Optimization of Dry Leaf Composting Using Banana MOL (*Musa paradisiaca* spp.) and Effective Microorganism-4 (EM4) Bio-Activator: Process Monitoring and Nutrient Quality

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ABSTRACT

Urban dry leaf waste is a persistent challenge for municipal solid waste management. Composting can valorize this biomass, but decomposition is often slow and commercial inoculants may be costly. This study compared a locally produced banana-waste Local Microorganism (MOL) solution (Banana MOL; *Musa paradisiaca* spp.) with Effective Microorganism-4 (EM4) to accelerate aerobic composting of dry leaves. Banana MOL was prepared by fermenting chopped banana waste (2.5 kg) with brown sugar (400 g), mature coconut water (2 L), and rice-washing water (3 L) for 14 days. Four treatments were evaluated: dry leaves only (P0), dry leaves + Banana MOL (P1), dry leaves + EM4 (P2), and dry leaves + Banana MOL + EM4 (P3). Process indicators (temperature, pH, and moisture) were monitored during 40 days of composting, and mature compost quality (C, N, P, K, and C/N ratio) was analyzed using one-way ANOVA ($p < 0.05$) and compared with the SNI 19-7030-2004 requirements. The combined inoculant (P3) produced the highest nutrient content, particularly total N and organic C, whereas Banana MOL alone (P1) provided the greatest co-benefit by reducing both dry leaf waste and banana residues used for MOL preparation. These findings support Banana MOL as a low-cost, locally available bio-activator that can complement EM4 for community-scale organic waste management.

Keywords-dry leaves waste; banana MOL; mature compost quality; circular economy

I. INTRODUCTION

The management of organic waste in metropolitan regions remains a persistent challenge, particularly in developing countries where rapid urbanization has intensified the complexity of solid waste systems [1-3]. Dry leaves, generated from fallen trees and plants, represent a significant fraction of organic waste. In Southeast Asia, organic waste accounts for approximately 57% of municipal solid waste [3], whereas in other areas such as Saudi Arabia, it comprises about 40% of the total volume [4]. In the United States, foliage and yard waste contribute over 13% of the total, amounting to 33 million tons annually [5]. Improper disposal of dry leaves can lead to environmental problems, including nutrient leaching, phosphorus loading in stormwater, drainage blockages during rainy seasons, and air pollution from open burning [6, 7].

Despite these challenges, dry leaves contain valuable macro- and micronutrients, making them suitable as a feedstock for composting [8, 9]. Composting offers ecological benefits by improving soil quality, conserving resources, and reducing disposal costs [3, 7, 9, 10]. However, natural decomposition of dry leaves is often slow due to high lignocellulosic content; therefore, microbial inoculants are commonly added to accelerate composting and improve maturity [9]. Commercial bio-activators such as Effective Microorganism-4 (EM4) have been widely applied [9, 11], but their cost limits accessibility. Locally sourced bio-activators, known as Local Microorganisms (MOL), provide a promising alternative. MOL is produced from organic substrates rich in carbohydrates and nutrients, supporting microbial proliferation and functioning as a liquid fertilizer after fermentation [12, 13]. Numerous studies have demonstrated the effectiveness of MOL as a bio-activator with vegetable waste, providing an optimal medium for the proliferation of decomposing microorganisms [12, 14-16]. However, the use of Banana MOL remains underexplored in aerobic composting studies.

The banana, a fruit primarily grown in tropical regions worldwide, produces approximately 60% of its biomass as residual waste after harvest, which is estimated at 114.08 million metric tons [17]. Banana peel can account for 35%–50% of fruit mass and is commonly discarded untreated, creating environmental and economic concerns [18-20]. Banana residues contain 66.2% carbohydrates and essential minerals that can support indigenous microbial growth, making them suitable substrates for MOL production [13, 18]. *Musa paradisiaca* spp. is among the widely cultivated banana types and has potential for use as a composting bio-activator substrate [17, 20].

Although several studies have evaluated MOL- and EM4-based composting, including direct comparisons between banana-derived MOL and EM4, the literature remains limited in simultaneously addressing three elements within a single controlled aerobic system: (i) testing single versus combined inoculation strategies (Banana MOL, EM4, and Banana MOL+EM4) under identical operating conditions, (ii) linking time-resolved process monitoring to maturity outcomes using quantitative time-series diagnostics (pairwise correlation heatmaps for temperature, pH, and humidity, complemented by Mean Absolute Difference (MAD) heatmaps for temperature and humidity to separate trend synchronization from magnitude separation), and (iii) statistically validating mature compost nutrient improvements (ANOVA with Tukey post-hoc comparisons) against SNI 19-7030-2004 benchmarks. Moreover, few studies explicitly frame Banana MOL as a circular-economy input produced from banana residues, thereby valorizing a secondary organic waste stream while reducing dependence on commercial inoculants. To address these gaps, we evaluated aerobic dry-leaf composting under four treatments (P0–P3) to determine whether Banana MOL can substitute for or complement EM4 in improving process dynamics and mature compost quality, while clarifying the performance trade-offs between single and combined bio-activator strategies.

II. MATERIALS AND METHODS

Aerobic dry-leaf composting was conducted using Banana MOL and EM4 bio-activators to evaluate their effectiveness in improving the composting process. The research was conducted using dry leaves at Hasanuddin University (Gowa Campus). The methodology is outlined in detail below, as shown in Figure 1.

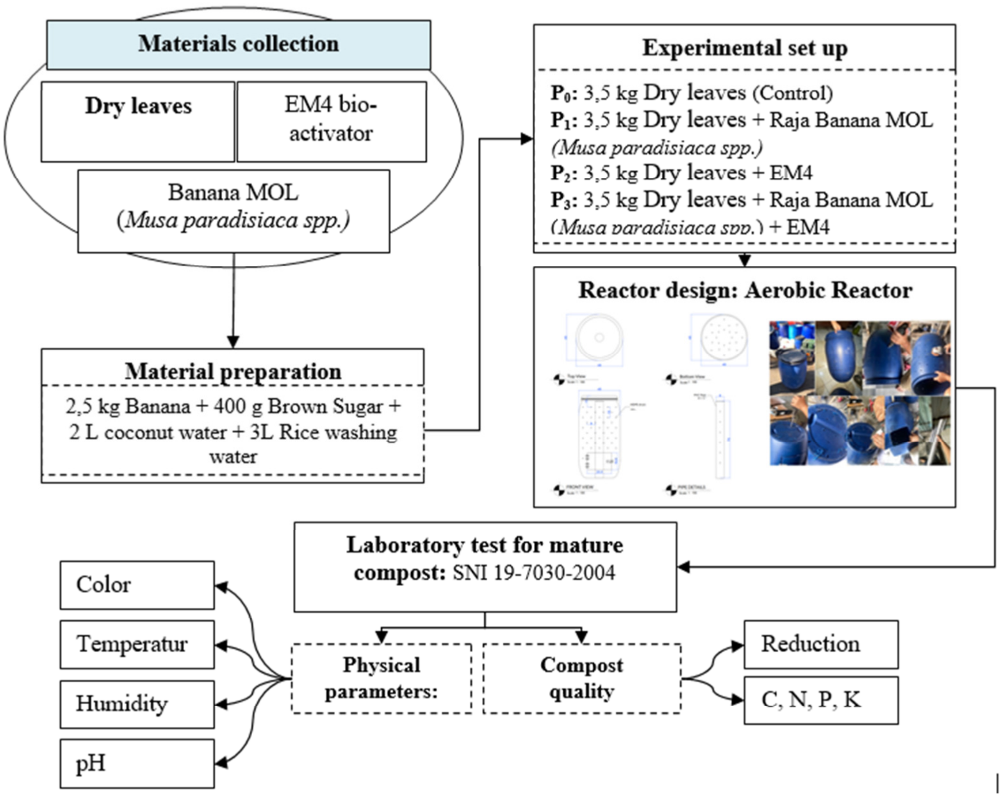


Fig. 1. Research framework.

A. Bio-Activator Fermentation

Banana MOL was prepared by mixing 2.5 kg of chopped banana (*Musa paradisiaca* spp.) waste (approximately 1 cm in size), 400 g of brown sugar, 2 L of mature coconut water, and around 3 L of rice-washing water in a covered container. According to research studies [13, 21], palm sugar and coconut water serve as an energy source for bacteria (glucose), whereas rice-washing water provides a carbohydrate source for microbes. The Banana MOL mixture was fermented for 14 days, protected from sunlight. The fermentation process is considered complete and successful when the bio-activator ceases to produce gas, emits a fermentative acidic odor, and the waste or organic material gradually settles to the bottom of the solution. Additionally, bubbles, threads, white spots, or clumps of bacteria should form on the surface of the bio-activator [13].

B. Composting Reactor Design (Aerobic Reactor)

A 100 L HDPE drum was used as the compost reactor, equipped with a 23.5 × 16.5 cm access door and aeration holes spaced every 10 cm to maintain aerobic conditions. Aerobic composting was selected for its rapid, efficient, and low-odor characteristics [8]. Reactor construction is presented in Figure 1.

C. Composting Process

The bio-activator solution was prepared by mixing 500 mL Banana MOL, 500 mL EM4, 500 g palm sugar, and 25 L groundwater (1:1:50), followed by fermentation in a sealed container for 1–3 days. Shredded leaf waste (14 kg total; 3.5 kg per treatment) was then loaded into the drum and mixed thoroughly with the solution. A 2.5-inch PVC pipe was positioned at the center of the composting mass to improve air circulation. Compost was harvested after 40 days, which falls within the 20–40 day maturation period reported for dry leaf substrates, depending on substrate [3, 22]

D. Data Analysis

Each treatment was implemented in one aerobic drum reactor (P0–P3). The physical characteristics measured included temperature, color, odor, humidity, and pH daily for 40 days and recorded in a logbook (n = 40 time points per treatment). At day 40, mature compost samples were collected and analyzed for physical characteristic, mass reduction, and organic C, total N, total P, total K using Indonesia National Standard 19-7030-2004.

All parameters were evaluated using one-way ANOVA ($p < 0.05$), followed by Tukey's HSD for post-hoc pairwise comparisons. To assess treatment similarity in process dynamics, Pearson correlation (r) was computed pairwise using the full daily time series for temperature, pH, and humidity, and visualized as correlation heatmaps. In addition, MAD heatmaps were calculated for temperature and humidity to quantify absolute magnitude separation. Correlation reflects trend synchronization, whereas MAD captures persistent level differences across the monitoring period.

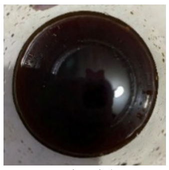
III. RESULTS AND DISCUSSION

This study focused on dry-leaf composting using different combinations of Banana MOL and EM4 bio-activators. The results are presented in three parts: the physical characteristics of the bio-activators, composting characteristics, and the quality of the mature compost.

A. Physical Characteristics of Bio-Activators

Table I summarizes the physical indicators of fermentation success for both bio-activators, including changes in organic matter, color, and odor. Banana MOL turned brownish-yellow, whereas the EM4 bio-activator developed white surface mold. The odor change observed after fermentation likely reflected anaerobic conditions, which promote the formation of ammonia, organic acids, and H_2S [23, 24].

TABLE I. PHYSICAL CHARACTERISTICS OF BIO-ACTIVATORS

Parameters	**EM4 Bio-activator**	**Banana MOL (*Musa paradisiaca* spp.)**
Physical characteristics before fermentation	 Liquid	 Liquid with abundant sediment
Color	Dark brick brown and slightly reddish	Light brown
Odor	Pungent odor (+)	Pungent smell of sour to sweet (+)
Physical characteristics after fermentation	 Liquid, with white threads indicating the presence of fungi and bubbles (bacteria), as well as a high concentration of microorganisms on the surface of the solution	 Liquid, with white threads indicating the presence of fungi and numerous bubbles (bacteria), as well as a high concentration of microorganisms on the surface of the solution
Color	Dark brown and non-dense color	Yellowish light brown, but not as intense as before
Odor	Pungent odor with fermented acid (+++)	Pungent odor with fermented fruit (+++)

During Banana MOL production, microbial degradation reduced banana waste mass from 2.5 kg to 1.85 kg wet weight and 0.42 kg dry weight, corresponding to an overall reduction of 83.2%. This result is consistent with previous reports of carbohydrate loss during fermentation [24]. Macronutrient analysis further showed that Banana MOL contained higher nutrient levels than the EM4 bio-activator (Figure 2).

B. Compost Characteristics

1) Temperature Dynamics

Composting typically begins at ambient temperature and then increases as microbial activity intensifies [25]. Across all treatments, composting temperatures ranged from 27 °C to 38 °C, with an overall mean of 32.0 ± 1.5 °C (Figure 3), indicating that decomposition proceeded predominantly in the mesophilic regime (30–45 °C) where aerobic microbes actively catabolize readily available organics and release metabolic heat [9, 26]. P1 exhibited the most rapid thermal response, reaching 38 °C by day 2, consistent with an early surge of microbial growth and enzymatic activity as labile organics were rapidly consumed [3, 25, 27, 28]. This early peak is plausibly linked to the bio-activator effect of Banana MOL, which can introduce active microbial consortia and fermentative metabolites that accelerate initial substrate turnover, thereby increasing respiratory heat release during the early mesophilic stage [26].

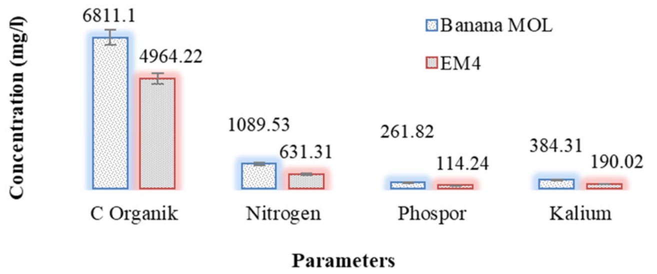


Fig. 2. Nutrient content of Banana MOL and EM4 bio-activator.

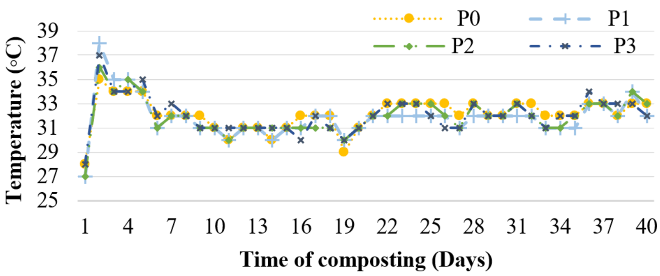


Fig. 3. Temperature changes during composting in 40 days across treatments.

Notably, thermophilic temperatures were not attained, which can be explained by limited heat retention under the study setup, as effective heat accumulation generally requires a pile height of 1–1.2 m [11, 26]. Although thermophilic conditions are not indispensable for compost maturity, their absence may result in a less efficient decomposition process [29]. Thereafter, the temperature of P1 declined to 31 °C by day 10 and progressively approached that of the other treatments, with all treatments stabilizing at around 32 °C by the end of the composting period [28]. The observed stabilization in temperature across treatments signifies the transition into the curing or maturation phase, during which microbial activity naturally subsides as easily degradable organic material becomes depleted [13, 15]. A one-way ANOVA confirmed that these differences were not statistically significant ($F = 0.23$, $p = 0.88 > 0.05$). This result demonstrates that the reactors exhibited uniform temperature behavior throughout the composting process, suggesting reproducible operational conditions and comparable microbial activity across treatments. Pairwise correlations of daily temperature profiles (Figure 4) were uniformly high across treatments ($r \approx 0.85$–0.93), indicating strong synchronization in the temporal progression of composting phases among reactors.

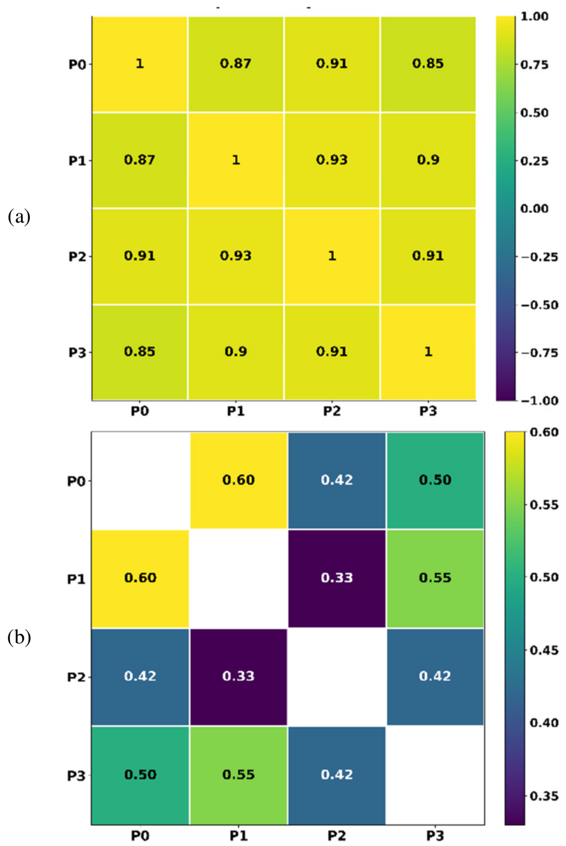


Fig. 4. Complementary similarity analysis of composting temperature dynamics across treatments: (a) Pearson correlation heatmap summarizes temporal synchronization of daily temperature trends, (b) MAD heatmap summarizes absolute magnitude differences in temperature across the same period.

This suggests that bio-activator addition did not substantially alter the timing of thermal stages, but primarily modulated the intensity of heat generation. In contrast, the MAD heatmap captured systematic differences in temperature magnitude: P1–P2 exhibited the smallest MAD (0.33), implying the most similar thermal intensities, whereas P0–P1 showed the largest divergence (MAD = 0.60) despite high correlation. Collectively, these results highlight an important distinction between trend similarity and absolute intensity: treatments can follow the same thermal trajectory while differing in metabolic strength, which likely reflects differences in effective microbial activity and substrate turnover rates induced by the applied inoculants.

2) pH

At the beginning of decomposition, all compost treatments exhibited mildly acidic to near-neutral pH (6–7), indicating conditions conducive to early microbial activity. Thereafter, pH increased gradually from day 2 and converged to a stable, near-neutral range (6.8–7.2) by day 40, which is widely considered optimal for aerobic composting (6–7.5) and aligns with Indonesian compost quality requirements [11, 25, 26, 30]. Although composting can occur across a broader pH interval (4.5–8.5), deviations from near-neutrality may compromise process efficiency: elevated pH can enhance ammonia volatilization, thereby increasing oxygen demand and heat generation, whereas low pH may inhibit microbial activity and reduce community viability [8]. Figure 5 shows the pH profiles of all treatments, which remained relatively stable throughout the composting period.

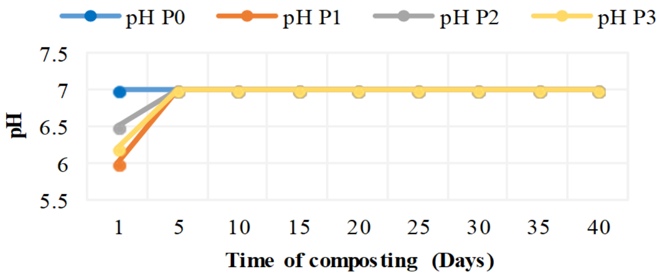


Fig. 5. pH changes during composting in 40 days across treatments.

The average pH across all treatments was 6.97 ± 0.1, remaining within the neutral to slightly acidic range. One-way ANOVA showed no significant differences in pH among treatments over time ($F = 0.97$, $p = 0.40 > 0.05$). Treatments P1–P3 initially exhibited acidic conditions, with P1 showing the lowest pH, likely reflecting early accumulation of organic acids generated during rapid microbial metabolism. Following the thermophilic peak, pH increased as readily degradable acids were progressively consumed and decomposition shifted toward more alkaline by-products [31]. As the process continued, pH rose in parallel with nitrogen mineralization and associated ammonia formation, and subsequently stabilized as the material approached maturity; in mature compost, pH tended to return toward neutrality as ammonia was either volatilized or assimilated into microbial biomass [26].

Complementing these temporal observations, the pH correlation heatmap revealed distinct treatment-dependent synchronization patterns (Figure 6): P1 and P2 exhibited an almost perfect correlation ($r = 0.98$), indicating highly aligned pH trajectories over time and suggesting that Banana MOL and EM4 produced comparable acidification–neutralization kinetics.

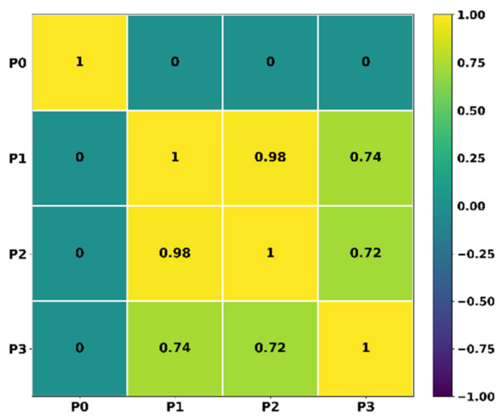


Fig. 6. Correlation heatmap of pH values across measurement points.

In contrast, the combined treatment (P3) showed only moderate correlations with P1 ($r = 0.74$) and P2 ($r = 0.72$), implying that inoculant combination altered the timing and/or rate of pH transitions rather than merely shifting absolute pH levels. Collectively, these results support a mechanistic interpretation in which the combined inoculants modulate the balance between acid-producing pathways and ammonia-generating processes, yielding a less synchronized pH progression relative to single-inoculant systems.

3) Humidity

Moisture availability is a primary regulator of composting microbiology because water controls solute diffusion, enzymatic contact, and transport of nutrients and energy substrates within the decomposing matrix [25]. Over the 40-day composting period, humidity fluctuated substantially, with 47 ± 11.4%, occasionally approaching levels where microbial activity may become water-limited [8, 25]. Values <45% can restrict microbial metabolism and slow decomposition, whereas the frequently reported operational optimum for organic-waste composting is typically within ~40–60% [8, 11, 25, 30]. The observed range implies a dynamic balance between periods favorable for aerobic degradation and intervals where moisture deficit could transiently constrain activity (Figure 7).

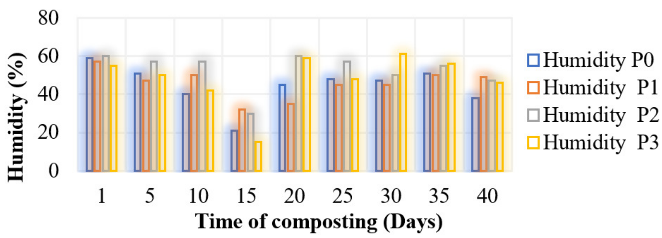


Fig. 7. Humidity changes during composting in 40 days.

A one-way ANOVA detected significant differences in moisture among treatments ($F = 2.97$, $p = 0.0337$), indicating that the applied amendments altered the reactor water balance. Tukey's HSD post-hoc analysis showed that most pairwise contrasts were not significant (P0–P1 MAD = 2.1, $p = 0.83$; P0–P3 = 4.85, $p = 0.21$; P3–P1 = 2.75, $p = 0.69$; P3–P2 = 2.075, $p = 0.84$; P1–P2 = 4.8, $p = 0.22$). In contrast, P0 differed significantly from P2 (MAD = 6.9, $p = 0.03$), suggesting a measurable treatment-driven shift in moisture dynamics.

Differences among inoculant strategies can further modulate moisture dynamics indirectly through their effects on decomposition intensity. In this study, P1 used Banana MOL alone, whereas P3 combined Banana MOL with EM4. Inoculant addition can increase microbial respiration and heat production, which accelerates evaporative water loss, while decomposition-driven structural changes (particle breakdown and altered pore architecture) can modify air-filled porosity and water-holding capacity, shifting the retention–drying balance under the same aeration conditions. Consistent with this mechanism, humidity similarity patterns indicate that P1 remained closest to the control (MAD 5.8) in absolute moisture magnitude, whereas P3 diverged more strongly from P1 (MAD 9.5), suggesting that adding EM4 to Banana MOL altered both the overall moisture status and the temporal coherence of humidity fluctuations (Figure 8).

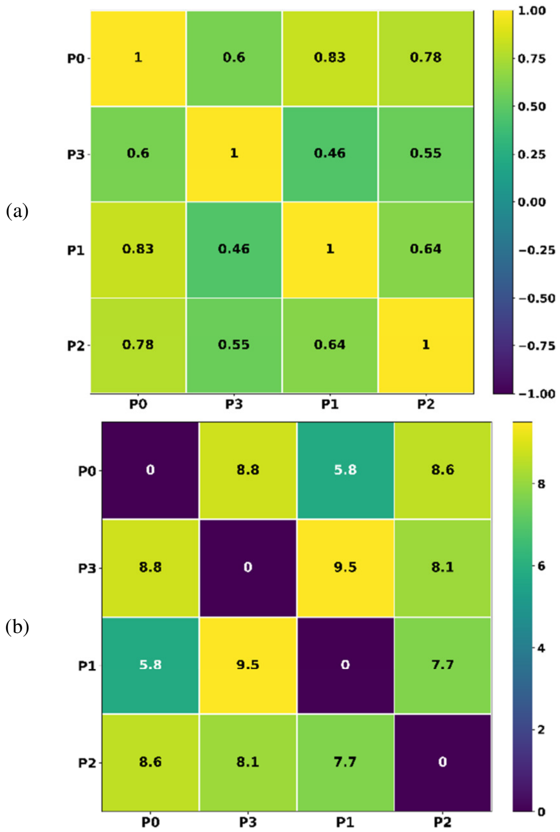


Fig. 8. Complementary similarity analysis of moisture (humidity) dynamics across composting treatments: (a) Pearson correlation heatmap summarizes trend synchronization of daily moisture profiles, (b) MAD heatmap summarizes absolute magnitude differences in moisture across the same period. Lower MAD indicates closer moisture levels between treatments, whereas higher MAD indicates larger, persistent differences in moisture magnitude even when temporal trends may appear similar.

Cross-parameter coupling further supports a phase-dependent interpretation (Figure 9). The temperature, humidity, pH correlation heatmap revealed weak overall linear relationships ($|r| \leq 0.29$). This finding is mechanistically plausible because temperature, humidity, and pH are influenced by different and sometimes competing processes across the mesophilic, thermophilic, cooling/curing, and maturation stages of composting [32]. Specifically, the weak temperature–humidity association ($r \approx 0.28$) reflects counteracting mechanisms: microbial heat generation tends to increase temperature, whereas higher temperature promotes evaporation that can reduce moisture, alongside redistribution effects within the matrix [33]. The near-zero humidity–pH correlation ($r \approx -0.14$) is also mechanistically plausible because bulk pH integrates multiple pathways (early organic-acid accumulation versus later alkalinization linked to nitrogen transformations and buffering), whereas moisture influences pH primarily indirectly through oxygen transport and micro-environmental constraints rather than as a direct linear driver [34].

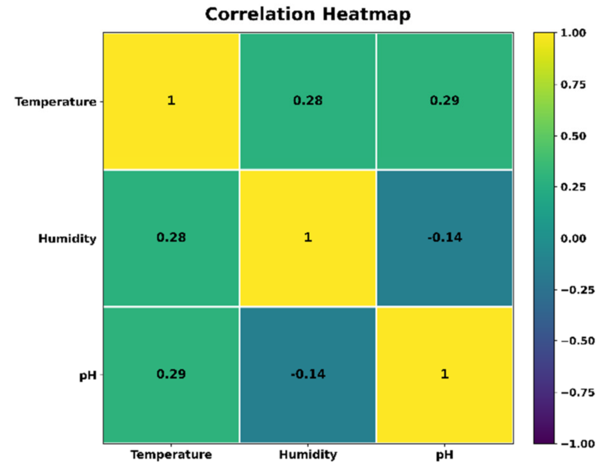


Fig. 9. The cross parameter correlation heatmap of humidity, temperature, and pH.

4) Compost Color

Compost maturity is commonly reflected by progressive darkening in color [30]. By day 40, all compost treatments exhibited visual characteristics consistent with maturity, as presented in Figure 10. The transition from green to brown and ultimately dark brown is associated with the progressive decomposition of organic carbon during composting [8]. No substantial differences in final compost color were observed among treatments after 40 days, likely due to the standardized materials, reactor conditions, and fermentation procedures applied throughout the experiment. Nevertheless, closer observation suggested that compost treated with activators softened more rapidly, although the magnitude of this difference remained limited.

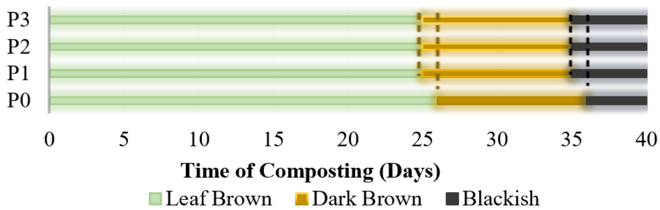


Fig. 10. Visual changes in compost color during 40 days of composting.

5) Compost Odor

Compost odor is an important indicator of maturity. According to SNI 19-7030-2004 (2004) [30], mature compost is characterized by a soil-like odor. During the initial stage of composting, most samples emitted a sour-sweet smell derived from the dry leaf materials, whereas sample P0 retained an odor resembling moist leaves. This leafy aroma appeared to become more intense under higher moisture conditions. By day 36, the odor had shifted to a more earthy scent. Following harvesting and drying, moisture levels stabilized, resulting in compost with a characteristic soil-like odor.

6) Nutrient Content of Mature Compost

Compost quality was benchmarked against SNI 19-7030-2004 to assess agronomic suitability, and Table II reveals clear treatment-driven shifts in nutrient status and maturity. The control (P0) failed to meet the SNI minimum for organic carbon (≥ 9.80%), achieving only 8.27%, whereas inoculated treatments satisfied this requirement and increased organic C progressively from P1 (9.91%) to P2 (10.60%) and P3 (11.38%). This pattern is consistent with the bio-activator role in accelerating decomposition while promoting carbon stabilization within the compost matrix [13]. In contrast, lower retained organic C in P0 plausibly reflects stronger net mineralization losses, where organic carbon is oxidized and released as CO_2, reducing residual carbon in the final material [35].

TABLE II. NUTRIENT CONTENT OF MATURE COMPOST

No.	Variation	Nutrient content (%)					
		Organic C	**Nitrogen**	**C/N ratio**	**P**	**K**	**Moisture content at harvest (wet basis)**
SNI 19-7030-2004		**Min: 9.80 Max: 32**	**Min: 0.40 Max: –**	**Min: 10 Max: 20**	**Min: 0.10 Max: –**	**Min: 0.20 Max: –**	**Min: – Max:50**
1	P0	8.27	0.50	16.49	0.18	0.36	74.41
2	P1	9.91	0.54	18.41	0.22	0.34	76.79
3	P2	10.60	0.59	17.98	0.22	0.45	71.42
4	P3	11.38	0.67	16.90	0.22	0.48	71.29

Total nitrogen exceeded the SNI minimum (≥ 0.40%) for all treatments (0.50–0.67%), yielding C/N ratios within the SNI maturity range (10–20%), indicating a chemically stabilized compost. Mechanistically, this supports the expected coupling between carbon as a microbial energy source and nitrogen as a biomass-building nutrient, where progressive carbon loss relative to nitrogen conservation drives the C/N ratio toward maturity [22, 28].

Macronutrient indicators further support the agronomic advantage of inoculation. All treatments met SNI minima for P (≥ 0.10%) and K (≥ 0.20%), with the combined inoculant P3 producing the highest K (0.48%) and maintaining elevated P (0.22%), suggesting enhanced nutrient mineralization and/or retention relative to single-inoculant and control conditions [13, 36, 37].

In contrast to the generally favorable nutrient and maturity metrics, moisture content at harvest substantially exceeded the SNI maximum (≤ 50%) in all treatments (71.29–76.79%) because compost quality was assessed on day 40 without a prior drying/curing step. High moisture is mechanistically important because water-filled pores reduce air-filled porosity and oxygen diffusion, increasing the likelihood of anaerobic micro-sites, odor formation, and slower stabilization when aeration is limited [36, 38, 39]. Under these conditions, anaerobic microorganisms may become dominant, and temperature may rise, although this does not always substantially reduce compost quality. Therefore, a curing or drying stage is typically required before compost is evaluated against final product standards.

C. Waste Reduction

The treatment of dry leaf waste with different combinations of Banana MOL and EM4 (P1, P2, P3) produced effective results and met the required standards. Compost maturity was reflected in waste reduction, which ranged from 53.7% to 59.9% (Figure 11). Composting, facilitated by microorganisms, leads to significant mass changes due to decomposition [9, 36]. The use of organic matter and evaporation decreases waste mass [11]. According to authors in [40], composting can reduce the initial volume by up to 65% and yield a nutrient-rich final product. Aerobic composting can result in a 50% reduction in the weight of the composting material [41], indicating the efficient aerobic processes at work.

Beyond nutrient performance, the treatments also differ in their circular-economy value. Although the combined inoculant (P3: Banana MOL + EM4) produced the strongest mature compost nutrient profile, Banana MOL alone (P1) represents the most resource-efficient pathway because the inoculant is generated from banana residues that would otherwise become organic waste. This creates a dual-waste valorization loop: dry leaves are converted into compost, whereas banana waste is simultaneously upcycled into a microbial starter that accelerates decomposition, reducing dependence on commercial inoculants and lowering input costs.

In this framing, P1 provides the highest environmental efficiency by maximizing waste reduction and minimizing external inputs, whereas P3 represents a performance-oriented strategy that can further enhance nutrient outcomes when additional inoculation is acceptable. Collectively, these results position Banana MOL as a locally scalable bio-activator that supports circular-economy principles by transforming ubiquitous banana residues into a value-adding process input and enabling more sustainable community-scale organic waste management.

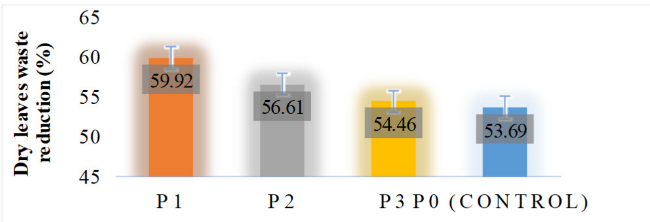


Fig. 11. Dry leaves waste reduction (%) in sample variation. P0 (dry leaves), P1 (Banana MOL), P2 (EM4 Bio-activator), P3 (Banana MOL + EM4 Bio-activator).

IV. CONCLUSION

This study demonstrates that both Banana Local Microorganism (MOL) and Effective Microorganism-4 (EM4) are effective inoculants for aerobic dry-leaf composting, with distinct functional advantages depending on the targeted outcomes. The combined inoculant treatment (P3) yielded the most optimal nutrient composition in mature compost, particularly with respect to organic carbon, total nitrogen, and potassium, indicating a synergistic effect of Banana MOL and EM4 in enhancing nutrient enrichment. Conversely, the application of Banana MOL alone (P1) represents a more resource-efficient and environmentally relevant strategy, as it simultaneously facilitates composting while valorizing banana residues as a locally sourced bio-activator.

Most evaluated compost quality parameters complied with the standards of SNI 19-7030-2004, including organic carbon (for inoculated treatments), total nitrogen, phosphorus, potassium, and C/N ratio. However, all treatments exceeded the prescribed moisture threshold at harvest, indicating the necessity of an additional curing or drying phase to achieve full compliance with final product specifications. These findings highlight Banana MOL as a viable local alternative or complement to EM4, particularly in community-based organic waste management systems prioritizing low-cost and locally available inputs.

Beyond product quality, this study introduces an integrated evaluation framework that combines process monitoring, nutrient benchmarking, and time-series similarity analysis to systematically compare single and combined inoculant strategies. The results further reinforce the circular economy potential of Banana MOL, whereby banana residues are diverted from waste streams and repurposed as functional composting inputs.

Nevertheless, the findings should be interpreted with caution. Each treatment was conducted in a single reactor unit, and statistical analyses relied on repeated temporal measurements rather than biological replication. Consequently, the observed differences should be considered preliminary yet informative within the experimental context, rather than definitive evidence of generalized treatment effects. Future studies should incorporate biological replicates, improved control of aeration and moisture conditions, and validation under larger-scale or field-relevant composting systems. Additional investigations are also required to assess compost maturity following post-harvest curing and to evaluate agronomic performance in soil and plant applications.

DECLARATION OF COMPETING INTERESTS

The authors declare no conflict of interest.

ACKNOWLEDGMENT

The authors express their gratitude to Hasanuddin University for providing facilities and support for conducting the experimental research.

DATA AVAILABILITY

The datasets generated and analyzed during this study are based on original experimental results. The datasets are available from the corresponding author upon reasonable request.

AI USE AND DECLARATION OF GENERATIVE AI USE

While preparing this work, the authors used ChatGPT-4 to assist with language editing and manuscript clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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