

Comparative Effects of *Trichoderma* and EM4 in Aerobic–Anaerobic Tiered-Bucket Production on Liquid Organic Fertilizer and Compost Quality

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Abstract. Organic waste is an abundant resource but remains underutilized as a safe and nutrient-rich organic fertilizer. This study aims to evaluate the effectiveness of *Trichoderma* as an alternative bioactivator to EM4 in improving the quality of liquid organic fertilizer (LOF) and compost through tiered bucket systems under aerobic (A₂) and anaerobic (A₁) conditions. A randomized complete block design was used with five *Trichoderma* doses (0; 15; 20; 25; 30 mL.L⁻¹) and EM₄ (30 mL.L⁻¹) as a comparison. The liquid and solid fractions were analyzed for C, N, C/N ratio, P₂O₅, K₂O, and heavy metals (Pb, Cd, Cu) using standard methods. The data were analyzed through ANOVA and orthogonal contrast tests. Results showed that the aerobic system consistently reduced the C/N ratio, producing more mature and stable products, while the anaerobic system tended to retain higher C-organic content. These differences were statistically significant as the aerobic condition (A₂) decreased the C/N ratio by 4.74 or 40.93% in liquid organic fertilizer and by 3.62 or 19.52% in compost compared to the anaerobic condition (A₁), while total P₂O₅ in liquid organic fertilizer increased by about 14.81% under A₂. Medium–high doses of *Trichoderma* (25–30 mL L⁻¹) in the aerobic system yielded the best quality in terms of maturity, whereas EM₄ generally resulted in higher macro-nutrient contents (N, P₂O₅, K₂O). All heavy metal levels were far below the SNI/Ministry of Agriculture thresholds, indicating product safety. Practically, the A₂–T₃/T₄ combination is recommended to produce mature, stable, and safe organic fertilizer, while co-inoculation strategies may be pursued to enhance nutrient content. This study confirms that *Trichoderma* primarily accelerates humification and stabilizes organic matter, offering a practical, low-cost option for household/community organic waste management within a circular-economy framework; accordingly, the aerobic bucket system with medium–high *Trichoderma* doses (A₂–T₃/T₄) is recommended to achieve mature, stable LOF–compost. However, the findings are lab-scale and substrate-specific.

Keywords: compost; liquid organic fertilizer; organic waste; tiered bucket system; *Trichoderma* sp

INTRODUCTION

Contemporary farming is under pressure to manage the organic waste generated by domestic and agro-industrial activities. Organic waste will continue to be an issue if it is not well handled (Ayilara et al., 2020). The rapid growth of the population is directly proportional to the amount of organic waste generated by human activities (Ganivet, 2020). Organic waste refers to waste originating from residential activities, including food scraps, leaves, fruits, and vegetable residues (Castillo et al., 2022; Ramady et al., 2022). This is the case in Indonesia, where organic waste management

has not been optimized. According to data from the Ministry of Environment and Forestry in 2021, the volume of waste in Indonesia, spread across 154 districts/cities, reached 18.2 million tons per year (Anggriyani et al., 2022).

In this study, the substrate formulation consisting of banana and pineapple peels, lemongrass leaves, and shallot skins was designed to represent the dominant fractions of Indonesian household organic waste, particularly fruit and vegetable residues as well as kitchen herb trimmings, while remaining practical for community-scale collection and processing. The fruit peels



supply readily degradable carbon and lignocellulosic matrices (Mridha et al., 2023), small additions of culinary herbs reflect seasoning scraps commonly discarded in domestic cooking, rabbit urine provides a locally available soluble nitrogen source that balances the C/N ratio, palm-sugar solution functions as a fermentable starter carbon to stimulate microbial activity, and rice-husk charcoal, widely produced in rice-growing regions, acts as a porous bulking and adsorptive agent to improve aeration and moisture regulation during fermentation. The composition and proportions described in the Methods section were established based on this rationale and on typical household access to inexpensive materials in Lampung and comparable regions, ensuring that the substrate mixture is both representative and scalable under local waste-stream conditions (Mridha et al., 2023; Syarifinnur et al., 2023).

Organic waste, such as fruit peels, vegetable residues, and livestock manure, is often underutilized, despite its potential as a raw material for liquid organic fertilizer (LOF) and compost. The use of organic fertilizers is one of the strategic solutions to support sustainable agriculture, improve soil fertility, and reduce dependence on chemical inorganic fertilizers that negatively impact the environment (Khan et al., 2024; Krasilnikov et al., 2022). A strategy for organic waste management is fermentation with bioactivators. *Trichoderma* sp. (a powerful biocontrol agent that also accelerates organic matter degradation and increases nutrient availability) (Tyśkiewicz et al., 2022). *Trichoderma* inoculation has also been found to effectively mitigate heavy metal accumulation, such as Cd and Pb, in soils (Altaf et al., 2023; Valenzuela et al., 2024). In addition, a fermentation innovation, based on fermentation technology and utilizing a tiered bucket system, enables the simultaneous production of LOF and compost, is relatively simple, low-cost, and efficient (Romaniuk et al., 2021).

Previous studies indicate two complementary roles of *Trichoderma* during

organic waste fermentation, which define the mechanistic basis and measurement parameters of this research. First, *Trichoderma* accelerates humification and stabilization by secreting cellulases, hemicellulases, and related oxidative enzymes that mineralize structural carbon, thereby reducing the C/N ratio and improving the maturity of compost and liquid organic fertilizer (Tyśkiewicz et al., 2022; Liu et al., 2020). Second, *Trichoderma* enhances nutrient solubilization by increasing phosphorus availability through the production of organic acids and phosphatases, mobilizing potassium via acidification and chelation processes, and influencing nitrogen transformations within the substrate matrix, which can increase dissolved N, P, and K levels in the liquid fraction (Lima et al., 2024). As humified organic matter accumulates, the formation of humic and fulvic substances together with microbial metabolites contributes to the immobilization or adsorption of toxic metals, and inoculation with *Trichoderma* has also been reported to reduce the availability and uptake of heavy metals such as Pb and Cd (Altaf et al., 2023; Valenzuela et al., 2024). Based on these mechanisms, the concentrations of Pb and Cd in liquid organic fertilizer and Pb and Cu in compost were analyzed to evaluate product safety and interpret metal partitioning dynamics in relation to material maturity and nutrient content.

The distinction of this study from previous research lies in its focus, methods, and outcomes. Zhang et al. (2022) emphasized seed coating with biochar to improve seed viability, not organic waste fermentation. Lima et al. (2024) conducted a theoretical review of the role of *Trichoderma* in agro-industrial waste bioconversion for biofuel production, whereas this study is an applied experiment directly testing the quality of LOF and compost. Meanwhile, Sani et al. (2020) linked *Trichoderma*-based biofertilizers with agronomic outcomes in tomato plants, whereas this study focuses on

the chemical parameters of compost and LOF. Few studies have simultaneously evaluated LOF quality based on parameters such as C-organic, total N, P_2O_5 , K_2O , and heavy metals, along with compost quality through C/N ratio and heavy metal content (Pb, Cu) within a single production system. Alias et al. (2022) employed digestate and solid-state fermentation (SSF) with various *Trichoderma* strains, while this study utilizes a tiered bucket system under aerobic and anaerobic conditions, comparing the effectiveness of *Trichoderma* with EM4 as a reference bioactivator. In addition, Sarah et al. (2023) emphasized statistical optimization (RSM, CCD) in producing LOF from vegetable waste, whereas this study applies a randomized complete block design (RCBD) with orthogonal contrast tests to evaluate the effects of aerobic/anaerobic fermentation and *Trichoderma* dosage on the quality of LOF and compost.

Through this research, the effect of *Trichoderma* as an alternative bioactivator to EM4 in improving the quality of liquid organic fertilizer (LOF) and compost in tiered bucket systems under aerobic and anaerobic conditions is expected to be clarified. EM4 was employed as a reference, as it is one of the most widely used collections of microorganisms in composting and as a biofertilizer; hence, the on-field protocols were well-defined. As for composition, EM is a probiotic of lactic acid bacteria, yeasts, and photosynthetic bacteria (sometimes containing other ingredients such as actinomycetes and fermenting bacteria), which metabolize organic matter rapidly and synergistically increase fermentation of organic matter and bioavailability of nutrients, making it a typical reference in bioactivator research (Li et al., 2023; Yap & Al-Mutairi, 2023). More recently, it has been substantiated that EM products enhance crop yield and nutrient utilization, and can be used effectively in large-scale composting systems (Boruszko, 2025; Demir et al., 2024). While *Trichoderma* stands for a single fungal bioactivator, empowered by a myriad of

mechanisms, involved in the instrumental roles of lignocellulose degradation, reduction of C/N ratio, and enzyme and organic acid-mediated solubilization of phosphorus and potassium, plus more biocontrol services (Guzmán et al., 2025). The consequence is that a direct comparison of *Trichoderma* with EM4 is not simply a novel alternative versus established standard it becomes a contrast of two fundamentally different modes of bioactivation—fermentative bacterial consortium vs specialized decomposer fungus—incorporated technical quality measures of both LOF and compost (organic C, total N, C/N ratio, P_2O_5 , K_2O) along with safety markers (Pb, Cd, Cu).

Therefore, the study demonstrates a new approach to biotechnology development based on the processing of organic wastes through fermentation combined with the action of *Trichoderma* sp. bacterium, which simultaneously verifies the decomposition and generation of liquid organic fertilizer (LOF) and solid manure in one step. From a soil microbiology perspective, this research enhances the understanding of the multifunctional roles of *Trichoderma* as a decomposer, increasing the availability of essential nutrients (e.g., N, P, and K), and as a mitigator of heavy metal accumulation, which indirectly promotes soil ecosystem health.

This research, from a soil science perspective, lays the scientific basis for enhancing organic fertilizer quality based on measurements of important indicators, including nutrient content, C/N ratio, and heavy metals. Thus, the findings can serve as practical strategies for more environmentally friendly and applicable organic waste management practices to support modern agriculture in Indonesia. Based on this explanation, the study aims to determine the effect of the bioactivator *Trichoderma* as an alternative to EM4 in improving the quality of liquid organic fertilizer (LOF) and compost in a tiered bucket system under aerobic and anaerobic conditions.

METHODS

Time and Place

The study was conducted from June to August 2025. Compost and LOF (liquid organic fertilizer) production was carried out at the Laboratory of the Faculty of Agricultural Technology, Universitas Satu Nusa Lampung. The chemical analysis of LOF and compost was conducted at the Integrated Laboratory of Universitas Lampung and the Testing Laboratory of the Agricultural Modernization Application Center in Lampung.

Materials and Tools

The materials used in this study included: banana peels (3,250 mL, 32.5%); pineapple peels (3,250 mL, 32.5%); lemongrass leaves (500 mL, 5%); rabbit urine (1,000 mL, 10%); rice husk charcoal (1,250 mL, 12.5%); shallot peels (150 mL, 1.5%); palm sugar solution (600 mL, 6%); *Trichoderma sp.* bioactivator according to treatment dosage; and EM₄ (30 mL/L material).

The *Trichoderma sp.* bioactivator used in this study was obtained from the Microbiology Laboratory of the Faculty of Agricultural Technology, Universitas Satu Nusa Lampung. The culture was originally isolated from composted organic waste and maintained on Potato Dextrose Agar (PDA) medium. Spore suspension was prepared by flooding a 7-day-old culture plate with sterile distilled water containing 0.05% Tween 80, then filtered through sterile gauze to obtain a uniform spore suspension. The concentration was adjusted to approximately 1×10^8 spores mL⁻¹ using a hemocytometer. The inoculum was stored at 4 °C and activated prior to application by dilution (1:10 v/v) in a palm sugar solution (1%) and incubated for 24 hours at room temperature (28 ± 2 °C) to stimulate spore germination. The activated suspensions were then administered according to the dose treatments (T₀ - T₄).

These were the instruments: Tiered aerobic and anaerobic buckets as fermentation substrates; digital scale for material weighing; graduated cylinders,

pipettes and beaker; thermometer and pH meter; stirrer and mixing recipient; (stationary and documentation camera; and perfumed laboratory tools for chemistry analysis, likes grating spectrophotometer, Atomic Absorption Spectrophotometer (AAS), oven, ICP-OES, and muffle furnace.

All analytical instruments were calibrated before measurement, following the established laboratory protocols. The determination was validated by running blanks and standards prepared from analytical-grade reagents, as stated in SNI 7763:2024 (BSN, 2024). The AAS and ICP-OES systems were calibrated with the multi-element standard solutions (Merck CertiPUR®), showing the correlation coefficients (R^2) ≥ 0.999 for each evaluated element (Pb, Cd, Cu, K). Internal quality control for internal quality control, reagent blanks, duplicates, and certified reference materials were employed to verify analytical quality and precision.

Experimental Design

The study was conducted using an experimental design with two treatment factors in a Randomized Complete Block Design (RCBD). The first factor was the fermentation condition (A) in the tiered bucket system, which consisted of two levels: A₁ = Anaerobic and A₂ = Aerobic. The second factor was the dosage of the *Trichoderma sp.* bioactivator (T) at six levels: T₀ = without bioactivator; T₁ = *Trichoderma sp.* 15 mL/L material, T₂ = *Trichoderma sp.* 20 mL/L material, T₃ = *Trichoderma sp.* 25 mL/L material, T₄ = *Trichoderma sp.* 30 mL/L material, and EM = EM₄ 30 mL/L material as reference. In total, 12 treatment combinations with three replications resulted in a total of 36 experimental units.

Research Procedure

Preparation of Materials

Preparation of the materials: The organic wastes included banana peels, pineapple peels, lemongrass leaves, shallot peels, rabbit urine, rice husk charcoal, and palm sugar solution. Materials were weighed according

to the recipe (total volume: 10 L of materials) and mixed thoroughly. The concoction was transferred into Multilayer buckets for treatments A₁ (anaerobic) and A₂ (aerobic). A *Trichoderma* sp. solution was sprayed according to the treatment levels (T0–T4), and EM4 was applied to the EM treatment.

The fermentation time was 60 days as an appropriate duration for organic waste degradation to attain the stable C/N ratio and mature compost-LOF products, as previously reported in related research in *Trichoderma* or EM-facilitated fermentations (Lima et al., 2024; Yang et al., 2021). During the monitoring of temperature, pH, odor, and color, these parameters were noted at regular intervals to confirm the stability of the process and identify its state of maturity. After the fermenting, the products were divided into liquid organic fertilizer (LOF) and solid compost.

Design of the Tiered Bucket System

The two 20-liter buckets were used in a tiered or stacked fashion in the tiered bucket system. The top bucket was where raw organic material was placed to make compost. The bottom of the top bucket was punctured with small holes, allowing the leachate to collect in the bottom bucket. Aerobic process (A₂): This process involves applying an upper bucket containing two vertically inserted perforated PVC pipes (diameter 1.5 cm) into the compost mass for internal aeration while the compost is fermenting inside the upper bucket. Four symmetrical 1 cm diameter holes were drilled on the lid and the upper side walls to provide passive airflow covering the so-called chimney effect. No forced (active) aeration was applied, as air exchange was total due to natural convection. The entire compost was turned by hand every seven days to enhance aeration and maintain even breakdown. The oxygen concentration in the headspace was determined using a portable O₂ meter (OXY-4, PreSens) at the beginning, at the midpoint (day 30), and at the end of fermentation. A qualitative observation of CO₂ accumulation was performed to ensure

the maintenance of aerobic conditions. By contrast, the anaerobic procedure (A₁) aimed at maximizing exposure to no oxygen. The upper bucket was completely solid, with no air holes, and was sealed airtight using a silicone gasket and locking lid. The lid was subsequently wrapped with parafilm to prevent any air infiltration through the junctions. The lower bucket contains the one-way hydraulic vent tube, which lets biogas out and prevents internal pressure build-up, thus maintaining an oxygen-limited environment. A drain tap was attached to the bottom of the lower bucket so that leachate could be harvested for analysis of liquid organic fertilizer (LOF).

Observation and Sampling

Fermentation environmental factors, including temperature, pH, odor, and color, were observed at regular intervals. On the 45th day, leachate was drained from the lower bucket tap, collected in bottles and left for two weeks. After the homogenization and filtration of LOF, aliquots were taken, whereas solid compost samples were recovered in a composite from several portions of the upper bucket on day 60. Samples of LOF were drawn to the 3100 mL level from each experimental unit. For heavy metal determinations, samples were stored at 4 °C and preserved with HNO₃ until pH < 2. Samples with turbidity > 1 NTU were predigested using a mixture of HNO₃ and HCl prior to analysis.

Laboratory Analysis

The LOF quality parameters observed included: (1) total C-organic (%), determined by the Walkley & Black method, SNI 7763:2024; (2) total N (%), analyzed by the Kjeldahl method, SNI 7763:2024; (3) C/N ratio, calculated from C and N analyses; (4) P₂O₅ (phosphate), analyzed using HNO₃ + HClO₄ and molybdovanadate spectrophotometry; (5) K₂O (potassium), analyzed using HNO₃ + HClO₄ and AAS; and (6) heavy metals Pb and Cd, analyzed using Inductively Coupled Plasma–Optical Emission Spectrometry (ICP-OES) according to US EPA Method 200.7 Rev.5.2001 (EPA,

2001). The solid compost quality parameters observed included: (1) total C-organic (%), Walkley & Black method, SNI 7763:2024; (2) total N (%), Kjeldahl method, SNI 7763:2024; (3) C/N ratio; and (4) Pb and Cu content analyzed using ICP-OES according to US EPA Method 200.7 Rev.5.2001 (BSN, 2024; EPA, 2001).

Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) based on the two-factor RCBD model. Prior to ANOVA, data were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene’s test to ensure the assumptions of ANOVA were met. If significant differences were found, orthogonal contrast tests were carried out according to the research objectives: (1) Anaerobic (A_1) vs Aerobic (A_2), (2) T_1 , T_2 , T_3 , T_4 vs T_0 , (3) T_1 , T_2 , T_3 , T_4 vs EM, (4) T_1 , T_2 vs T_3 , T_4 , (5) T_1 vs T_2 , and (6) T_3 vs T_4 . Data processing was performed using SAS statistical software.

RESULTS AND DISCUSSION

Observation Results

The contents of C-organic, total N, C/N ratio, total P_2O_5 , total K_2O , and heavy metals (Pb, Cd, and Cu) in LOF and compost from organic waste fermented under anaerobic and aerobic conditions with *Trichoderma* sp. bioactivator showed variation among treatments. The prerequisite tests for ANOVA (normality and homogeneity) were completed, and the required assumptions were fulfilled. The analysis of variance (ANOVA) revealed that the fermentation condition factor (A), bioactivator dosage (T), and the interaction between fermentation condition and *Trichoderma* bioactivator treatment ($A \times T$) had a highly significant effect on all observed parameters.

C-organic Content

In compost, the C-organic content (29.86%) was higher than in LOF (0.77%) because compost is expressed on a dry weight basis of solids, whereas LOF is in liquid form. The results showed that compost was significantly richer in the C-organic matter

than LOF under all combinations of treatments. C-organic matter content of the LOF with various treatments. The C-organic content of the anaerobic system (A_1) was significantly higher than that of the aerobic system (A_2) ($p < 0.05$), suggesting that carbon degradation was slower under anaerobic conditions. The maximum content of C-organic was recorded in the control treatment (T_0) for both methods ($A_1=1.01\%$, $A_2=0.75\%$). *Trichoderma* (T_1 – T_4) or EM applications significantly reduced the C-bond values ($p < 0.05$); however, T_4 was not significantly different from the control. The results suggest that microbial inoculation stimulated carbon mineralization, particularly under aerobic conditions. The amount of C-organic in the compost under various *Trichoderma* and EM applications is shown. The C-organic content of the compost was 25–32 %. The highest percentages were obtained for the control (T_0) ($A_1 = 31.83\%$, $A_2 = 31.44\%$), and the lowest was observed with the EM treatment at the aerobic condition ($A_2 = 25.75\%$). A12 The statistical analyses ($p < 0.05$) indicated that the C-organic content of the anaerobic systems (A_1) was significantly greater than that of the aerobic systems (A_2), implying that carbon degradation is slower in oxygen-limited environments.

Addition of *Trichoderma* (T_1 – T_4) significantly decreased the C-organic content ($p < 0.05$) compared to the control, indicating that lignocellulose decomposition was accelerated along with C mineralization. On the other hand, a high rate of *Trichoderma* (T_3 – T_4) in aerobic treatment produced a mature and stable compost, whereas the anaerobic treatments (A_1 – T_1/T_2) retained carbon more effectively. These results highlight that *Trichoderma* and aerobic conditions exert a positive synergistic effect in promoting carbon turnover and compost stabilization, which confirms previous findings (Chen et al., 2025; Organo et al., 2022). The same trend is observed in comparative reviews (Aguilar-Paredes et al., 2023), which corroborate the *Trichoderma*-

mediated degradation of lignocellulose, leading to faster humification compared to other microbial inoculants. These results are consistent with those of Hemati et al. (2022), who stated that *Trichoderma* promotes cellulose decay and carbon oxidation in crop residue composts, degrading the organic carbon pool more rapidly in the presence of increased oxygen. Similarly, Bohacz & Kowalska (2020) reported that *Trichoderma* sp. Secretes lignocellulolytic enzymes, which are the main factor transforming recalcitrant complex organic matter into more labile organic matter, thus accelerating the process of humification. Meanwhile, Elbasiouny et al. (2022) and Zhu et al. (2024) demonstrated that rapid mineralization causes the loss of C as CO₂ which accounts for the decline of organic C in the inoculated samples compared to the control.

Total N Content

The total N content of LOF and compost varied across treatments. Compost, as a solid material, contained significantly higher total N (1.48%) than LOF (0.06%) ($p < 0.01$). In LOF, nitrogen occurred mainly in dissolved forms (ammonium and nitrate), which are readily available to plants despite their lower percentage. In LOF, total N ranged from 0.04 to 0.07%. The aerobic condition (A₂) produced significantly higher total N than the anaerobic condition (A₁) ($p < 0.05$), with an average increase of 13.89%. The highest value was observed in the control (T₀) under A₂ (0.07%), while the lowest value was found under A₁ (0.04%). Treatments with *Trichoderma* (T₁–T₄) did not significantly differ from one another ($p > 0.05$), but EM₄ treatment maintained total N at levels comparable to or higher than *Trichoderma* (0.06–0.07%). These results suggest that nitrogen stabilization in a soluble form is promoted and N loss via denitrification is reduced under aerobic fermentation. The overall N content in the compost was significantly higher than that in the LOF, ranging from 1.26 to 1.64% ($p < 0.01$). T₀ had the highest total N, and *Trichoderma* treatments (T₁–T₄) had significantly lower

total N ($p < 0.05$), indicating that the decomposition of OM was promoted and N was lost through volatilization. The EM₄ treatment held an intermediate amount of N (1.43–1.61%), which was significantly greater than some of the *Trichoderma* treatments in the aerobic trend ($p < 0.05$). In general, total N was slightly higher for the aerobic system (A₂) than for the anaerobic system (A₁) ($p < 0.05$), indicating greater conversion of organic N to stable mineral forms. Together, these outcomes reveal that controlled aeration facilitates N retention and maturity of compost, and that microbial inoculants, such as *Trichoderma* and EM₄, have an impact on N cycling via enzymatic mineralization (Maciag et al., 2023; Poveda et al., 2020).

These results are in agreement with Organo et al. (2022), who observed *Trichoderma* increases N mineralization during composting, but potentially also stimulates volatilization in conditions of high microbial respiration. Abdelghany et al. (2025) indicated that EM preparations have a tendency to stabilize more nitrogen as a result of microbial diversity and synergistic nitrifying populations, which is why EM₄ was better than *Trichoderma* in preserving N levels. This pattern is consistent with Liu et al. (2020), who demonstrated that aerobic fermentation drives a higher ammonium–nitrate equilibrium than waterlogged fermentation, thereby enhancing N availability and fertilizer quality.

C/N Ratio Values

The C/N ratios of LOF and compost are presented. The C/N ratio of the compost (20.37) was, on average, greater than that of the LOF (14.51%), which was due to the compost's solidity and slower rate of decomposition. The orthogonal contrast test revealed significant differences among treatments ($p < 0.01$), and the C/N ratio was affected by both the fermentation conditions and the bioactivators. The LOF indicates that the aerobic system (A₂) yielded significantly lower C/N ratios than the anaerobic system (A₁) ($p < 0.05$), suggesting a higher rate of

carbon mineralization and greater nitrogen retention in the soil with aeration. The highest C/N ratio was observed in the control (T_0) ($A_1 = 25.25$; $A_2 = 10.71$), whereas the *Trichoderma* treatments (T_1 – T_4) and EM₄ brought down the ratio to a lower and more stable range (9.86–13.12), which may be considered to conform to the maturity criterion (10–20). The combination of A_2 – T_1 gave the best two-like result (C/N = 11.19), indicating that under aerobic conditions, appropriate addition of *Trichoderma* could improve the decomposition efficiency and fertilizer stability. On the other hand, similar findings are also reported in Yang et al. (2021) and Sun et al. (2025) that aeration is an effective treatment to lower the C/N ratio through promoting carbon oxidation and nitrogen stabilization. Likewise, Sahu et al. (2020) and Huang et al. (2021) have observed that, under anaerobic conditions, higher C/N ratios imply incomplete degradation. This is consistent with the study of Liu et al. (2020), which confirmed that *Trichoderma* is effective in decreasing the C/N ratio through enzymatic degradation, similar to the EM application.

The C / N ratio in the compost was between 15.99 to 24.53 and significantly higher than that of LOF ($p < .01$). The aerobic treatment (A_2) significantly reduced the C / N ratio compared to the anaerobic treatment (A_1) ($p < 0.05$), implying that the carbon oxidation rate and the maturity degree of compost were higher. The *Trichoderma* treatments (T_1 – T_4) were also found to significantly lower the C/N ratio ($p < 0.05$) compared to the control (T_0), indicating a faster degradation of lignocellulose. The EM₄ treatment produced C/N ratios that were comparable to or slightly lower than those of the *Trichoderma* treatments, with A_2 –EM (15.99) and A_2 – T_1 (19.24) being closest to the optimal maturity value (10–20). To summarize, aerobic fermentation, paired with either *Trichoderma* or EM₄, promoted the stabilization of organic matter and resulted in the formation of compost with elevated maturity and nutritive equilibrium. In

conclusion, the results revealed that microbial agents and oxygen signals synergistically facilitated a decrease in Cr/Cn ratios through enhanced enzymatic degradation and N retention, which aligns with the results of the previous study (Lima et al., 2024; Yang et al., 2021).

Total P and Total K Content

The contents of total P_2O_5 and K_2O in LOF from organic waste varied among the treatments. The orthogonal contrast indicated that the aerobic system (A_2) significantly increased the P_2O_5 amount compared with the anaerobic system (A_1) ($p < 0.05$) by an average value of 14.81%. This suggests that aerobic fermentation promotes phosphorus solubilization and mineralization, thereby increasing phosphorus availability in the liquid phase. In contrast, total K_2O was significantly greater under A_1 (19.82%) ($p < 0.05$), indicating higher potassium retention in low oxygen conditions.

In LOF, total P_2O_5 was in the range of 0.03–0.06%. The aerobic treatments A_2 yielded higher P_2O_5 content at all times, mainly in T_3 , T_4 , and EM treatments, which were not significantly different from each other ($p > 0.05$). Under A_2 , the EM treatment had the maximum P_2O_5 content (0.06%), which also confirms that aerobic conditions promote processes of P mineralization and solubilization by microbes, thereby enhancing the nutrient quality of the LOF.

The content of total K_2O in LOF was in the range 0.66–0.92% and exhibited an inverse trend against that of P_2O_5 . K_2O content in the anaerobic system (A_1) was significantly higher than in the aerobic system (A_2) ($p < 0.05$), with an average increase of 19.82%. This indicates that oxygen-free *Trichoderma* activity and acid production from organics were able to solubilize more potassium from the bound forms. Among the treatments, EM exhibited the highest K_2O content (0.92%); however, the A_1 – T_3 and A_1 – T_4 were nonsignificant ($p > 0.05$). These results prove that *Trichoderma* in anaerobiosis efficiently enhances K

availability by enzymatic and acid-mediated solubilization. While aerobic treatments (A₂–T₃/T₄) resulted in moderate K₂O contents and relatively balanced nutrient profiles, these treatments were intended to enhance nutrient stability in LOF.

These results are in accordance with [Hidalgo et al. \(2022\)](#) that stated that EM's diverse microbial composition facilitate phosphorus solubilization via organic acid and phosphatase activity, thus accounting for the elevated P₂O₅ contents in EM₄. In a similar vein, [Waheed & Zeng \(2020\)](#) reported that aerobic fermentation increases phosphorus availability by boosting oxidative microbial metabolism. On the other hand, as noted by [Dutta et al. \(2024\)](#), there was a preference for potassium solubilization over potassium under anaerobic conditions because it produced organic acids by *Trichoderma*, which is in line with trends in A₁ treatment.

Heavy Metal Content

The heavy metal content in compost and LOF was analyzed to assess product safety and compliance with national quality standards. In compost, Pb and Cu were evaluated, while in LOF, the parameters were Pb and Cd. According to SNI 19-7030-2004 and Regulation of the Minister of Agriculture Number 261/Kpts/SR.310/M/4/2019, the permissible limits are ≤50 mg/kg for Pb and ≤100 mg/kg for Cu in compost, and ≤5 mg/L for Pb and ≤1 mg/L for Cd in LOF ([BSN, 2004](#); [Mentan RI, 2019](#)).

All heavy metal concentrations were well below the regulatory limits, confirming that both compost and LOF are safe for agricultural use. In compost, Pb ranged from 0.16–9.87 mg/kg and Cu from 3.94–5.36 mg/kg, while in LOF, Pb ranged from 0.048–0.215 mg/L and Cd was not detected (<0.027 mg/L). Although the aerobic system (A₂) showed slightly higher Pb and Cu levels than the anaerobic system (A₁), the differences were not statistically significant ($p > 0.05$). Concentrations reported as <0.027 mg/L, represent values below the instrument's limit of detection (LOD = 0.027 mg/L) and limit of

quantification (LOQ = 0.05 mg/L) measured using ICP-OES. For statistical analyses, non-detect values were treated as half of the LOD (0.0135 mg/L) to avoid bias in mean estimates, following standard censored-data methods. As more than 80% of Cd measurements were lower than the LOD, no inferential analysis was conducted for Cd, and results were interpreted qualitatively as non-detectable. Together, these results suggest that neither the composting nor the fermentation process caused heavy metal accumulation, and that clean raw materials were used for a controlled bioconversion process.

The total Pb content in the compost varied significantly among the fermentation types ($p < 0.05$), with the value for aerobic (A₂) being higher than that for anaerobic (A₁). The maximum Pb concentration was found in A₂–T₄ (9.87 mg/kg), while the minimum was detected in A₁–T₀ (0.16 mg/kg). All of them were well below the allowable limit (50 mg/kg). Total Cu concentration in compost showed a significant difference among the fermentation treatments ($p < 0.05$). The result of aerobic condition (A₂) having a higher Cu content than anaerobic condition (A₁) is well-known. All Cu levels were below the 100 mg/kg maximum.

These results align with those of [Munir et al. \(2022\)](#), who highlighted that controlled composting in a clean environment reduces heavy metal contamination. [Feszterová et al. \(2024\)](#) and [Wang et al. \(2024\)](#) further demonstrated that aeration can slightly increase Pb and Cu concentrations through oxidation and complexation with humic substances, although such increments are still considered safe. The results also strengthen the opinion of [Zhao et al. \(2025\)](#) that *Trichoderma*-based composting maintains environmental safety indicators and enhances maturity.

The orthogonal contrast test showed significant differences ($p < 0.01$) in Pb and Cu contents between aerobic (A₂) and anaerobic (A₁) conditions, with higher values

under A₂. Significant effects ($p < 0.01$) were also observed between the *Trichoderma* treatments (T₁–T₄) and both controls (T₀ and EM), as well as between T₃ and T₄ for both Pb and Cu. These results are consistent

with previous findings that aerobic conditions and humification processes influence metal dynamics in compost (Feszterová et al., 2024; Wang et al., 2024).

Table 1. Main Significant Effects of Fermentation System and *Trichoderma* Treatment

Parameter	Main Effect: Fermentation System	Optimal <i>Trichoderma</i> Dose	Significance Level	Main Finding
C-organic (%)	Higher under anaerobic conditions	T ₃ –T ₄ (25–30 mL/L) under aerobic system	$p < 0.01$	Anaerobic fermentation retained more carbon; high <i>Trichoderma</i> doses enhanced carbon stabilization.
Total N (%)	Higher under aerobic conditions	T ₁ –T ₂ (15–20 mL/L) under aerobic system	$p < 0.05$	Aerobic fermentation improved nitrogen retention; moderate doses of <i>Trichoderma</i> maintained higher N levels.
C/N Ratio	Lower under aerobic conditions	T ₁ (15 mL/L) under aerobic system	$p < 0.01$	Aerobic conditions reduced the C/N ratio; low to moderate <i>Trichoderma</i> doses produced mature compost (C/N $\approx$ 10–20).
Total P ₂ O ₅ (%)	Higher under aerobic conditions	T ₃ –T ₄ (25–30 mL/L) under aerobic system	$p < 0.01$	Aerobic fermentation enhanced phosphorus solubilization; higher <i>Trichoderma</i> doses increased P ₂ O ₅ content.
Total K ₂ O (%)	Higher under anaerobic conditions	T ₃ –T ₄ (25–30 mL/L) under anaerobic system	$p < 0.01$	Anaerobic fermentation favored potassium retention; high <i>Trichoderma</i> doses further improved K availability.
Pb (mg/kg)	Slightly higher under aerobic conditions (within safe limits)	T ₄ (30 mL/L) under aerobic system	$p < 0.01$	Pb concentration increased slightly with high <i>Trichoderma</i> dose but remained below safety limits.
Cu (mg/kg)	Higher under aerobic conditions (within safe limits)	T ₃ –T ₄ (25–30 mL/L) under aerobic system	$p < 0.01$	Aerobic composting slightly increased Cu concentration, all within permissible limits.

Table 1 shows this study aligns with previous works confirming that *Trichoderma* improves compost maturity through C/N ratio reduction (Liu et al., 2020; Yang et al., 2021),

while EM contributes more to nutrient enrichment (Abdelghany et al., 2025; Hidalgo et al., 2022). Aerobic systems enhanced decomposition and nutrient

stabilization (Ren et al., 2025; Sun et al., 2025), whereas anaerobic systems better preserved organic C and K. The combined findings confirm that integrating *Trichoderma* and proper aeration can produce mature, safe, and stable LOF-compost products that meet SNI and Permentan standards.

Beyond statistical significance, the magnitude of the observed effects was also examined to assess their agronomic relevance. Most nutrient differences among treatments, such as total N increase of 8–12% and P_2O_5 increase of up to 15%, were relatively small and would not substantially alter fertilizer recommendations. Similar magnitudes were previously reported as agronomically minor by Hemati et al. (2022) and Lima et al. (2024), who found that composts showing less than 0.2% variation in total N or less than 0.1% in P_2O_5 rarely affect field fertilization strategies. However, reductions in the C/N ratio by 15–20% (equivalent to 2–4 units) and higher K_2O levels under anaerobic conditions (approximately a 20% increase) are agronomically meaningful because they shorten compost maturation time and enhance potassium availability for K-demanding crops. This is consistent with Yang et al. (2021), who found that reducing the C/N ratio over 2 levels could effectively speed up the process of compost maturity, and with Hidalgo et al. (2022), who reported that a 20 % enhancement in K_2O might contribute to the improvement of the nutrient balance and functionality of organic fertilizers. Therefore, although EM₄ had a positive but slight effect on N and P, the relevance of this improvement was slight, and it was more important for process development than for revising any nutrient management strategies.

From a broader environmental point of view, the quicker breakdown and intensified aeration of the aerobic system (A₂) might additionally enhance volatilization of nitrogen (NH₃, N₂O) and greenhouse gases. A₂ promoted N stabilization and compost

maturity but it could amplify gaseous N losses if too intense aeration or respirative activity rates, especially when C/N ratios decrease or pH conditions favor NH₃ generation. Given the potential trade-offs, future work should incorporate direct measurements of gaseous emissions (NH₃, N₂O, CO₂) and further explore mitigation strategies, including customized aeration schedules, water content regulation, or co-inoculations with nitrifying microbial consortia, to achieve the best fit between decomposing proficiency and nitrogen protection. To reinforce these insights, specific follow-up studies are proposed, such as enzyme activity assays to clarify the decay mechanisms, microbial community sequencing to identify the predominant functional taxa, greenhouse studies to quantify plant response and nutrient acquisition efficiency, as well as LCA and cost-benefit analysis for evaluating environmental and economic aspects. These follow-ups should be prioritized sequentially, progressing from biochemical and microbial-level investigations to applied agronomic and sustainability evaluations.

CONCLUSION

This study demonstrates that *Trichoderma* sp. is effective as a bioactivator for enhancing the maturity of compost and liquid organic fertilizer in a tiered bucket system, particularly under aerobic fermentation conditions. The aerobic treatment (A₂) accelerated humification, lowered the C/N ratio, and produced mature and stable organic fertilizer that met national safety standards. For practical application, the recommended formulation is an aerobic system with a *Trichoderma* dose of 25–30 mL L⁻¹. While *Trichoderma* enhanced maturity and stability, EM₄ generally produced higher N, P, and K contents. Therefore, *Trichoderma* should be viewed not as a replacement, but as a strong alternative with complementary strengths; future co-inoculation or enrichment strategies may combine the benefits of both

bioactivators. Further research should include field validation, co-inoculation studies, process optimization, and environmental–economic assessments to support wider and sustainable adoption at household and community scales.

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