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PROCESS OPTIMIZATION OF MICROBIAL CONSORTIUM-ASSISTED WINDROW COMPOSTING FOR ENHANCED NUTRIENT RECOVERY AND SAFE ORGANIC FERTILIZER PRODUCTION

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ABSTRACT

The rapid increase in municipal and agro-industrial organic waste generation, coupled with declining soil fertility, necessitates efficient and sustainable waste-to-resource conversion strategies. Conventional composting systems often exhibit limitations such as slow degradation rates, incomplete pathogen removal, and persistence of bioavailable heavy metals, thereby restricting their agronomic and environmental applicability.

This study presents a process-optimized microbial consortium-assisted windrow composting approach for the production of high-quality organic fertilizer from municipal organic solid waste under field-scale conditions. A synergistic consortium comprising bacterial strains (Bacillus subtilis, Pseudomonas fluorescens, Lactobacillus spp.) and fungal species (Trichoderma harzianum, Aspergillus niger) was applied at 2% (w/w). The novelty of this study lies in the integrated evaluation of nutrient enrichment, pathogen inactivation, and heavy metal immobilization within a single composting system under practical operational conditions. Physicochemical, microbiological, and maturity parameters were systematically monitored over a 45-day composting period.

The consortium significantly enhanced composting efficiency, reducing stabilization time from over 70 days to 45 days. Total nitrogen increased from 0.5% to 1.5%, with corresponding increases in phosphorus and potassium (200–250%). Pathogenic indicators, including Escherichia coli and coliforms, were completely eliminated within 21 days during the thermophilic phase (65–70°C). Bioavailable heavy metals (Pb, Cd, and Zn) were reduced by 55–66%, indicating effective immobilization.

The improved performance is attributed to synergistic microbial interactions, where bacterial activity enhances enzymatic degradation and nutrient mineralization, while fungal metabolism facilitates lignocellulosic breakdown and promotes the formation of humic substances that stabilize heavy metals through complexation and adsorption mechanisms. These combined processes enable simultaneous enhancement of compost quality and biosafety.

Overall, this study demonstrates that microbial consortium-assisted windrow composting provides a scalable and efficient strategy for optimized organic fertilizer production, supporting sustainable waste management and circular bioeconomy applications.

Keywords: Municipal Organic Solid Waste, Windrow Composting, Microbial Consortium, Process Optimization, Organic Fertilizer Production, Nutrient Enrichment, Heavy Metal Immobilization, Pathogen Reduction

1. INTRODUCTION

The generation of municipal organic solid waste (MOSW) has increased substantially in recent decades due to rapid urbanization, population growth, and changing consumption patterns, posing significant environmental and management challenges worldwide [1,2]. Improper handling and disposal of biodegradable waste contribute to landfill

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accumulation, greenhouse gas emissions, and contamination of soil and water resources [3]. Simultaneously, modern agricultural systems are experiencing a decline in soil fertility, organic carbon content, and microbial activity, largely attributed to intensive cultivation practices and excessive reliance on chemical fertilizers. These interconnected challenges necessitate the development of sustainable strategies that enable efficient conversion of organic waste into value-added products while restoring soil health [4].

Composting is widely recognized as an environmentally sustainable and cost-effective method for recycling organic waste into stable, humus-rich soil amendments [5]. Among available techniques, windrow composting is particularly suitable for large-scale applications due to its operational simplicity, economic feasibility, and adaptability to heterogeneous waste streams. However, conventional composting systems often exhibit limitations, including slow degradation rates, inconsistent nutrient stabilization, incomplete pathogen inactivation, and the persistence of bioavailable heavy metals in mixed municipal waste. These constraints reduce the agronomic value and environmental safety of the final compost product, thereby limiting its large-scale application [6].

Recent advances in microbial biotechnology have highlighted the potential of microbial inoculation to enhance composting efficiency and product quality [7,8,9]. Bacterial species such as *Bacillus subtilis* and *Pseudomonas fluorescens* are known to facilitate enzymatic degradation and nutrient mineralization, whereas fungal species such as *Trichoderma harzianum* and *Aspergillus niger* contribute to lignocellulosic degradation and humification processes. The synergistic interaction between bacterial and fungal communities has been shown to accelerate organic matter decomposition, improve compost maturity, and enhance nutrient availability [10]. Furthermore, microbial activity plays a critical role in the immobilization of heavy metals through mechanisms such as biosorption, complexation, and incorporation into humic substances [11]. Despite these advances, most existing studies have focused on individual microbial groups or isolated performance indicators, with limited attention to integrated system-level optimization.

It is therefore hypothesized that a process-optimized microbial consortium-based composting system can simultaneously enhance nutrient enrichment, ensure effective pathogen elimination, and reduce the bioavailability of heavy metals compared to conventional composting practices.

Despite extensive research on composting technologies, a significant knowledge gap remains in the development of integrated approaches that address multiple quality parameters within a single system. In particular, the synergistic interactions between bacterial and fungal consortia under field-scale windrow composting conditions have not been sufficiently explored. Moreover, many studies have been conducted under controlled laboratory environments, which do not adequately represent the heterogeneous composition and operational variability of municipal organic waste systems encountered in real-world scenarios.

The present study addresses these limitations by developing and optimizing a microbial consortium-assisted windrow composting system for MOSW under field-scale conditions. A synergistic combination of bacterial and fungal strains was employed to enhance decomposition efficiency, improve nutrient recovery, achieve complete pathogen inactivation, and reduce heavy metal bioavailability. Unlike previous studies, this work simultaneously evaluates these critical parameters within a single integrated framework, providing a comprehensive assessment of compost quality, biosafety, and process efficiency. The primary objective is to optimize organic fertilizer production through microbial-assisted composting, thereby contributing to sustainable waste management, environmental protection, and circular bioeconomy practices [12].

2. LITERATURE REVIEW

2.1. ROLE OF MICROBIAL CONSORTIA IN ORGANIC WASTE DECOMPOSITION

The efficiency of composting is strongly governed by the structure and activity of microbial communities responsible for organic matter degradation [4]. In recent years, microbial consortia composed of complementary bacterial and fungal species have been increasingly recognized as an effective strategy to enhance composting performance [9]. Bacterial species such as *Bacillus subtilis* and *Pseudomonas fluorescens* play a critical role in the production of extracellular enzymes, including cellulases, proteases, and amylases, which facilitate the breakdown of complex organic substrates into simpler compounds. This enzymatic activity accelerates mineralization and promotes rapid stabilization of organic matter.

In addition, *Lactobacillus* spp. contribute to the early stages of composting through the production of organic acids, resulting in a temporary reduction in pH that suppresses undesirable microorganisms and enhances nutrient solubility. The synergistic interaction between bacterial metabolism and fungal activity creates a dynamic microenvironment that supports continuous degradation and microbial succession. Previous studies have demonstrated that microbial inoculation can significantly reduce composting duration and improve nutrient retention compared to non-inoculated systems [13,14]. However, most studies have focused on isolated microbial groups rather than integrated consortia under field-scale conditions. Recent metagenomic studies have further confirmed that complex microbial consortia significantly enhance composting efficiency through coordinated metabolic pathways [15]. Microbial degradation processes also contribute significantly to compost stability and safety by reducing harmful compounds during decomposition [16].

2.2. ROLE OF FUNGI IN HUMIFICATION AND HEAVY METAL STABILIZATION

Fungal communities play a crucial role in composting due to their ability to degrade recalcitrant organic compounds such as lignin and cellulose [17]. Species such as *Trichoderma harzianum* and *Aspergillus niger* produce oxidative enzymes, including laccases and peroxidases, which facilitate lignocellulosic degradation and promote humification. The formation of humic substances enhances compost stability and improves its agronomic value.

Beyond organic matter degradation, fungi contribute significantly to heavy metal immobilization. Functional groups present in fungal cell walls, including carboxyl, hydroxyl, and amino groups, enable the binding of metal ions, while the secretion of organic acids promotes metal complexation and precipitation. These mechanisms reduce the bioavailability and mobility of toxic metals such as cadmium and lead. Previous studies have reported substantial reductions in heavy metal mobility during fungal-assisted composting processes [18], highlighting the importance of fungal activity in improving compost safety.

2.3. PATHOGEN REDUCTION AND COMPOST BIOSAFETY

The elimination of pathogenic microorganisms is a critical requirement for the safe agricultural application of compost. Organic waste streams frequently contain pathogenic bacteria, including *Escherichia coli* and fecal coliforms, as well as yeasts and molds. The thermophilic phase of aerobic composting plays a central role in pathogen inactivation, with temperatures exceeding 55°C for sustained periods being sufficient to eliminate most pathogens [19,20] (Fig. 1). The importance of pathogen inactivation in composting systems has been extensively documented, particularly in relation to public health and environmental safety [21]. Similar improvements in humification and pathogen suppression have been reported in microbial-assisted composting systems [22].

Efficient aeration and periodic turning of compost piles ensure uniform heat distribution and prevent the formation of anaerobic zones, thereby facilitating consistent pathogen reduction throughout the compost mass [23]. In addition to thermal inactivation, microbial antagonism contributes to pathogen suppression through the production of antimicrobial compounds. The combined effect of temperature and microbial interactions ensures the production of biosafe compost suitable for agricultural use.

Figure 1

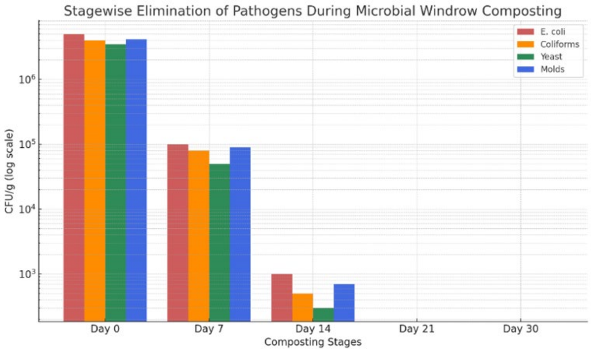

Figure 1 Temporal variation in pathogenic microbial populations (CFU g^{-1}) during composting. A logarithmic decline in *E. coli*, coliforms, yeasts, and molds was observed from Day 0 to Day 30. Error bars represent standard deviation (n = 3). Complete pathogen elimination was achieved by Day 21 during the thermophilic phase ($p < 0.05$).

2.4. REDUCTION OF BIOAVAILABLE HEAVY METALS

Municipal and agro-industrial organic wastes often contain trace concentrations of heavy metals such as Pb, Cd, and Zn, which pose potential risks to soil, plants, and human health if not adequately stabilized [24]. Therefore, the reduction of bioavailable metal fractions, rather than total metal concentration, is a critical parameter in compost quality assessment.

Microbial activity significantly influences heavy metal immobilization during composting through mechanisms such as biosorption, complexation, and precipitation [11]. Functional groups present in microbial cell walls facilitate metal binding, while extracellular polymeric substances (EPS) and organic acids contribute to the formation of stable metal complexes. These processes reduce metal mobility and limit their bioavailability in the soil–plant system.

Previous studies have reported that microbial-assisted composting can reduce bioavailable heavy metal fractions by 45–70% through adsorption and bio-precipitation mechanisms [25,26]. Fungal species, particularly *Trichoderma* and *Aspergillus*, exhibit enhanced tolerance to metal stress and contribute to intracellular sequestration and extracellular immobilization processes. These findings highlight the role of microbial consortia in improving the environmental safety of compost products (Fig. 2).

Figure 2

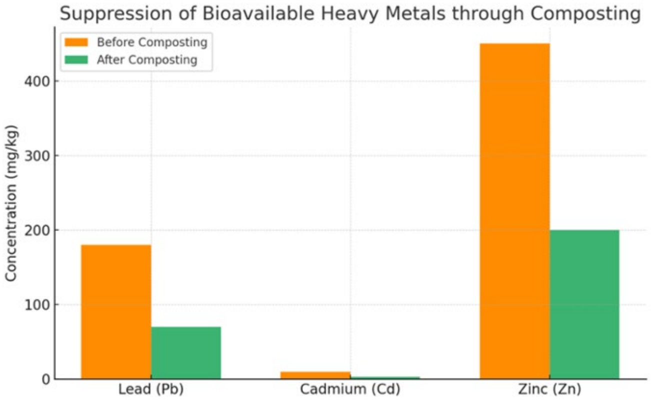

Figure 2 Reduction in bioavailable heavy metal concentrations (Pb, Cd, Zn) during composting. Bars represent mean values ± standard deviation (n = 3). A significant decrease in metal bioavailability was observed in microbial consortium-treated compost compared to control ($p < 0.05$).

2.5. COMPOST QUALITY AND ITS IMPACT ON SOIL HEALTH

The agronomic value of compost is determined by its maturity, nutrient balance, and biological stability. Mature compost is typically characterized by a C:N ratio below 15, near-neutral pH (6.5–7.5), and a stable humified structure, indicating effective decomposition and low phytotoxicity (Fig. 3).

The application of mature compost has been shown to improve soil physical, chemical, and biological properties. It enhances microbial biomass and enzymatic activity, thereby promoting nutrient cycling and organic matter turnover. Humic substances formed during composting improve soil aggregation, porosity, and water-holding capacity, supporting plant growth and root development [27]. Microbial succession plays a crucial role in compost stability and maturation [28].

Furthermore, compost application improves nutrient retention and reduces leaching losses through the formation of stable organo-mineral complexes. Increased availability of micronutrients through chelation enhances plant nutrient uptake efficiency. Compost has also been associated with the suppression of soil-borne pathogens due to competitive microbial interactions and improved soil health conditions. Previous studies have demonstrated that microbial-enriched compost significantly enhances soil fertility and crop productivity while supporting environmental sustainability [29,30]. Recent studies have highlighted the role of microbial metabolic pathways in improving composting efficiency [36].

Figure 3

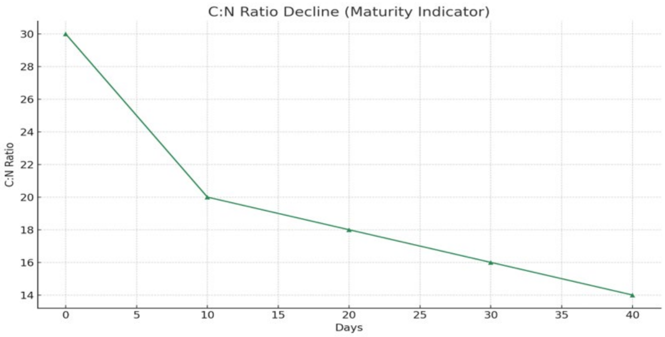

Figure 3 Changes in C ratio during composting as an indicator of compost maturity. A progressive decline from approximately 30:1 to below 15:1 was observed over the composting period. Error bars indicate standard deviation (n = 3), confirming stabilization and maturity of organic matter.

3. MATERIALS AND METHODS

3.1. EXPERIMENTAL DESIGN AND COMPOSTING SETUP

The experiment was conducted using a completely randomized design (CRD) comprising two treatments (Fig. 4): (i) control compost without microbial inoculation and (ii) microbial consortium-treated compost. Each treatment was performed in triplicate (n = 3) to ensure statistical reliability.

Composting was carried out under aerobic conditions using the windrow method, which is widely adopted for large-scale organic waste processing due to its operational simplicity and cost-effectiveness [31]. Windrows were constructed with approximate dimensions of 1.5 m (height), 3 m (width), and 6 m (length). The composting process was maintained for 45 days, with manual turning performed at 7-day intervals to ensure adequate aeration and uniform microbial activity.

The feedstock consisted of municipal organic solid waste (kitchen and market waste), agricultural residues, and cow dung. All materials were pre-processed to particle sizes <5 cm and thoroughly homogenized. The initial carbon-to-nitrogen (C:N) ratio was adjusted to approximately 30:1 to optimize microbial degradation efficiency [29]. Composting was conducted on a concrete platform equipped with a leachate collection and recirculation system to minimize nutrient loss and environmental contamination [32].

Figure 4

Figure 4 Experimental design and workflow of microbial consortium-assisted windrow composting. Municipal organic waste was pre-processed and adjusted to an optimal C:N ratio before being divided into control (without inoculum) and treatment (microbial consortium) groups under a completely randomized design. Composting was carried out for 45 days, with sampling performed at regular intervals (Day 0, 10, 20, 30, and 45) for nutrient, pathogen, and heavy metal analyses.

3.2. MICROBIAL CONSORTIUM PREPARATION AND APPLICATION

The microbial consortium consisted of bacterial strains (*Bacillus subtilis*, *Pseudomonas fluorescens*, *Lactobacillus* spp.) and fungal species (*Trichoderma harzianum*, *Aspergillus niger*), selected based on their known roles in enzymatic degradation, nutrient mineralization, and humification [9].

Individual strains were cultured separately under controlled laboratory conditions (28–30°C) until a cell density of approximately 10^8 CFU mL^{-1} was achieved. Equal proportions of each culture were then combined to prepare the consortium [33].

The inoculum was applied at a rate of 2% (w/w) of the total composting material at the start of the experiment (Day 0), followed by a second application on Day 15 to sustain microbial activity. The inoculum was uniformly distributed using a spraying method during pile formation and subsequent turning operations. Moisture content was maintained at 55–60%, which is considered optimal for aerobic composting processes.

3.3. PROCESS MONITORING

Temperature was monitored daily using a digital probe inserted at three different depths (top, middle, and bottom layers) of each windrow (Fig. 5). The thermophilic phase was maintained within the range of 50–65°C to promote rapid organic matter degradation and effective pathogen inactivation [20].

Ambient environmental parameters, including temperature and relative humidity, were recorded throughout the composting period to evaluate their potential influence on process dynamics.

Figure 5

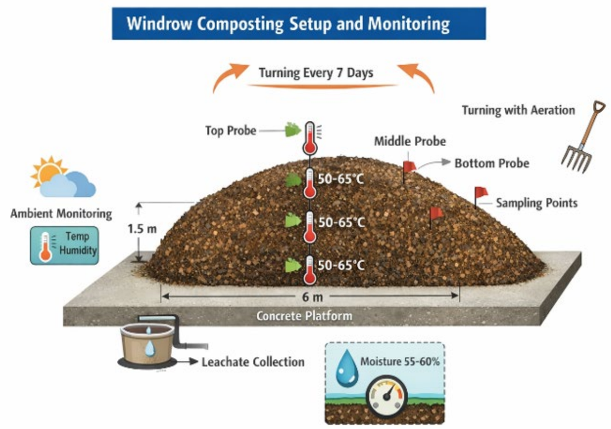

Figure 5. Schematic representation of the windrow composting setup and monitoring strategy. The windrow was constructed with dimensions of 1.5 m height, 3 m width, and 6 m length on a concrete platform equipped with leachate collection. Temperature was monitored at three depths (top, middle, and bottom layers) using digital probes, maintaining thermophilic conditions (50–65°C). Sampling points were distributed across the windrow to ensure representative analysis. Moisture content (55–60%) and ambient environmental parameters were continuously monitored. Turning was performed at 7-day intervals to maintain aeration and uniform microbial activity.

3.4. SAMPLING AND ANALYTICAL METHODS

Composite compost samples were collected at 0, 10, 20, 30, and 45 days from multiple locations within each windrow to ensure representativeness. All analyses were conducted in triplicate, and results were expressed as mean ± standard deviation.

3.4.1. NUTRIENT ANALYSIS (N, P, K)

Total nitrogen (N) was determined using the Kjeldahl digestion method, phosphorus (P) was analyzed using the ascorbic acid method with a UV–Vis spectrophotometer, and potassium (K) was measured using flame photometry. All analytical procedures were performed in accordance with standard protocols [34,31].

3.4.2. PATHOGEN ANALYSIS

Microbial pathogen load was quantified using selective culture techniques. *Escherichia coli* was enumerated using eosin methylene blue (EMB) agar, total coliforms were determined using MacConkey agar, and yeasts and molds were cultured on Sabouraud dextrose agar (SDA). Microbial counts were expressed as colony-forming units per gram (CFU g^{-1}). Pathogen elimination was confirmed when no detectable colonies were observed.

3.4.3. HEAVY METAL ANALYSIS

Bioavailable concentrations of Pb, Cd, and Zn were determined using inductively coupled plasma–optical emission spectrometry (ICP–OES) following acid digestion based on USEPA Method 3050B [35]. The reduction efficiency of bioavailable metals was evaluated by comparing treated and control samples.

3.4.4. COMPOST MATURITY AND STABILITY PARAMETERS

Compost maturity was assessed using multiple indicators, including C:N ratio (CHNS analyzer), pH and electrical conductivity (digital probes), humification index (UV–Vis absorbance ratio), and CO_2 evolution rate determined by respirometric analysis. These parameters are widely used to evaluate compost stability and maturity [29].

3.5. STATISTICAL ANALYSIS

All experimental data were analyzed using one-way analysis of variance (ANOVA) to assess differences between treatments. Statistical significance was determined at $p < 0.05$. When significant differences were observed, Tukey's honestly significant difference (HSD) test was applied for multiple comparisons.

Statistical analyses were performed using IBM SPSS software (version 26.0). Graphical representations were generated using Microsoft Excel. All results are presented as mean ± standard deviation (n = 3).

4. RESULTS AND DISCUSSION

4.1. NUTRIENT ENRICHMENT AND MINERALIZATION

A significant enhancement in macronutrient content was observed in the microbial consortium-treated compost compared to initial values ($p < 0.05$). Total nitrogen increased from 0.5% to 1.5%, while phosphorus and potassium increased from 0.3% to 0.9% and 0.6% to 2.1%, respectively, corresponding to increases of 200–250% (Table 1; Fig. 6).

These results indicate efficient mineralization of organic matter facilitated by microbial activity [25,26]. Bacterial species such as *Bacillus subtilis* and *Pseudomonas fluorescens* are known to enhance proteolysis and phosphorus solubilization, whereas fungal species such as *Trichoderma harzianum* and *Aspergillus niger* contribute to lignocellulosic degradation and nutrient release. The synergistic interaction between these microorganisms accelerates nutrient transformation and improves compost quality. Similar improvements in nutrient enrichment following microbial inoculation have been reported [29,30].

Table 1

Table 1 Changes in macronutrient concentrations (nitrogen, phosphorus, and potassium) during composting. Significant increases in nutrient content were observed in the microbial consortium-treated compost, indicating enhanced mineralization and nutrient availability.

Parameter	Initial Value (%)	Final Value (%)	% Increase
Nitrogen (N)	0.5	1.5	200
Phosphorus (P)	0.3	0.9	200

Potassium (K)	0.6	2.1	250

Figure 6

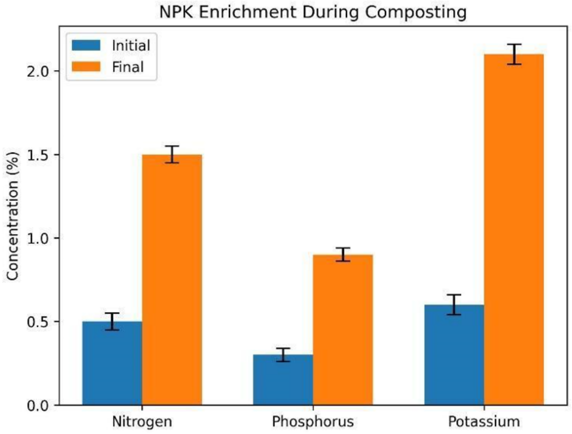

Figure 6 Changes in macronutrient concentrations (N, P, and K) before and after composting. Bars represent mean values ± standard deviation (n = 3). Significant increases ($p < 0.05$) indicate enhanced nutrient mineralization due to microbial consortium activity.

4.2. PATHOGEN ELIMINATION AND COMPOST BIOSAFETY

A substantial reduction in pathogenic microorganisms was observed during the composting process. Initial populations of *Escherichia coli*, coliforms, yeasts, and molds were reduced to non-detectable levels by Day 21. This reduction corresponds to >99.999% removal efficiency and is attributed to sustained thermophilic conditions (65–70°C), which are known to ensure effective pathogen die-off during composting [20] (Table 2; Fig. 7).

The thermophilic phase plays a critical role in pathogen inactivation through protein denaturation and disruption of cellular structures [20]. Additionally, microbial antagonism contributed to pathogen suppression, particularly through the activity of *Lactobacillus* spp. and *Trichoderma harzianum*, which produce antimicrobial metabolites. These findings are consistent with established composting standards [19,38] and confirm the biosafety of the final compost product.

Table 2

Table 2 Reduction in pathogenic microbial populations (CFU g^{-1}) during composting. Complete elimination of E. coli, coliforms, yeasts, and molds was achieved by Day 21 under thermophilic conditions, confirming effective pathogen inactivation and compost biosafety.

Microbial Indicator	**Initial CFU/g**	**Final CFU/g**	**% Reduction**
E. coli	5.0×10^6	Not detected	>99.999
Coliforms	4.0×10^6	Not detected	>99.999
Yeasts	3.5×10^6	Not detected	100
Molds	4.2×10^6	Not detected	>99.999

Figure 7

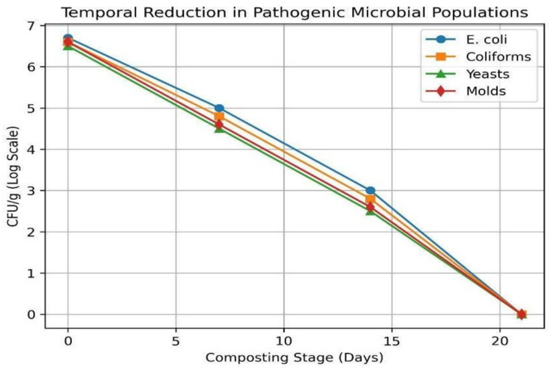

Figure 7 Temporal reduction in pathogenic microbial populations (CFU g^{-1}) during composting. A logarithmic decline was observed from Day 0 to Day 21, with complete elimination achieved by Day 21 ($p < 0.05$).

4.3. REDUCTION OF BIOAVAILABLE HEAVY METALS

A significant reduction in bioavailable heavy metal fractions was observed in the treated compost. Lead decreased from 180 mg kg^{-1} to 70 mg kg^{-1}, cadmium from 9.5 mg kg^{-1} to 3.2 mg kg^{-1}, and zinc from 450 mg kg^{-1} to 200 mg kg^{-1}, corresponding to reductions of 55–66% ($p < 0.05$) (Fig. 8).

The reduction in metal bioavailability can be attributed to microbial-mediated immobilization mechanisms, including biosorption, complexation, and precipitation [11]. Fungal species such as *Aspergillus niger* contribute through organic acid production and metal chelation, while bacterial species such as *Pseudomonas fluorescens* facilitate metal binding via extracellular polymeric substances.

These findings are consistent with previous studies reporting similar reductions in bioavailable heavy metals during microbial-assisted composting [26,25,24].

Table 3

Table 3 Reduction in bioavailable heavy metal concentrations (Pb, Cd, and Zn) during composting. Significant decreases in metal bioavailability were observed in the microbial consortium-treated compost, indicating effective immobilization through microbial-mediated processes.

Heavy Metal	Initial (mg kg^{-1})	Final (mg kg^{-1})	% Reduction
Lead (Pb)	180	70	61.1
Cadmium (Cd)	9.5	3.2	66.3
Zinc (Zn)	450	200	55.5

Figure 8

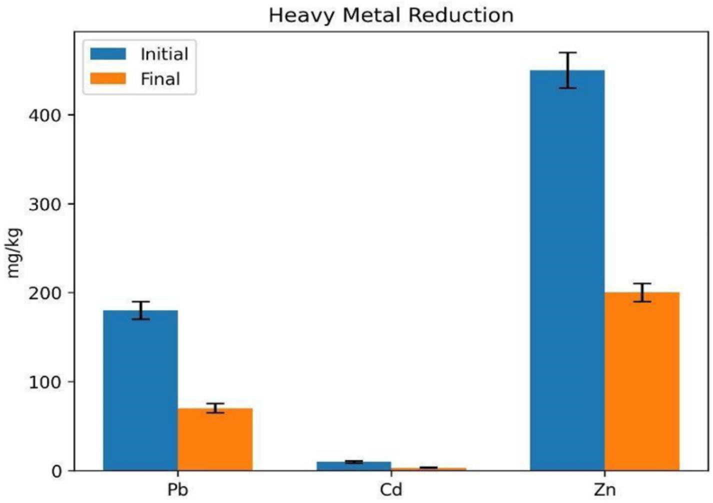

Figure 8 Reduction in bioavailable heavy metal concentrations (Pb, Cd, Zn) following composting. Error bars represent standard deviation (n = 3), with significant differences observed between initial and final values ($p < 0.05$).

4.4. COMPOST MATURITY AND STABILITY

Compost maturity was achieved within 45 days, as indicated by a reduction in the C:N ratio from 32:1 to 13:1. Additional indicators included stabilization of pH from 6.2 to 7.1, a decrease in humification index from 4.2 to 1.3, and a reduction in CO_2 evolution rate from 18 to 4 mg CO_2-C g^{-1} day^{-1} (Table 4; Fig. 9).

The decline in C:N ratio reflects efficient decomposition and stabilization of organic matter, while the reduction in respiration rate indicates decreased microbial activity in the final stage [29]. The formation of humic substances contributes to compost stability and agronomic value [27].

These results are consistent with established maturity indicators reported in composting studies [29,27].

Table 4

Table 4 Changes in compost maturity and stability parameters during the composting process. A reduction in C:N ratio, stabilization of pH, decrease in humification index, and lower CO_2 evolution rate indicate effective organic matter stabilization and compost maturity.

Parameter	Initial Value	Final Value	Interpretation
C:N Ratio	32:01:00	13:01	Indicates organic matter stabilization
pH	6.2	7.1	Shift to near-neutral range (ideal for plant growth)
Humification Index (HI)	4.2	1.3	High humification and compost maturity
CO_2 Evolution (mg CO_2-C g^{-1} day^{-1})	18	4	Reflects reduced microbial activity and compost stability

Figure9

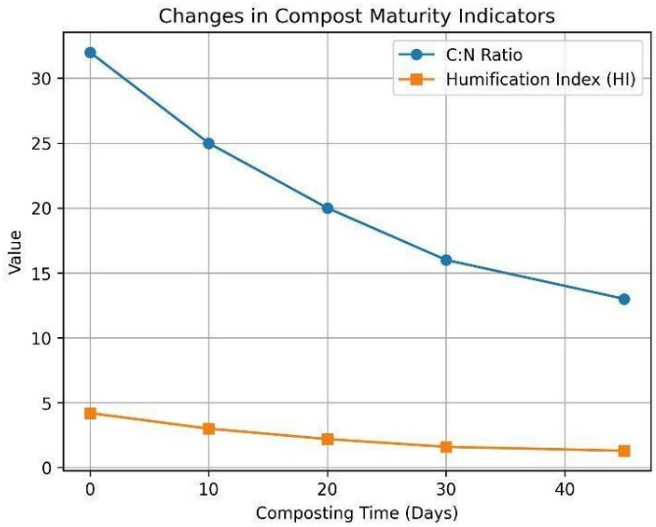

Figure 9 Changes in compost maturity indicators during the composting process. A progressive decline in C:N ratio and humification index confirms stabilization and maturity of compost.

4.5. COMPARATIVE PERFORMANCE OF MICROBIAL CONSORTIUM AND CONTROL COMPOST

The microbial consortium-treated compost demonstrated significantly improved performance compared to the control system. Nutrient enrichment increased by over 200%, pathogen elimination was complete, and heavy metal bioavailability was reduced by up to 65%. Furthermore, composting duration was reduced from 70 days (control) to 45 days, indicating enhanced process efficiency (Table 5).

These improvements highlight the effectiveness of microbial consortium-based composting in optimizing both process performance and product quality [9] (Fig. 10). The integration of bacterial and fungal species enables simultaneous enhancement of nutrient availability, biosafety, and environmental sustainability, making this approach suitable for large-scale organic fertilizer production [12].

Table 5

Table 5 Comparative performance of control and microbial consortium-treated compost. The treated system demonstrated significant improvements in nutrient enrichment, pathogen elimination, heavy metal reduction, compost maturity, and reduced processing time.

Parameter	Control Compost (No Inoculum)	Microbial Compost (Consortium)	% Improvement
Nutrient Increase (NPK)	40%	+200–250%	+160–200
Pathogen Reduction	Partial	Complete (100%)	100
Heavy Metal Suppression	<20%	55–65%	45
Composting Duration	70 days	45 days	36% faster
Maturity (C:N Ratio)	18:01	13:01	+27% improvement

Figure 10

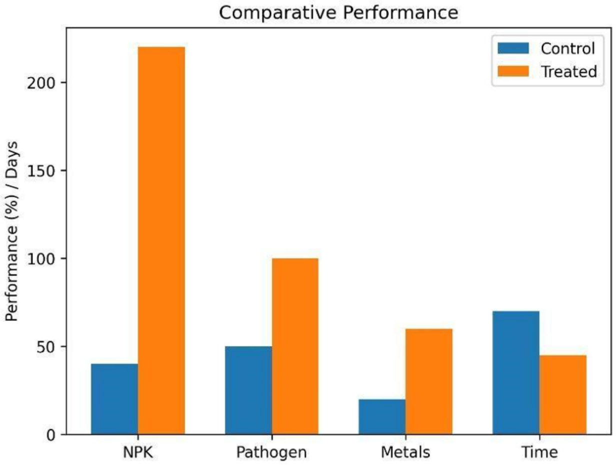

Figure 10 Comparative performance of control and microbial consortium-treated compost. Significant improvements in nutrient enrichment, pathogen elimination, heavy metal reduction, and compost maturity were observed in the treated system ($p < 0.05$).

5. OVERALL IMPLICATIONS

The findings of this study demonstrate that microbial consortium-assisted windrow composting significantly enhances both process efficiency and compost quality [9]. The synergistic activity of bacterial (*Bacillus subtilis*, *Pseudomonas fluorescens*, *Lactobacillus* spp.) and fungal (*Trichoderma harzianum*, *Aspergillus niger*) species resulted in accelerated organic matter degradation and improved nutrient mineralization, as evidenced by a >200% increase in NPK content.

Complete elimination of pathogenic microorganisms within 21 days under thermophilic conditions confirms the effectiveness of the process in ensuring compost biosafety [20]. In addition, the substantial reduction (55–66%) in bioavailable heavy metals (Pb, Cd, and Zn) highlights the role of microbial-mediated immobilization mechanisms in improving the environmental safety of compost derived from heterogeneous municipal waste streams.

The reduction in composting duration from conventional timelines (~70 days) to 45 days indicates significant process optimization, aligning with the objectives of efficient organic fertilizer production. Furthermore, the attainment of maturity indicators (C:N ratio < 15, stabilized pH, and reduced respiration activity) confirms the production of a stable and agronomically suitable compost. This approach supports circular bioeconomy frameworks and sustainable waste management strategies [39].

Overall, the integration of microbial consortium technology within windrow composting systems provides a scalable and sustainable approach for organic waste valorization. This strategy contributes to circular bioeconomy frameworks by enabling the production of high-quality organic fertilizers while mitigating environmental risks associated with municipal organic waste management [12].

DATA AVAILABILITY STATEMENT

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

CONFLICT OF INTERESTS

None.

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