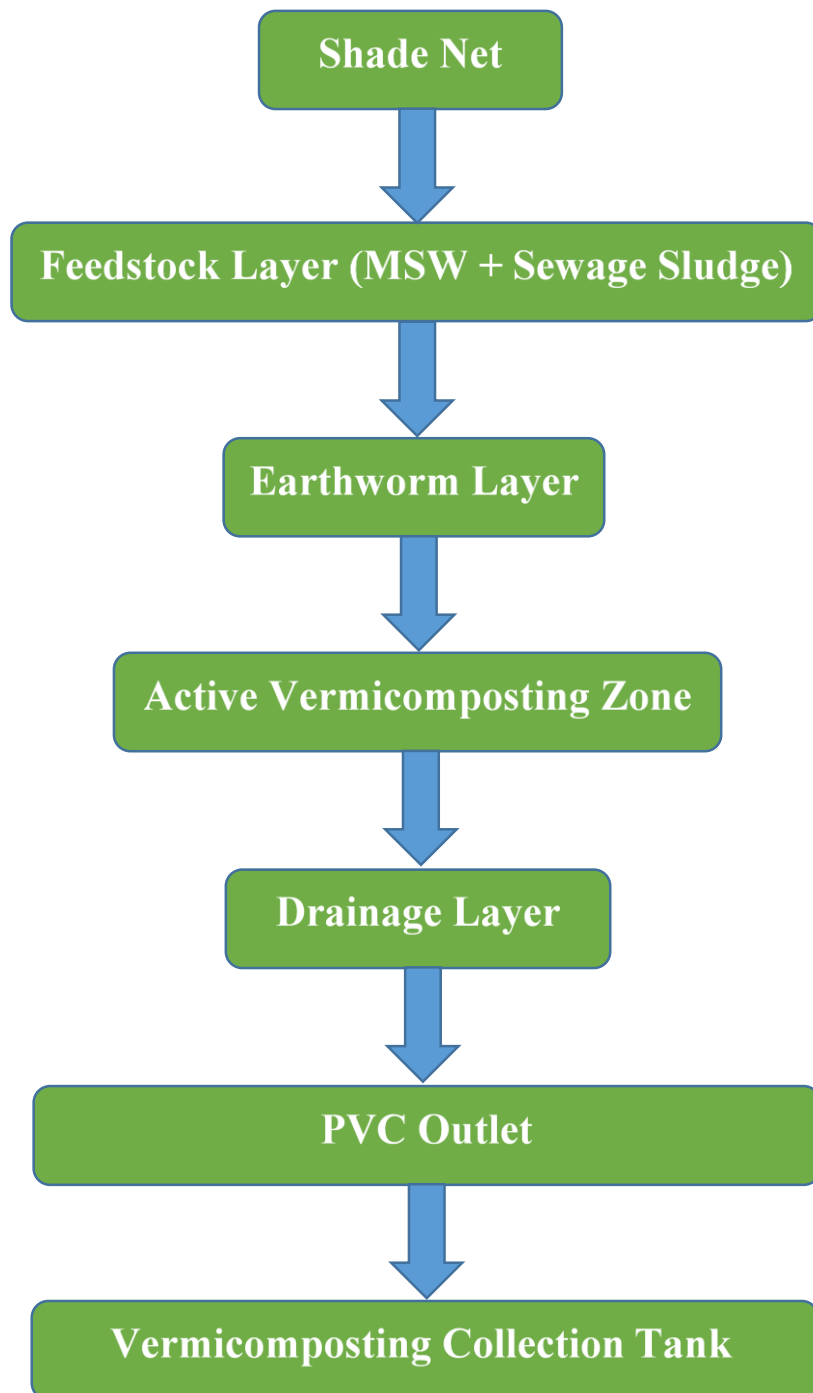


Figure 1. Schematic representation of the developed low-cost vermicomposting unit.

2.3 SAMPLING, ANALYTICAL METHODS AND STATISTICAL ANALYSIS

Samples were collected at four stages of the vermicomposting process, namely Day 0, Day 30, Day 60, and Day 90. Composite samples were collected from each treatment in triplicate to ensure representative analysis. The sampling schedule adopted during the study is presented in Table 2.

Table 2. Sampling schedule adopted during the vermicomposting study.

Sr. No	Sampling Day	Analysis Performed
1	Day 0	Initial characterization of feedstock
2	Day 30	Physical, chemical and biological analyses
3	Day 60	Physical, chemical and biological analyses
4	Day 90	Final compost quality assessment and earthworm performance

Physical parameters including temperature, moisture content, pH and electrical conductivity (EC) were monitored throughout the experimental period. Chemical analyses included total organic carbon (TOC), total nitrogen (TN), C:N ratio and humification index (HI). Biological observations included earthworm biomass, cocoon production and Coliform Count. The quality of the final vermicomposting was evaluated using the selected physical, chemical and biological parameters. The analytical parameters included in the study are summarized in Table 3.

Table 3. Parameters analyzed during the vermicomposting study.

Sr. No	Category	Parameters
1	Physical	Temperature, Moisture content, pH, Electrical conductivity (EC)
2	Chemical	Total organic carbon (TOC), Total nitrogen (TN), C:N ratio, Humification Index (HI)
3	Biological	Earthworm biomass, Cocoon production, Coliform Count, Earthworm Mortality
4	End products	Vermicomposting

All laboratory analyses were performed using standard analytical procedures. Physico-chemical parameters were determined according to standard methods for the examination of water and wastewater wherever applicable, while compost quality analyses followed established procedures described in the literature. Quality control was maintained throughout the analytical process to ensure the reliability of the experimental data.

For graphical presentation, the values obtained from the six administrative divisions were averaged treatment-wise at each sampling interval (Day 0, Day 30, Day 60, and Day 90). These mean values were used to prepare the summary graphs presented in the Results section to facilitate comparison among treatments while maintaining the overall experimental trends.

The experimental data were expressed as mean $\pm$ standard deviation of three replicates. Statistical differences among treatments and climatic regions were evaluated using one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) test at a significance level of $p < 0.05$. Pearson correlation analysis was performed to determine the relationships among the measured parameters. Linear regression analysis was further used to validate the relationships among the principal compost maturity indicators.

3. RESULTS

3.1 OVERALL PERFORMANCE OF THE DEVELOPED VERMICOMPOSTING SYSTEM

The developed low-cost vermicomposting system successfully converted municipal solid waste and sewage sludge into a stable organic product under all treatment conditions. Continuous changes in the physical, chemical and biological properties of the feedstock confirmed the steady progress of vermicomposting throughout the 90-day experimental period. The overall experimental workflow and performance of the developed system are presented in Figure 2.

All treatments showed gradual improvement in waste stabilization. However, the level of improvement varied among the treatment combinations. Treatment T3, which consisted of municipal solid waste, sewage sludge, bulking agents and a microbial inoculant, consistently produced better overall performance. Greater organic matter stabilization, improved nutrient enrichment, enhanced humification and better earthworm growth were recorded in T3 than in Treatments T1 and T2. Treatment T2 also performed better than the control, indicating that partial incorporation of sewage sludge improved the composting process.

Climatic conditions also influenced the efficiency of the developed system. Composting units located in humid and moderate climatic regions reached stabilization earlier than those maintained under semi-arid conditions. Even so, all treatment combinations produced stable vermicomposting by the end of the experimental period. This demonstrates the adaptability of the developed low-cost technology under different environmental conditions.

The developed vermicomposting system can be effectively applied for the integrated management of municipal solid waste and sewage sludge. At the same time, it produces stable and nutrient-rich vermicomposting suitable for resource recovery.

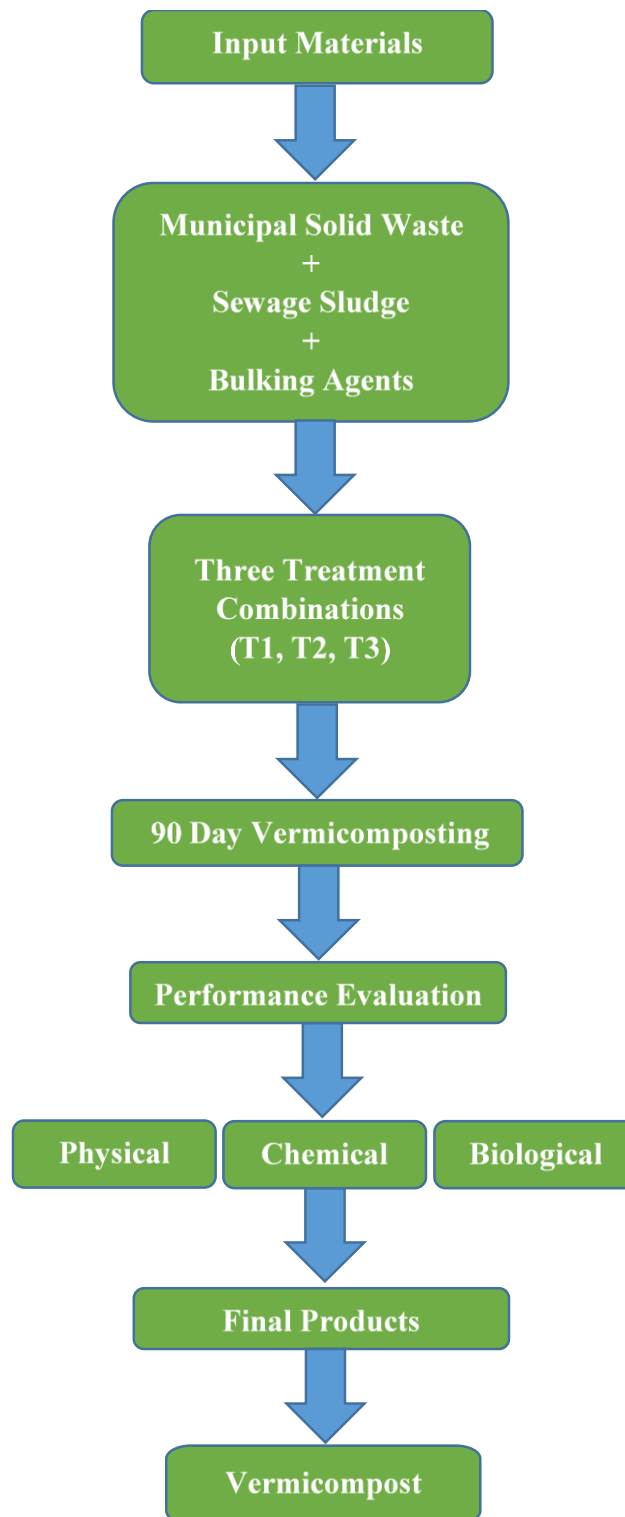


Figure 2. Overall performance of the developed low-cost vermicomposting technology for integrated management of municipal solid waste and sewage sludge .

3.2 CHANGES IN PHYSICAL PARAMETERS

Temporal changes in the physical parameters during vermicomposting are presented in Figure 3, while the final mean values recorded on Day 90 are summarized in Table 4.

Temperature remained within the mesophilic range throughout the experimental period (Figure 3A) . This provided favorable conditions for microbial activity and earthworm survival . A slight increase was observed during the initial stage of composting, followed by gradual stabilization towards Day 90 . The highest final mean temperature was recorded in Treatment T3 (28.60°C), followed by T2 (28.48°C) and T1 (28.38°C) (Table 4) . Temperature fluctuations were also influenced by climatic conditions . Composting units in humid and moderate regions remained more stable than those in semi-arid areas .

Moisture content gradually declined in all treatments during vermicomposting (Figure 3B) . This reduction was associated with microbial respiration, evaporation and continuous decomposition of organic matter . Even so, moisture remained within the range required for active earthworm growth . By Day 90, Treatment T3 retained the highest mean moisture content (59.00%), followed by T2 (58.00%) and T1 (57.00%) (Table 4) .

The pH of the composting material gradually shifted from slightly acidic to nearly neutral conditions during the composting process (Figure 3C). This change reflects progressive stabilization of organic matter and the reduction of intermediate organic acids. The final mean pH ranged from 7.18 in T1 to 7.38 in T3, indicating favourable conditions for compost maturity (Table 4).

Electrical conductivity (EC) increased steadily throughout the composting period (Figure 3D). The increase reflects the release of soluble mineral salts during organic matter mineralization. Treatment T3 recorded the highest final mean EC (2.75 dS/m), followed by T2 (2.55 dS/m) and T1 (2.35 dS/m) (Table 4). Higher EC values indicate greater nutrient availability in the final vermicomposting.

The physical properties changed steadily throughout the composting period. Together, these changes confirm efficient stabilization of the feedstock. Among the three treatments, T3 maintained the most favorable physical conditions and showed the best overall process performance.

Table 4. Final mean values of physical parameters recorded at Day 90 under different treatments.

Parameter	T1	T2	T3	Overall trend
Temperature (°C)	28.38	28.48	28.60	Stabilized after the active decomposition phase
Moisture content (%)	57.00	58.00	59.00	Gradual decrease throughout the composting period
pH	7.18	7.28	7.38	Shifted towards near-neutral conditions
Electrical conductivity (dS/m)	2.35	2.55	2.75	Progressive increase due to mineralization

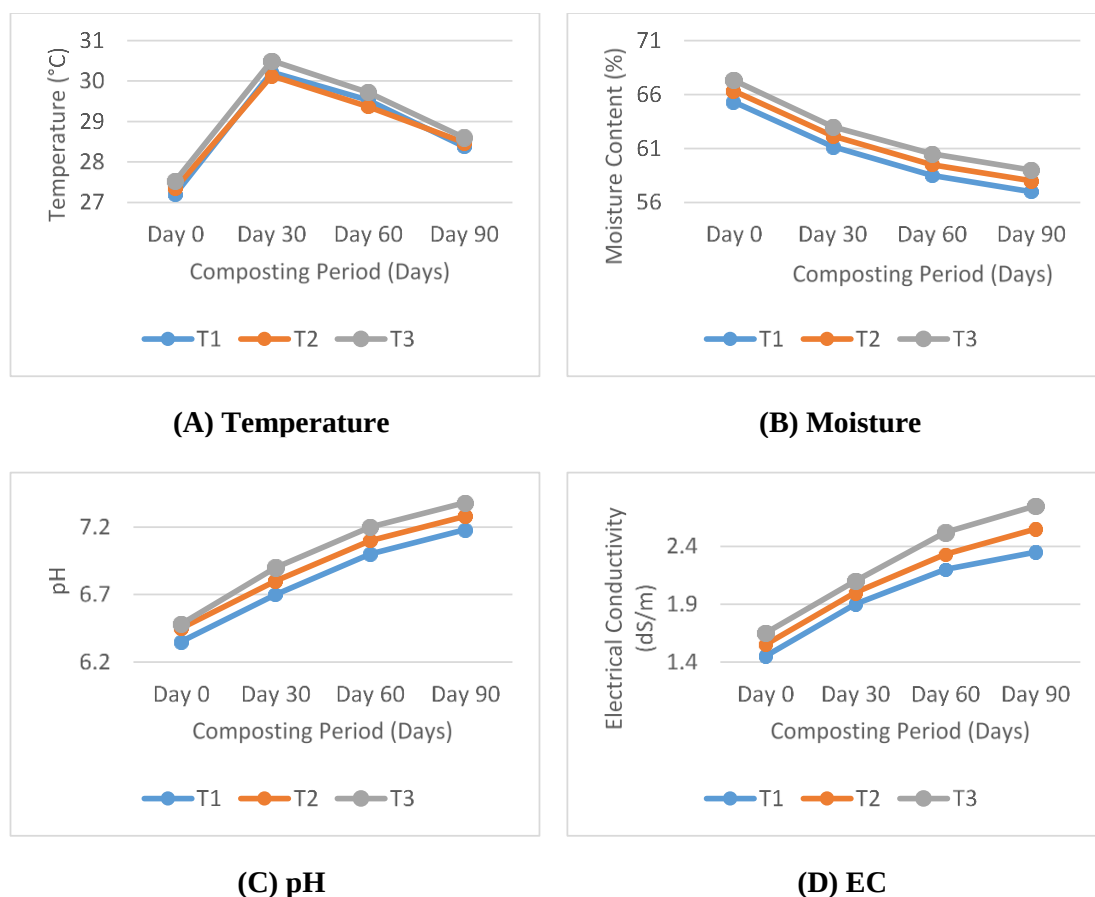


Figure 3. Changes in physical parameters during vermicomposting under different treatment combinations based on the mean values of six administrative divisions.

3.3 CHANGES IN CHEMICAL PARAMETERS

The changes in chemical parameters during vermicomposting are presented in Figure 4, which was prepared using the treatment-wise mean values from the six administrative divisions. The final mean values recorded on Day 90 are summarized in Table 5. Progressive changes in total organic carbon, total nitrogen, C:N ratio and humification index confirmed the continuous decomposition and stabilization of the organic waste mixtures throughout the composting period.

Total organic carbon (TOC) declined steadily in all treatments during vermicomposting (Figure 4A). The reduction reflects the mineralization of organic matter through the combined activity of earthworms and microorganisms. Treatment T3

showed the greatest reduction, reaching a final mean TOC of 16.28%. In contrast, T1 retained the highest residual organic carbon (18.60%) (Table 5).

Total nitrogen (TN) increased gradually throughout the composting period (Figure 4B). The increase was associated with organic matter degradation, nutrient concentration and microbial transformation of nitrogenous compounds. Treatment T3 recorded the highest final mean TN (1.51%), followed by T2 (1.41%) and T1 (1.32%) (Table 5).

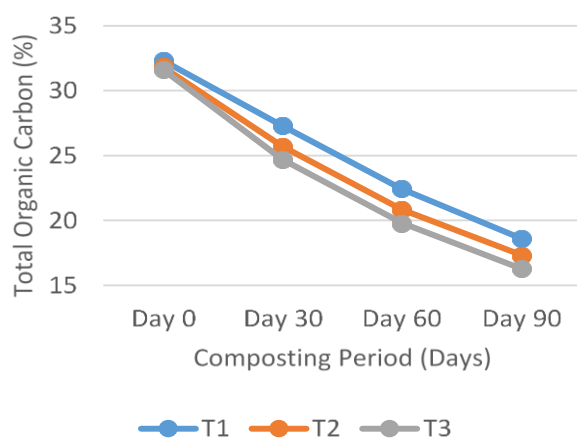
The C:N ratio declined continuously in all treatments during vermicomposting (Figure 4C). This change reflects the gradual stabilisation of the composting material. The lowest final mean C:N ratio was recorded in T3 (11.20), followed by T2 (11.95) and T1 (13.10). These values indicate more efficient decomposition in the sludge-amended treatment (Table 5).

The humification index increased steadily throughout the composting period (Figure 4D). This reflects the gradual formation of stable humic substances and improved compost maturity. Treatment T3 recorded the highest final mean humification index (5.20), while T1 showed the lowest value (4.45) (Table 5).

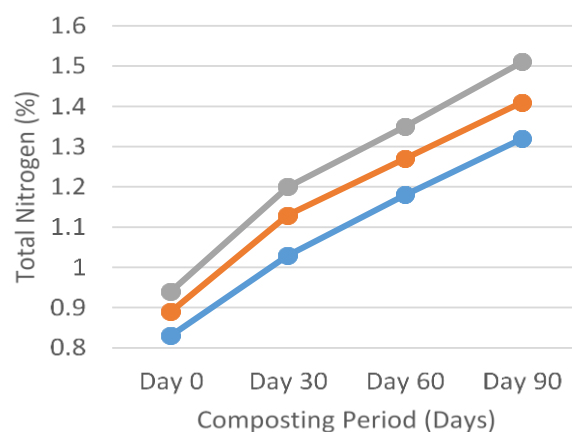
The chemical properties changed consistently throughout the composting period. Together, these changes confirm efficient organic matter stabilisation and nutrient transformation. Among the three treatments, T3 produced the highest degree of compost maturity, with lower TOC and C:N ratio together with higher total nitrogen and humification index.

Table 5. Final mean values of selected chemical parameters recorded at Day 90 under different treatments.

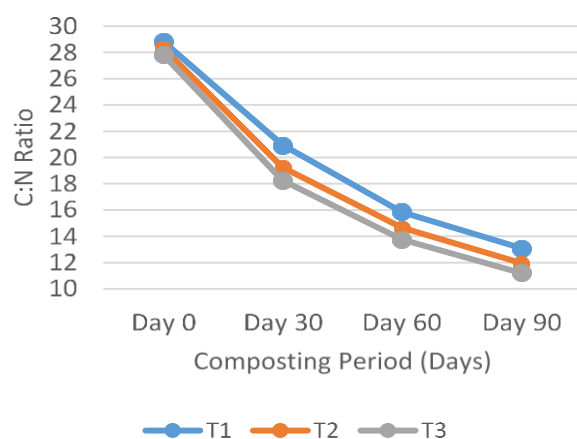
Parameter	T1	T2	T3	Overall trend
Total Organic Carbon (%)	18.60	17.33	16.28	Progressive reduction indicating organic matter stabilization
Total Nitrogen (%)	1.32	1.41	1.51	Gradual increase due to nutrient mineralization
C:N Ratio	13.10	11.95	11.20	Continuous decline indicating compost maturity
Humification Index	4.45	4.85	5.20	Progressive increase indicating humus formation



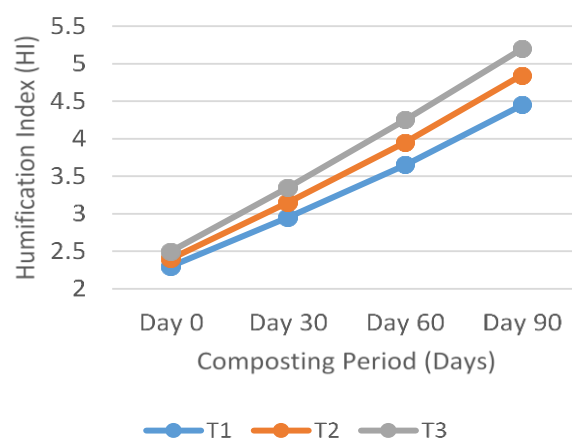
(A) Total Organic Carbon (TOC)



(B) Total Nitrogen (TN)



(C) C:N Ratio



(D) Humification Index (HI)

Figure 4. Changes in chemical parameters during vermicomposting under different treatment combinations based on the mean values of six administrative divisions.

3.4 CHANGES IN BIOLOGICAL PARAMETERS

The changes in biological parameters during vermicomposting are presented in Figure 5, which was prepared using the treatment-wise mean values from the six administrative divisions. The final mean values recorded on Day 90 are summarised in Table 6. Earthworm biomass, cocoon production, coliform count and earthworm mortality changed gradually throughout the 90-day composting period, reflecting favorable biological conditions and continuous stabilisation of the organic waste mixture.

Earthworm biomass increased steadily in all treatments during vermicomposting (Figure 5A). The increase reflects favourable environmental conditions and adequate nutrient availability for earthworm growth. Treatment T3 recorded the highest final mean biomass (368.50 g), followed by T2 (364.00 g) and T1 (355.33 g) (Table 6).

Cocoon production also increased throughout the composting period (Figure 5B). No cocoons were observed at the beginning of the experiment. A marked increase was recorded after Day 30, indicating active earthworm reproduction. Treatment T3 produced the highest final mean cocoon count (505.33), followed by T2 (492.83) and T1 (472.83) (Table 6).

Coliform counts declined steadily during vermicomposting (Figure 5C). The reduction reflects effective pathogen removal during the stabilisation process. Treatment T3 recorded the lowest final mean coliform count (1.50 log CFU g⁻¹), followed by T2 (1.62 log CFU g⁻¹) and T1 (1.82 log CFU g⁻¹). These values indicate improved hygienic quality of the final vermicompost (Table 6).

Earthworm mortality remained low throughout the experimental period despite a gradual increase with composting duration (Figure 5D). The final mean mortality ranged from 4.22% in T1 to 4.92% in T3 (Table 6). The low mortality observed in all treatments confirms that the developed vermicomposting system maintained suitable conditions for earthworm survival.

The biological properties changed consistently throughout the composting period. Higher earthworm biomass and cocoon production, together with lower coliform counts and low mortality, confirm the efficient performance of the developed low-cost vermicomposting technology. Among the three treatments, T3 provided the most favourable biological conditions for organic waste stabilisation.

Table 6. Final mean values of selected biological parameters recorded at Day 90 under different treatments.

Parameter	T1	T2	T3	Overall Trend
Earthworm Biomass (g)	355.33	364.00	368.50	Progressive increase throughout vermicomposting
Cocoon Production (No. of cocoons)	472.83	492.83	505.33	Continuous increase indicating active reproduction
Coliform Count (log CFU g ⁻¹)	1.82	1.62	1.50	Progressive reduction indicating pathogen removal
Earthworm Mortality (%)	4.22	4.57	4.92	Low mortality observed throughout the experimental period

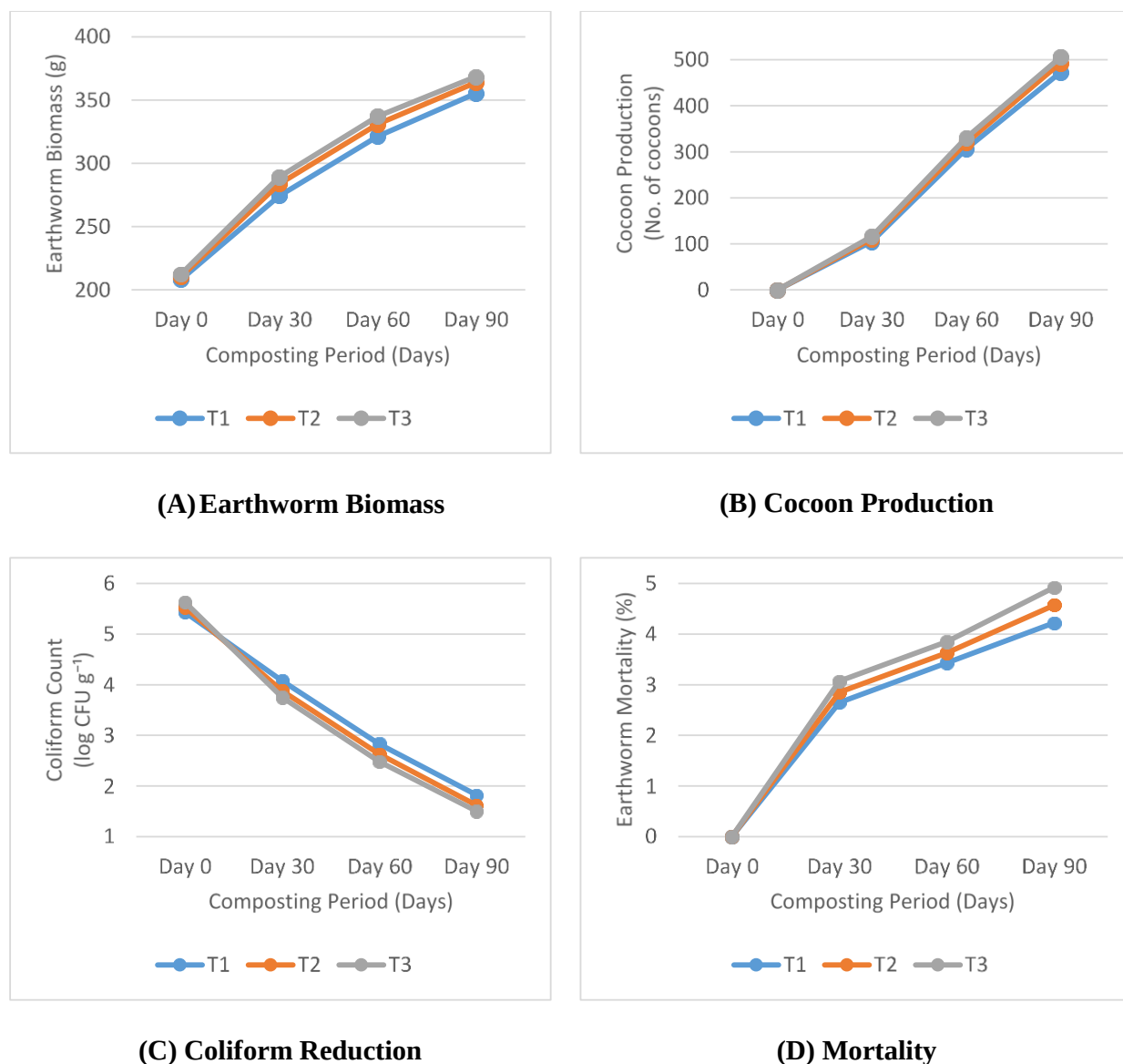


Figure 5. Changes in biological parameters during vermicomposting under different treatment combinations based on the mean values of six administrative divisions .

3.5 STATISTICAL ANALYSIS

Statistical analyses were carried out to compare treatment performance and examine the relationships among the major compost maturity indicators. The graphical results presented in this study were prepared using treatment-wise pooled mean values from the six administrative divisions of Maharashtra. The same dataset was therefore used for all statistical analyses.

One-way analysis of variance (ANOVA) was applied to determine significant differences among the three treatment combinations (T1, T2 and T3). Tukey's Honest Significant Difference (HSD) test was then used for pairwise comparison of the significant parameters. Pearson correlation analysis was performed to examine the relationships among the principal physicochemical indicators of compost maturity. Linear regression analysis was used to further validate these relationships. Statistical significance was considered at $p < 0.05$.

3.5.1 Analysis of Variance (ANOVA)

One-way ANOVA was used to examine the effect of treatment composition on the vermicomposting process. The analysis showed significant differences among the three treatments for several physicochemical parameters (Table 7). Significant treatment effects ($p < 0.05$) were observed for pH, electrical conductivity (EC), total organic carbon (TOC), total nitrogen (TN), C:N ratio, humification index (HI) and earthworm mortality. In contrast, temperature, moisture content, coliform count, earthworm biomass and cocoon production did not differ significantly among the treatments.

Among all measured parameters, electrical conductivity showed the strongest treatment effect ($F = 12.632$, $p = 0.0006$). It was followed by total nitrogen ($F = 12.433$, $p = 0.0007$), pH ($F = 10.588$, $p = 0.0014$) and C:N ratio ($F = 8.923$, $p = 0.0028$). These results show that the addition of sewage sludge and microbial inoculation influenced nutrient transformation during vermicomposting. Similar responses were observed for TOC and the humification index, both of which changed significantly as compost maturity progressed.

Treatment T3 produced the best overall compost quality. By Day 90, it recorded the lowest TOC (16.28%) and C:N ratio (11.20). It also showed the highest total nitrogen (1.51%) and humification index (5.20). Together, these changes confirm faster organic matter stabilisation and improved compost maturity in the integrated treatment.

Earthworm biomass and cocoon production increased throughout the composting period. However, the differences among treatments were not statistically significant. A similar pattern was observed for coliform reduction. These results indicate that all three treatments maintained suitable conditions for earthworm activity and biological stabilisation.

Earthworm mortality was the only biological parameter that showed a significant treatment effect ($p = 0.0426$). Even so, mortality remained below 5% in all treatments. This confirms that the developed vermicomposting system provided suitable conditions for earthworm survival despite the incorporation of sewage sludge.

Overall, the ANOVA results support the experimental observations. The integrated treatment consistently produced better compost quality than the other treatments. Improvements in nutrient transformation, organic matter stabilisation and humification were also supported by the statistical analysis.

Table 7. One-way ANOVA summary for the selected vermicomposting parameters evaluated at Day 90.

Sr.No	Parameter	F-value	p-value	Interpretation
1	Temperature	0.360	0.7033	Not Significant
2	Moisture Content	0.441	0.6514	Not Significant
3	pH	10.588	0.0014	Significant
4	Electrical Conductivity (EC)	12.632	0.0006	Significant
5	Total Organic Carbon (TOC)	6.659	0.0085	Significant
6	C:N Ratio	8.923	0.0028	Significant
7	Total Nitrogen (TN)	12.433	0.0007	Significant
8	Humification Index (HI)	5.741	0.0178	Significant
9	Coliform Count	1.629	0.2289	Not Significant
10	Earthworm Biomass	1.319	0.2966	Not Significant
11	Cocoon Production	1.684	0.2189	Not Significant
12	Earthworm Mortality	3.923	0.0426	Significant

Interpretation : Parameters with $p < 0.05$ were considered significantly influenced by treatment composition.

3.5.2 Tukey's Honest Significant Difference (HSD) Test

Tukey's Honest Significant Difference (HSD) test was performed after one-way ANOVA to compare the treatment combinations for the statistically significant parameters (Table 8). Clear differences were observed among the three treatments. Treatment T3 consistently produced the best overall performance, while T2 remained intermediate between the control (T1) and T3. This pattern agrees with the changes observed in the physicochemical parameters discussed in Section 3.3.

Total organic carbon (TOC) declined from 18.60% in T1 to 16.28% in T3. The lower TOC reflects greater degradation of biodegradable organic matter during vermicomposting. The C:N ratio also decreased from 13.10 to 11.20, indicating faster compost stabilisation and maturity. In contrast, total nitrogen (TN) increased from 1.32% to 1.51%. The humification index (HI) also increased from 4.45 to 5.20. Together, these changes confirm improved nutrient transformation and humus formation in the integrated treatment.

Electrical conductivity increased from 2.35 to 2.75 dS m^{-1} between T1 and T3. This increase reflects the release of soluble mineral nutrients during decomposition. A gradual shift in pH towards neutral conditions was also observed. The change indicates progressive stabilisation of the composting material and a reduction in intermediate organic acids.

The pairwise comparison clearly separated T3 from the control treatment for the major compost maturity indicators. Treatment T2 showed intermediate values for most parameters. These results confirm that the combined application of sewage sludge and microbial inoculation improved vermicomposting efficiency and produced a more stable and nutrient-rich compost.

Table 8. Tukey's Honest Significant Difference (HSD) multiple comparison test for significant vermicomposting parameters at Day 90.

Sr. No.	Parameter	T1	T2	T3
1	pH	7.18 ^a	7.28 ^{ab}	7.38 ^b
2	Electrical Conductivity (dS m ⁻¹)	2.35 ^a	2.55 ^{ab}	2.75 ^b
3	Total Organic Carbon (%)	18.60 ^a	17.33 ^{ab}	16.28 ^b
4	Total Nitrogen (%)	1.32 ^a	1.41 ^{ab}	1.51 ^b
5	C:N Ratio	13.10 ^a	11.95 ^{ab}	11.20 ^b
6	Humification Index	4.45 ^a	4.85 ^{ab}	5.20 ^b

Means followed by different superscript letters (a, ab and b) differ significantly at $p < 0.05$ according to Tukey's Honest Significant Difference (HSD) multiple comparison test.

3.5.3 Pearson Correlation Analysis

Pearson correlation analysis was carried out using the pooled mean values from the six administrative divisions. The relationships among the major compost maturity indicators are presented in Figure 6 and Table 9. Strong positive and negative correlations were observed among the selected physicochemical parameters. These relationships reflect the simultaneous progression of organic matter degradation, nutrient transformation and compost stabilisation during vermicomposting.

Total organic carbon (TOC) showed strong negative correlations with total nitrogen (TN) ($r = -0.912$), electrical conductivity (EC) ($r = -0.902$) and the humification index (HI) ($r = -0.895$). As organic carbon declined, nutrient availability and humification increased. Electrical conductivity also increased with the release of soluble mineral salts during decomposition.

The C:N ratio followed a similar pattern. Strong negative correlations were recorded with total nitrogen ($r = -0.901$), humification index ($r = -0.872$) and electrical conductivity ($r = -0.879$). The gradual decline in the C:N ratio therefore reflects continuous compost stabilisation. Carbon loss through microbial respiration was accompanied by nitrogen enrichment and humus formation throughout the composting period.

Positive relationships were also observed among the maturity indicators. Total nitrogen showed strong positive correlations with electrical conductivity ($r = 0.951$) and the humification index ($r = 0.936$). The humification index was also strongly correlated with electrical conductivity ($r = 0.948$). These relationships confirm that nutrient enrichment, mineralization and humification progressed together during vermicomposting.

The correlation analysis showed a clear relationship between carbon loss and compost maturity. Lower TOC and C:N ratio were consistently associated with higher nitrogen content, electrical conductivity and humification index. These relationships demonstrate the efficiency of the developed low-cost vermicomposting technology for the combined treatment of municipal solid waste and sewage sludge under different climatic conditions.

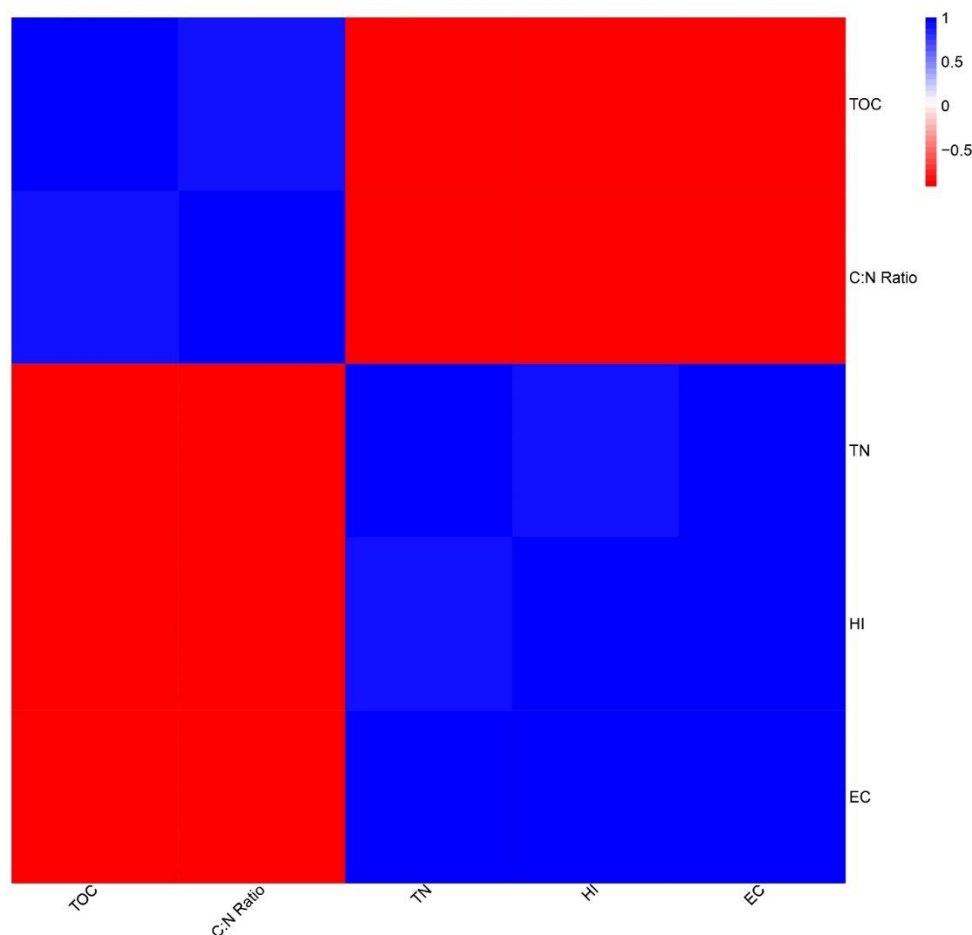


Figure 6. Pearson correlation heatmap illustrating the relationships among the principal compost maturity indicators based on treatment-wise pooled mean values obtained from the six administrative divisions of Maharashtra . (Blue colours indicate positive correlations, whereas red colours indicate negative correlations) .

Table 9. Pearson correlation coefficients among the principal compost maturity indicators .

Sr. No	Parameter	TOC	C : N Ratio	TN	HI	EC
1	TOC	1.000	0.934	-0.912	-0.895	-0.902
2	C : N Ratio	0.934	1.000	-0.901	-0.872	-0.879
3	Total Nitrogen (TN)	-0.912	-0.901	1.000	0.936	0.951
4	Humification Index (HI)	-0.895	-0.872	0.936	1.000	0.948
5	Electrical Conductivity (EC)	-0.902	-0.879	0.951	0.948	1.000

3.5.4 Regression Analysis

Linear regression analysis was used to further examine the relationships among the major compost maturity indicators identified through Pearson correlation analysis. The regression models showed consistent linear trends throughout the vermicomposting process. Changes in total organic carbon (TOC), total nitrogen (TN), C:N ratio and humification index (HI) followed predictable patterns, confirming that these parameters are reliable indicators of compost maturity.

A gradual decline in TOC was closely associated with increases in total nitrogen and the humification index. This relationship reflects continuous mineralisation of organic matter and the formation of stable humic substances during vermicomposting. The C:N ratio showed a similar response. As the ratio declined, total nitrogen and humification increased, indicating continuous decomposition of biodegradable carbon together with improved nutrient availability.

The high coefficients of determination (R^2) obtained for the regression models confirm the consistency of the experimental data. The strong linear relationships observed among the selected parameters demonstrate that the developed vermicomposting system followed a stable and predictable pattern of organic matter degradation and compost maturation.

Table 10. Linear regression statistics for selected compost maturity indicators .

Sr. No .	Regression Relationship	R ²
1	Total Organic Carbon vs Total Nitrogen	0.832
2	Total Organic Carbon vs Humification Index	0.801
3	C : N Ratio vs Total Nitrogen	0.812
4	C : N Ratio vs Humification Index	0.760

Higher R² values indicate stronger linear relationships among the selected compost maturity indicators .

3.5.5 Overall Statistical Interpretation

The statistical analyses confirmed the performance of the developed low-cost vermicomposting technology for the integrated treatment of municipal solid waste and sewage sludge . One-way ANOVA identified significant treatment effects for the major compost maturity indicators . These included pH, electrical conductivity, total organic carbon, total nitrogen, C : N ratio and the humification index . The results show that treatment composition played an important role in compost stabilisation .

Tukey's HSD test clearly separated the three treatment combinations . Treatment T3 consistently produced better compost quality than T1 and T2 . The improvement was reflected by lower TOC and C : N ratio together with higher total nitrogen, electrical conductivity and humification index . These changes confirm the positive effect of sewage sludge and microbial inoculation on the vermicomposting process .

Pearson correlation analysis showed strong relationships among the selected physicochemical parameters . Lower TOC and C : N ratio were closely associated with higher nitrogen content, electrical conductivity and humification . These relationships reflect the continuous progression of organic matter degradation, nutrient transformation and compost maturation throughout the experimental period .

The regression models supported these observations . Strong linear relationships were obtained among the major compost maturity indicators . The high coefficients of determination (R²) confirm the consistency of the experimental data and the reliability of the selected parameters for evaluating vermicomposting efficiency .

The statistical results consistently identified Treatment T3 as the best-performing treatment . Better compost stabilisation, nutrient enrichment and humification were achieved under this treatment . The same pattern was observed across the six administrative divisions of Maharashtra . This demonstrates that the developed low-cost vermicomposting technology can maintain reliable performance under different climatic conditions .

4. DISCUSSION

4.1 PERFORMANCE OF THE DEVELOPED LOW-COST VERMICOMPOSTING TECHNOLOGY

The integration of municipal solid waste with sewage sludge and microbial inoculation improved the overall efficiency of the vermicomposting process under all six administrative divisions of Maharashtra . Among the three treatment combinations, Treatment T3 consistently produced better compost quality than T1 and T2 . The additional nutrients supplied by sewage sludge, together with microbial inoculation, created favourable conditions for earthworm activity and microbial degradation . Similar improvements following sludge incorporation and microbial amendment have been reported by Wang et al . (2019) , Hemalatha et al . (2024) and Vyas et al . (2022) .

The improved performance of the combined treatment is closely linked to the complementary roles of earthworms and microorganisms . Earthworms fragment organic residues, improve aeration and increase the surface area available for microbial colonisation . This accelerates decomposition and nutrient cycling . At the same time, microbial inoculation enhances enzymatic activity and promotes the breakdown of complex organic compounds . These mechanisms are well documented in vermicomposting systems and are recognised as key drivers of organic waste stabilisation (Rakkini et al ., 2017; Chattopadhyay, 2017; Panwar, 2017) . Similar effects of microbial inoculation on nutrient mineralisation have also been reported by Vyas et al . (2022) .

The overall trend observed in this study is consistent with previous reports on vermicomposting of biodegradable wastes . Progressive degradation of organic matter was accompanied by improved nutrient availability and humification, indicating continuous compost stabilisation . Karmakar et al . (2024) , Boruah et al . (2020) and Singh et al . (2023) similarly reported that earthworm-mediated decomposition enhances nutrient enrichment while promoting the formation of stable humic substances . Alshehrei and Ameen (2021) also highlighted vermicomposting as a sustainable approach for converting biodegradable municipal waste into value-added organic products .

Another notable finding was the stable performance of the developed system across the six administrative divisions . Although climatic conditions differed among the study locations, the vermicomposting process remained effective throughout the experimental period . This suggests that the developed technology can perform under a wide range of environmental conditions . Comparable observations have been reported by Karmakar et al . (2024) , Mishra et al . (2014) , Rakkini et al . (2017) and

Alshehrei and Ameen (2021), who described vermicomposting as a robust biological process suitable for different organic wastes and environmental conditions.

From a practical perspective, the developed low-cost technology offers a simple and sustainable option for decentralized municipal solid waste management. The consistent performance observed across all six administrative divisions indicates that the system can be adapted to different climatic regions without compromising compost quality. Such an approach supports resource recovery, reduces organic waste disposal and contributes to circular bioresource management, in agreement with the broader applications of vermicomposting reported by Ganapathy et al. (2025), Karmakar et al. (2024) and Alshehrei and Ameen (2021).

4.2 PHYSICAL PARAMETERS

4.2.1 Temperature

Temperature remained within the mesophilic range throughout the vermicomposting period, providing favourable conditions for microbial activity and earthworm survival. This stable thermal environment supported continuous decomposition of organic matter without exposing earthworms to heat stress. A similar optimum temperature range (20–30 °C) was reported by Pande and Gulhane (2020) and Ponmani et al. (2014), who identified it as ideal for maintaining active microbial degradation and healthy earthworm populations.

A moderate rise in temperature was observed during the initial stage of composting, followed by gradual stabilisation towards the end of the experiment. Such behaviour is commonly associated with active microbial decomposition during the early phase and reduced biological activity as the substrate becomes progressively stabilised. Comparable temperature profiles have been reported for vermicomposting of biodegradable organic wastes, where the process remains within the mesophilic range rather than entering a thermophilic phase. Rakkini et al. (2017) and Singh et al. (2017) also noted that earthworm-assisted vermicomposting maintains moderate temperatures that favour continuous biological degradation and efficient waste stabilisation.

Despite differences in climatic conditions among the six administrative divisions of Maharashtra, only small variations in temperature were recorded during the composting period. This suggests that the developed vermicomposting system maintained a stable biological environment under humid, subtropical, moderate, tropical and semi-arid conditions. Similar adaptability of vermicomposting systems under different environmental conditions has been reported by Alshehrei and Ameen (2021) and Karmakar et al. (2024), who described vermicomposting as a reliable biological treatment process suitable for a wide range of organic wastes.

The stable temperature profile observed throughout the study supported efficient decomposition and continuous compost stabilisation. It also indicates that the developed low-cost system can maintain suitable operating conditions across different climatic regions, making it a practical option for decentralized municipal solid waste management.

4.2.2 Moisture Content

Moisture content remained within the range required for efficient vermicomposting throughout the experimental period. Adequate moisture is essential because it supports microbial metabolism, facilitates nutrient transport and maintains earthworm activity. The gradual decline in moisture observed during composting is a normal consequence of microbial respiration, organic matter degradation and water loss through evaporation. Comparable results were reported by Pande and Gulhane (2020) and Hemalatha et al. (2024), who identified a moisture range of 50–90% as favourable for maintaining biological activity during vermicomposting.

The integrated approach showed better moisture retention than the control treatment, probably due to the combined effect of sewage sludge and microbial inoculation. Sewage sludge contributes additional moisture and organic matter, creating a more favourable environment for microbial growth. This helps sustain decomposition during the active phase of vermicomposting. Comparable improvements in substrate conditions following sewage sludge incorporation have been described by Hemalatha et al. (2024), Wang et al. (2019) and Vyas et al. (2022), who reported enhanced biological activity and improved compost stabilisation in sludge-amended vermicomposting systems.

A gradual reduction in moisture towards the end of the composting period is generally regarded as an indicator of compost maturation rather than process deterioration. As decomposition progresses, easily degradable organic substrates become limited and biological activity gradually declines, reducing the water-holding capacity of the composting material. Similar moisture dynamics have been reported during vermicomposting of municipal organic wastes by Rakkini et al. (2017), Boruah et al. (2020) and Mashur et al. (2021).

Even though climatic conditions fluctuated throughout the six administrative divisions, moisture maintained within a favorable range during the experiment. This indicates that the developed vermicomposting system was capable of maintaining suitable environmental conditions under different climatic regions. Such operational stability is important for decentralized municipal solid waste management, where seasonal and regional variations often influence composting performance. Similar

adaptability of vermicomposting systems under diverse environmental conditions has been highlighted by Alshehrei and Ameen (2021) .

4.2.3 pH

The gradual shift in pH towards neutral conditions reflects the normal progression of the vermicomposting process . Fresh organic wastes generally exhibit slight acidity because of the formation of organic acids during the initial stages of decomposition . As composting progresses, these intermediate compounds are further degraded, resulting in a more stable and nearly neutral pH . Similar changes have been reported by Pande and Gulhane (2020) and Hemalatha et al. (2024) , who identified neutral pH as a characteristic of mature vermicompost .

The sludge-amended treatment exhibited a more stable pH than the control treatment, suggesting that sewage sludge and microbial inoculation promoted balanced microbial activity throughout the composting period . Earthworm burrowing and casting also contribute to pH regulation by improving aeration and enhancing microbial decomposition . Comparable observations have been reported by Rakkini et al. (2017) and Singh et al. (2017) , who described earthworm activity as an important factor influencing the chemical stabilization of composting substrates .

The gradual increase in pH also corresponds with ongoing mineralisation of organic matter and the decline of acidic intermediates produced during the early stages of decomposition . Similar trends have been observed in vermicomposting studies involving municipal solid waste and sewage sludge, where microbial activity and earthworm metabolism jointly contributed to substrate stabilisation Wang et al. (2019) , Singh et al. (2023) and Vyas et al. (2022) .

Only small differences in pH were observed among the six administrative divisions, indicating that regional climatic variation had little influence on the overall stabilization process . The ability to maintain near-neutral pH under different environmental conditions supports the suitability of the developed vermicomposting system for decentralized municipal waste management . Similar conclusions regarding the adaptability of vermicomposting systems have been reported by Alshehrei and Ameen (2021) .

4.2.4 Electrical Conductivity (EC)

Electrical conductivity increased steadily during the vermicomposting process, reflecting the continuous release of soluble mineral salts as organic matter decomposed . This increase is commonly associated with mineralisation and nutrient transformation, both of which contribute to compost maturation . A similar pattern was reported by Pande and Gulhane (2020) and Hemalatha et al. (2024) , who observed an initial rise in EC during active decomposition due to the release of soluble ions .

The integrated treatment produced higher EC values than the control, indicating greater nutrient availability in the final compost . This response is likely associated with the combined effects of sewage sludge and microbial inoculation . Microbial activity accelerates the breakdown of organic compounds, while earthworm feeding and casting promote the release of mineral nutrients into the compost matrix . Comparable improvements in nutrient transformation have been reported by Wang et al. (2019) , Hemalatha et al. (2024) and Vyas et al. (2022) following the addition of sewage sludge and microbial amendments .

The increase in EC should be interpreted together with the reduction in total organic carbon and C : N ratio observed in this study . These changes reflect the same biological process rather than independent responses . As decomposition progresses, complex organic compounds are converted into simpler mineral forms, leading to greater ionic concentration in the compost . Similar relationships between mineralisation and compost maturity have been described by Boruah et al. (2020) , Singh et al. (2023) and Rakkini et al. (2017) .

Regional climatic differences had only a limited influence on the overall EC trend . The gradual increase was observed across all six administrative divisions, suggesting that nutrient mineralisation remained consistent under different environmental conditions . This supports the practical applicability of the developed vermicomposting system for decentralized municipal waste management . A comparable level of process stability under different operating conditions has also been highlighted by Alshehrei and Ameen (2021) and Ganapathy et al. (2025) .

4.3 CHEMICAL PARAMETERS

4.3.1 Total Organic Carbon (TOC)

A continuous decline in total organic carbon was observed during the vermicomposting process, reflecting the progressive breakdown of biodegradable organic matter . Such a reduction is widely accepted as one of the primary indicators of compost stabilisation because carbon is continuously consumed by microorganisms and earthworms during decomposition . Similar reductions in organic carbon have been reported by Wang et al. (2019) , who observed enhanced carbon mineralisation following the incorporation of sewage sludge into vermicomposting systems . Comparable trends were also described by Pande and Gulhane (2020) during the vermicomposting of garden waste .

The combined treatment consistently recorded lower TOC than the control treatment, indicating faster degradation of organic residues . This improvement may be attributed to the combined action of microbial inoculation and earthworms . Microbial inoculants accelerate the degradation of complex organic compounds, while earthworms continuously fragment the

substrate and stimulate microbial activity through casting and burrowing. Similar mechanisms have been discussed by Vyas et al. (2022) and Rakkini et al. (2017), who reported that the interaction between microorganisms and earthworms plays a major role in accelerating organic matter decomposition.

Carbon loss during vermicomposting is primarily associated with microbial respiration, where a substantial proportion of organic carbon is released as carbon dioxide while the remaining fraction is gradually transformed into stable humic substances. As a result, a lower TOC value usually indicates increased compost maturity rather than nutrient depletion. Boruah et al. (2020) also reported that progressive carbon loss accompanies nutrient enrichment and humification during vermicomposting, leading to the production of biologically stable compost.

The decline in TOC followed a similar pattern across all six administrative divisions despite differences in climatic conditions. This consistency indicates that the developed vermicomposting system maintained efficient carbon mineralisation under different environmental settings. Such operational stability is particularly important for decentralized municipal solid waste management, where climatic variability often influences biological treatment processes. Comparable observations on the adaptability of vermicomposting under diverse environmental conditions have been reported by Alshehrei and Ameen (2021).

4.3.2 Total Nitrogen (TN)

Total nitrogen increased steadily during the vermicomposting process, reflecting continuous mineralisation of organic matter and improved nutrient availability. An increase in nitrogen is widely recognised as an indicator of compost maturation because carbon is lost during decomposition while nutrients become progressively concentrated. Similar trends have been reported by Singh et al. (2025) and Ponmani et al. (2014) during the vermicomposting of floral waste and paper mill sludge, respectively.

The integrated treatment recorded higher nitrogen content than the control treatment. This improvement is likely due to the combined action of sewage sludge and microbial inoculation. Microbial activity accelerates protein degradation and nitrogen mineralisation, while earthworm casting enriches the substrate with plant-available nutrients. A comparable increase in nitrogen has been reported by Boruah et al. (2020) and Wang et al. (2019) following the combined action of earthworms and microbial communities.

The increase in nitrogen occurred alongside reductions in total organic carbon and C:N ratio. These changes are closely linked and reflect the natural progression of compost stabilisation. Similar relationships between carbon loss and nitrogen enrichment have been described by Mishra et al. (2014) and Hemalatha et al. (2024) during the vermicomposting of municipal and industrial organic wastes.

The nitrogen trend remained consistent across all six administrative divisions despite differences in regional climate. This indicates that the developed vermicomposting system maintained efficient nutrient transformation under diverse environmental conditions. Such consistency supports its application in decentralized municipal solid waste management across different climatic regions.

4.3.3 C:N Ratio

A progressive decline in the C:N ratio was observed throughout the vermicomposting period. This is a widely accepted indicator of compost maturity because carbon is lost more rapidly than nitrogen during decomposition. Similar reductions have been reported by Crutchik et al. (2020) during the vermicomposting of market waste and by Ponmani et al. (2014) in paper mill sludge-based vermicomposting systems.

The integrated approach recorded the lowest C:N ratio at the end of the composting period, suggesting more efficient stabilisation of organic matter. The combined action of earthworms and microorganisms accelerates carbon degradation while conserving nitrogen within the compost. A comparable response was described by Mishra et al. (2014), who reported improved compost quality with a continuous decline in the C:N ratio during vermicomposting.

The reduction in the C:N ratio also supports the increase in total nitrogen and the decline in total organic carbon observed in this study. These changes occur simultaneously and reflect the normal progression of compost maturation. Hemalatha et al. (2024) and Wang et al. (2019) found comparable relationships between carbon loss, nitrogen enrichment, and compost stabilization.

A similar pattern was observed across all six administrative divisions despite differences in climatic conditions. This suggests that the developed vermicomposting system maintained stable decomposition under different environmental settings. Such consistency improves the suitability of the developed technology for decentralized municipal solid waste management across diverse climatic regions.

4.3.4 Humification Index (HI)

The humification index increased steadily during the vermicomposting process, reflecting the gradual conversion of biodegradable organic matter into stable humic substances. An increase in the humification index is widely recognised as a reliable indicator of compost maturity and stabilization. Similar observations were reported by Crutchik et al. (2020) during the vermicomposting of market waste, where progressive humification accompanied the maturation of compost.

The integrated treatment recorded the highest humification index at the end of the composting period. This response may be attributed to the combined activity of earthworms and microorganisms, which continuously transform unstable organic compounds into more stable humic fractions. A comparable improvement in humification during vermicomposting has been reported by Karmakar et al. (2024), who described humus formation as an essential step in producing mature and biologically stable compost.

The increase in the humification index occurred together with a reduction in total organic carbon and C:N ratio. These changes represent different stages of the same stabilisation process. As decomposition progresses, organic carbon declines while humic substances continue to accumulate. Similar relationships between carbon degradation and humification have been described by Boruah et al. (2020) and Hemalatha et al. (2024).

A consistent increase in the humification index was observed across all six administrative divisions. This suggests that the developed vermicomposting system promoted stable compost maturation under different climatic conditions. Such consistency supports the practical application of the developed technology for decentralized municipal solid waste management and sustainable organic resource recovery.

4.4 BIOLOGICAL PARAMETERS

4.4.1 Earthworm Biomass

Earthworm biomass increased gradually throughout the composting period. Better growth was observed in the combined treatment than in the control. The addition of sewage sludge and microbial inoculation probably improved the nutritional quality of the substrate, allowing earthworms to remain active during vermicomposting. Similar responses have been reported by Rani and Shukla (2014), who described earthworms as the primary biological agents responsible for organic waste stabilisation.

Earthworm activity also accelerates decomposition by fragmenting organic residues and improving microbial colonisation. This interaction enhances nutrient transformation and supports continuous compost maturation. Shinde et al. (2025) reported a similar improvement in earthworm performance during the vermicomposting of municipal organic waste using suitable earthworm species.

Biomass increased in all three treatments. However, the differences among treatments were not statistically significant. This shows that all treatment combinations provided suitable conditions for earthworm growth, although the integrated treatment consistently supported better biological performance.

4.4.2 Cocoon Production

Cocoon production increased continuously as vermicomposting progressed. Healthy reproduction usually reflects favourable environmental conditions and adequate food availability. The steady increase observed in this study confirms that the developed system supported normal reproductive activity throughout the composting period.

More cocoons were produced in the integrated approach than in the control. Improved substrate quality and active microbial decomposition probably created a more suitable environment for reproduction. Similar findings were reported by Panwar (2017) and Mashur et al. (2021), who linked higher cocoon production with stable composting conditions and sufficient nutrient availability.

The differences among treatments were relatively small and were not statistically significant. Even so, the same reproductive trend was observed across all six administrative divisions. This demonstrates that the developed vermicomposting system maintained favourable conditions for earthworm reproduction under different climatic conditions.

4.4.3 Coliform Count

Coliform numbers declined throughout the vermicomposting period. The reduction reflects gradual biological stabilisation of the composting material. Earthworms and microorganisms work together to suppress pathogenic populations during decomposition. Similar reductions have been reported by Karimi et al. (2016) during the vermicomposting of household waste mixed with sewage sludge.

Lower coliform counts were recorded in the integrated treatment than in the control. Earthworm feeding, gut-associated microorganisms and microbial competition are known to reduce pathogen survival during vermicomposting. Vyas et al. (2022) reported a comparable improvement in the hygienic quality of organic waste following vermicomposting.

Coliform reduction was observed in all treatments. However, treatment-wise differences were not statistically significant. A similar trend was recorded across all six administrative divisions. This shows that the developed system maintained effective biological stabilisation under different environmental conditions.

4.4.4 Earthworm Mortality

Earthworm mortality remained low throughout the experimental period. The low mortality confirms that the developed vermicomposting system provided suitable conditions for earthworm survival. Similar observations were reported by Shinde et al. (2025) during the vermicomposting of municipal organic waste.

Small differences in mortality were observed among the treatments. These differences were probably related to variations in substrate composition rather than unfavorable environmental conditions. Rani and Shukla (2014) also reported that earthworm survival depends largely on adequate moisture, aeration and substrate quality.

Unlike earthworm biomass and cocoon production, earthworm mortality showed a significant treatment effect in the statistical analysis. Even so, mortality remained low in every treatment. Earthworm survival was consistent across all six administrative divisions. This confirms that the developed system maintained stable biological performance under different climatic conditions without affecting the overall efficiency of the vermicomposting process.

4.5 STATISTICAL INTERPRETATION OF VERMICOMPOSTING PERFORMANCE

The statistical analysis confirmed the treatment-wise differences observed during vermicomposting. Significant differences were recorded for pH, electrical conductivity, total organic carbon, total nitrogen, C:N ratio, humification index and earthworm mortality. These parameters responded directly to changes in substrate composition, particularly after the addition of sewage sludge and microbial inoculation. The statistical results therefore support the improvements in compost quality observed in the integrated treatment.

In contrast, temperature, moisture content, earthworm biomass, cocoon production and coliform count did not show significant differences among the treatments. Even though these parameters followed similar trends throughout the composting period, the statistical analysis indicates that the overall biological process remained stable under all treatment combinations. This is important because efficient vermicomposting depends on maintaining suitable environmental conditions rather than producing large treatment-wise differences in every parameter.

The correlation analysis further strengthened the experimental findings. Total organic carbon showed a strong negative relationship with total nitrogen and the humification index, while the C:N ratio also declined as compost maturity progressed. These relationships reflect the normal sequence of organic matter degradation, nutrient enrichment and humus formation during vermicomposting. The correlation coefficients obtained in this study therefore agree well with the observed changes in compost maturity.

Regression analysis produced similar results. Strong linear relationships were obtained between the principal maturity indicators, confirming that the measured parameters changed in a predictable manner throughout the composting process. The high coefficients of determination indicate that reductions in organic carbon were closely associated with improvements in nitrogen content, humification and overall compost stability.

Taken together, the statistical analyses validate the experimental observations and demonstrate the reliability of the developed low-cost vermicomposting technology. The agreement between ANOVA, correlation and regression analyses confirms that the integrated treatment consistently produced better compost quality while maintaining stable biological performance across the six administrative divisions of Maharashtra.

4.6 OVERALL PERFORMANCE OF THE DEVELOPED LOW-COST VERMICOMPOSTING TECHNOLOGY

The developed vermicomposting system performed consistently across all six administrative divisions of Maharashtra. Improvements in physical, chemical and biological parameters followed a similar pattern across the different climatic regions. This consistency shows that the developed system can operate under a wide range of environmental conditions without affecting compost quality. Similar observations have been reported by Karmakar et al. (2024) and Alshehrei and Ameen (2021).

The combined approach produced the best overall compost quality. Faster decomposition, improved nutrient transformation and stable biological activity together indicate efficient compost maturation. These responses agree with earlier studies on vermicomposting of municipal organic waste and sewage sludge reported by Wang et al. (2019) and Vyas et al. (2022).

Beyond waste stabilisation, the developed technology offers practical advantages for decentralized municipal solid waste management. The system is simple to operate, requires low investment and converts biodegradable waste into a value-added vermicompost. Similar applications of earthworm-based treatment systems for sustainable waste management have been discussed by Krishnasamy et al. (2013).

The final compost produced by the developed system also has potential for agricultural use and resource recovery. Recycling biodegradable waste into stable organic manure supports circular waste management and reduces the environmental burden associated with municipal waste disposal. Comparable applications of vermicompost-derived products in sustainable horticulture have been highlighted by Bidabadi (2018).

The overall results show that the developed low-cost technology can be effectively used for sustainable management of municipal organic waste. Its consistent performance across the six administrative divisions supports its wider application in decentralized waste management and sustainable bioresource recovery.

5. CONCLUSION

A low-cost vermicomposting system was developed for the integrated treatment of municipal solid waste and sewage sludge. The system performed successfully under the six administrative divisions of Maharashtra throughout the 90-day composting period. All treatment combinations resulted in stable vermicompost, demonstrating that the designed system may function efficiently under various environmental conditions.

Clear improvements were recorded in the physical, chemical and biological properties of the composting material. Temperature remained within the mesophilic range and moisture was maintained at levels suitable for earthworm activity. The pH gradually approached neutral conditions, while electrical conductivity increased as decomposition progressed. These changes created favourable conditions for continuous compost stabilisation.

The chemical properties also changed consistently during vermicomposting. Total organic carbon and the C:N ratio declined throughout the composting period. At the same time, total nitrogen and the humification index increased steadily. These changes reflect continuous organic matter decomposition, nutrient transformation and compost maturation. The biological response remained stable throughout the experiment. Earthworm biomass and cocoon production increased with composting time. Coliform counts declined continuously, while earthworm mortality remained low in all treatments. Together, these observations confirm that the developed system maintained favourable conditions for biological activity.

Among the three treatment combinations, Treatment T3 produced the best overall performance. The combined use of municipal solid waste, sewage sludge, bulking agents and microbial inoculation improved compost quality more effectively than the other treatments. Better nutrient enrichment, greater humification and faster stabilisation were consistently achieved under this treatment.

The statistical analysis supported the experimental observations. ANOVA identified significant treatment effects for the major compost maturity indicators. Tukey's HSD test distinguished the treatment combinations, while correlation and regression analyses confirmed strong relationships among the selected physicochemical parameters. These results increase confidence in the consistency and reliability of the developed system.

The developed vermicomposting technology performed consistently across all six administrative divisions despite differences in climatic conditions. Similar treatment responses were observed in each region, indicating that the system can adapt to a wide range of environmental conditions. This makes the technology suitable for decentralized composting programmes in different parts of Maharashtra.

The developed low-cost vermicomposting technology offers a practical approach for the integrated management of municipal solid waste and sewage sludge. It converts biodegradable waste into stable and nutrient-rich vermicompost using a simple and economical process. The system also supports resource recovery and sustainable waste management, making it a promising option for large-scale municipal applications.

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