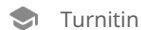


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Utilization of Organic Waste as Liquid Organic Fertilizer and Compost with *Trichoderma* Bioactivator in a Tiered Bucket System

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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, with data 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. 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 plays a role in accelerating humification and stabilization of organic matter, offering a practical and low-cost solution for household/community organic waste management within the framework of a circular economy.

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

INTRODUCTION

Modern agriculture faces serious challenges in managing organic waste generated from household and agro-industrial activities. Organic waste will remain a persistent problem if not properly managed (Ayilara et al., 2020). The rapid growth of the population is directly proportional to the increasing volume of organic waste derived from 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. Data from the Ministry of Environment and Forestry in 2021 recorded that the volume of waste in Indonesia, spread across 154 districts/cities, reached 18.2 million tons per year (Anggriyani et al., 2022).

Organic waste such as fruit peels, vegetable residues, and livestock manure is often underutilized, even though it has 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). One approach to utilizing organic waste is through fermentation with bioactivators. *Trichoderma* sp. is known as an effective biological agent that accelerates the decomposition of organic matter, enhances nutrient availability, and functions as a biocontrol agent against plant pathogens (Tyśkiewicz et al., 2022). Inoculation of *Trichoderma* has also been proven effective in reducing the accumulation of heavy metals such as Cd and Pb in plant environments (Altaf et al., 2023; Valenzuela et al., 2024). Furthermore, fermentation technology using a tiered bucket system offers a simple, inexpensive, and efficient innovation to simultaneously produce LOF and compost (Romaniuk et al., 2021).

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, while 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, P₂O₅, K₂O, 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 LOF and compost in tiered bucket systems under aerobic and anaerobic conditions is expected to be clarified. Thus, the novelty of this study lies in the integration of tiered bucket systems with aerobic and anaerobic fermentation conditions and the use of *Trichoderma* as an alternative to EM4. Unlike previous studies that emphasized a single aspect (seed coating, fermentation optimization, agronomic application, or biotechnology review), this study comprehensively evaluates the effects of *Trichoderma* dosage and fermentation conditions on the chemical quality of LOF and compost, including C-organic, total N, C/N ratio, P₂O₅, K₂O, and heavy metals. Therefore, this research addresses a gap by offering a practical, measurable, and applicable approach to producing high-quality, safe, and sustainable organic fertilizer and compost from local organic waste.

Accordingly, this study contributes to the development of biotechnology through the application of organic waste fermentation assisted by *Trichoderma* sp., which accelerates decomposition and produces both liquid organic fertilizer (LOF) and compost simultaneously. From a soil microbiology perspective, this study enriches the understanding of the role of *Trichoderma* not only as a decomposer that enhances the availability of essential nutrients such as N, P, and K but also as an agent that can reduce heavy metal accumulation, thereby supporting soil ecosystem health. Meanwhile, from a soil science perspective, this research provides a scientific foundation for improving organic fertilizer quality through the evaluation of critical parameters such as nutrient content, C/N ratio, and heavy metal presence. Thus, the findings can serve as practical strategies for more environmentally friendly and applicable organic waste management practices to support modern agriculture in Indonesia.

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 performed at the Integrated Laboratory of Universitas Lampung and the Testing Laboratory of the Agricultural Modernization Application Center, 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 tools used included: tiered aerobic and anaerobic buckets as fermentation media; digital balance for weighing materials; measuring cylinders, pipettes, and beakers; thermometer and pH meter; stirrers and mixing containers; stationery and documentation camera; as well as laboratory instruments for chemical analysis (spectrophotometer, AAS, oven, ICP-OES, muffle furnace, and others).

Experimental Design

The research was conducted using an experimental method with a Randomized Complete Block Design (RCBD) consisting of two treatment factors. The first factor was fermentation condition (A) in the tiered bucket system, consisting of two levels: A₁ = Anaerobic and A₂ = Aerobic. The second factor was *Trichoderma sp.* bioactivator dosage (T) with 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 a comparison. In total, there were 12 treatment combinations with three replications, resulting in 36 experimental units.

Research Procedure

Preparation of Materials

The materials were prepared by collecting organic waste consisting of banana peels, pineapple peels, lemongrass leaves, and shallot peels, along with rabbit urine, rice husk charcoal, and palm sugar solution. All materials were weighed according to the composition (a total of 10 L of material) and mixed until homogeneous. The mixture was then placed in tiered buckets according to treatments A₁ (anaerobic) and A₂ (aerobic). *Trichoderma sp.* solution was added according to treatment dosage (T₀–T₄), and EM4 was added to the EM treatment. The fermentation process lasted for 60 days with periodic observations of temperature, pH, odor, and color. After fermentation, the products were separated into LOF and solid compost.

Design of the Tiered Bucket System

The tiered bucket system consisted of two 20-liter buckets stacked vertically. The upper bucket served as the container for organic materials to be fermented into compost. The bottom of the upper bucket had small holes that allowed the fermented liquid (leachate) to flow into the lower bucket. The aerobic tiered bucket system was designed to allow adequate airflow or oxygen supply during fermentation. The upper bucket was equipped with two perforated pipes placed in the middle of the organic material layers, and the top of the bucket was fitted with ventilation holes to support optimal aerobic microbial activity. The anaerobic tiered bucket system was designed to minimize or eliminate oxygen entry during fermentation. The upper bucket had no ventilation holes and was sealed tightly with an airtight lid. The lower bucket was equipped with a tap to release the fermented liquid (leachate), which would be used as LOF.

Observation and Sampling

Periodic observations were conducted on fermentation environmental parameters (temperature, pH, odor, and color). Leachate was collected from the lower bucket tap on the 45th day, stored in bottles, and left for two weeks. Samples were taken after homogenization

and filtration of LOF, while solid compost samples were collected compositely from several parts of the upper bucket on the 60th day. LOF samples were taken at 100 mL from each experimental unit. For heavy metal analysis, samples were stored at 4 °C and preserved with HNO₃ until pH < 2. Samples with turbidity above 1 NTU were digested beforehand using a mixture of HNO₃ and HCl before 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. 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.

Statistical Analysis

The data obtained were analyzed using analysis of variance (ANOVA) according to the two-factor RCBD model. If significant differences were found, orthogonal contrast tests were carried out according to the research objectives: (1) Anaerobic (A₁) vs Aerobic (A₂), (2) T₁, T₂, T₃, T₄ vs T₀, (3) T₁, T₂, T₃, T₄ vs EM, (4) T₁, T₂ vs T₃, T₄, (5) T₁ vs T₂, and (6) T₃ vs T₄. Data processing was performed using SAS statistical software.

RESULTS AND DISCUSSION

Observation Results

The contents of C-organic, total N, C/N ratio, total P₂O₅, total K₂O, 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 analysis of variance (ANOVA) revealed that the fermentation condition factor (A), bioactivator dosage (T), as well as the interaction between fermentation condition and *Trichoderma* bioactivator treatment (A×T) had a highly significant effect on all observed parameters.

C-organic Content

The C-organic content in LOF and compost is presented in Figures 1 and 2. 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 consistently showed that compost had higher C-organic content than LOF across all treatment combinations

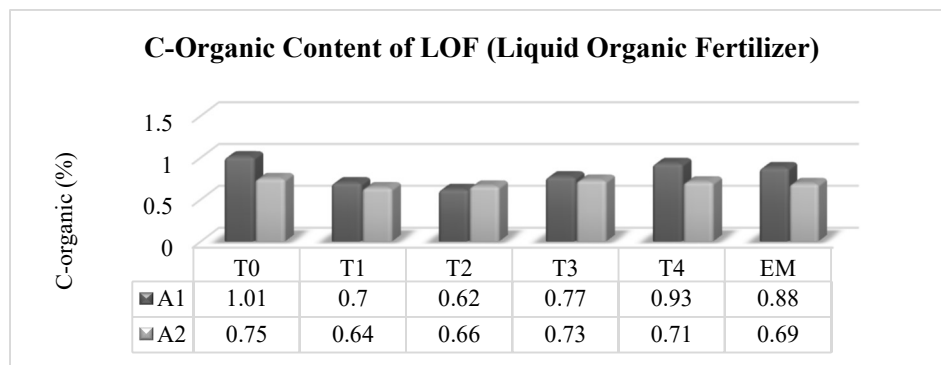


Figure 1. Diagram of C-organic Content in LOF from Organic Waste

Figure 1 shows the C-organic content of LOF under various treatments. In general, the anaerobic system (A₁) produced higher C-organic values compared to the aerobic system (A₂). This is consistent with the results of the orthogonal contrast test, which indicated that under anaerobic conditions carbon degradation occurs more slowly, thus C-organic tends to be maintained at a higher level, whereas under aerobic conditions carbon mineralization occurs more rapidly, resulting in slightly lower C-organic content but indicating a better level of maturity. In the control treatment (T₀), C-organic was recorded as the highest (A₁ = 1.01% and A₂ = 0.75%), while the addition of *Trichoderma* (T₁–T₄) or EM reduced these values, although at certain doses such as T₄ the results were relatively close to the control.

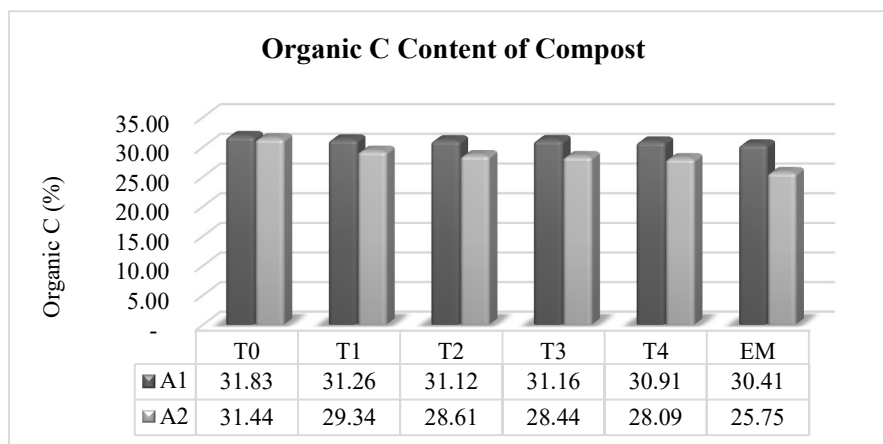


Figure 2. Diagram of C-organic Content in Compost from Organic Waste

Figure 2 shows the C-organic content in compost treated with various doses of *Trichoderma* and EM. In general, the C-organic content of compost ranged from 25–32%. The highest value was obtained in the control treatment (T₀) with A₁ = 31.83% and A₂ = 31.44%, while the lowest value was found in the EM treatment with A₂ = 25.75%. The results indicate that the anaerobic system (A₁) consistently had higher C-organic content compared to the aerobic system (A₂). This condition is consistent with the orthogonal contrast test results, which confirmed that under anaerobic conditions carbon degradation occurs more slowly, thus C-organic tends to be maintained at a higher level. Conversely, in the aerobic system, carbon mineralization occurs more rapidly, resulting in lower C-organic content, although this indicates a better level of compost maturity.

Thus, the results of the orthogonal contrast test on C-organic data (Table 1) showed that in compost, A₁ (anaerobic) tended to retain higher C-organic content (slower carbon degradation), while A₂ (aerobic) mineralized carbon more rapidly, resulting in slightly lower C-organic content (8.75%) but producing more mature compost. In LOF, the A₁–A₂ differences were more

variable; A₁ tended to be slightly higher (17.35%) due to the soluble–stored fraction of dissolved carbon compounds. *Trichoderma sp.* (T₁–T₄) accelerated lignocellulose decomposition. In compost, this reduced C-organic content (5.59%) compared to without *Trichoderma sp.* (T₀), as carbon was oxidized into CO₂. In LOF, *Trichoderma sp.* could increase the short-term dissolved C fraction, but the final effect was a reduction in C-organic content (18.18%) compared to T₀. The performance of *Trichoderma sp.* on C-organic in LOF was not different from that of the EM₄ bioactivator; in some combinations T₁–T₄ were slightly lower than EM₄, but in compost there were cases where T₁–T₄ outperformed EM₄ in maintaining C-organic. For compost maturity and stability purposes, the aerobic condition (A₂) with higher *Trichoderma* doses (T₃–T₄) appeared consistent; if the goal was to retain C-organic, then the A₁–T₁/T₂ condition was more suitable. For LOF, A₂–T₃/T₄ provided a good compromise between C-organic content and solution maturity. This fact is closely related to the role of *Trichoderma* as a producer of cellulolytic/hemi-cellulolytic enzymes that accelerate the degradation of structural carbon (Chen et al., 2025; Ren et al., 2025), while aerobic conditions enhance C oxidation and reduce the C/N ratio (Yang et al., 2021; Zhu et al., 2024).

Table 1. Effect of Fermentation Conditions and Bioactivators on C-organic Content of LOF and Compost

Comparison	LOF: % C-organic			Compost: % C-organic		
	Significance	Difference		Significance	Difference	
		-	%		-	%
(A ₁) vs (A ₂)	**	0,12	17,35	**	2,50	8,75
T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	**	-0,17	-19,18	**	-1,77	-5,59
T ₁ ,T ₂ ,T ₃ ,T ₄ vs Em	ns	-0,07	-9,39	**	1,79	6,36
T ₁ ,T ₂ vs T ₃ ,T ₄	ns	-0,01	-1,74	**	0,43	1,46
T ₁ vs T ₂	ns	0,10	15,27	**	0,43	1,46
T ₃ vs T ₄	ns	0,04	5,00	**	0,30	1,02
A ₁ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	**	-0,27	-26,24	**	-0,72	-2,25
A ₁ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs Em	*	-0,14	-15,34	**	0,70	2,31
A ₁ : T ₁ ,T ₂ vs T ₃ ,T ₄	ns	-0,04	-5,23	**	0,16	0,50
A ₁ : T ₁ vs T ₂	ns	0,15	23,08	*	0,14	0,45
A ₁ : T ₃ vs T ₄	ns	0,01	1,32	**	0,25	0,81
A ₂ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	ns	-0,07	-9,67	**	-2,82	-8,97
A ₂ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	ns	-0,01	-1,81	**	2,87	11,15
A ₂ : T ₁ ,T ₂ vs T ₃ ,T ₄	ns	0,02	2,24	**	0,71	2,51
A ₂ : T ₁ vs T ₂	ns	0,05	7,58	**	0,73	2,55
A ₂ : T ₃ vs T ₄	ns	0,06	9,37	**	0,35	1,25

Note: ns = not significant; * = $p < 0.05$; ** = $p < 0.01$; anaerobic condition (A₁); aerobic condition (A₂); *Trichoderma sp.* 0 mL/L (T₀); 15 mL/L (T₁); 20 mL/L (T₂); 25 mL/L (T₃); 30 mL/L (T₄); EM4 30 mL/L (Em). Negative differences (-) indicate that the group on the right has higher values; percentage differences are calculated relative to the values of the group on the right.

Total N Content

The total N content of LOF and compost from organic waste fermented under anaerobic and aerobic conditions with *Trichoderma sp.* bioactivator showed variation among treatments (Figures 3 and 4). The total N level was relatively higher in compost (1.48%), which is solid-based. In LOF, N was available mainly as dissolved N, so its percentage value was lower

(0.06%), but it was readily absorbed by plants. The orthogonal contrast test of total N data (Table 2) showed significant differences among treatments, both in LOF and compost. A₂ tended to reduce the loss of organic N into more stable forms (nitrate/ammonium within the compost matrix), but it carried the risk of volatilization loss (ammonia) if aeration/pH was not well controlled. A₂ often resulted in higher total N compared to A₁ in both compost (8.63%) and LOF (13.89%).

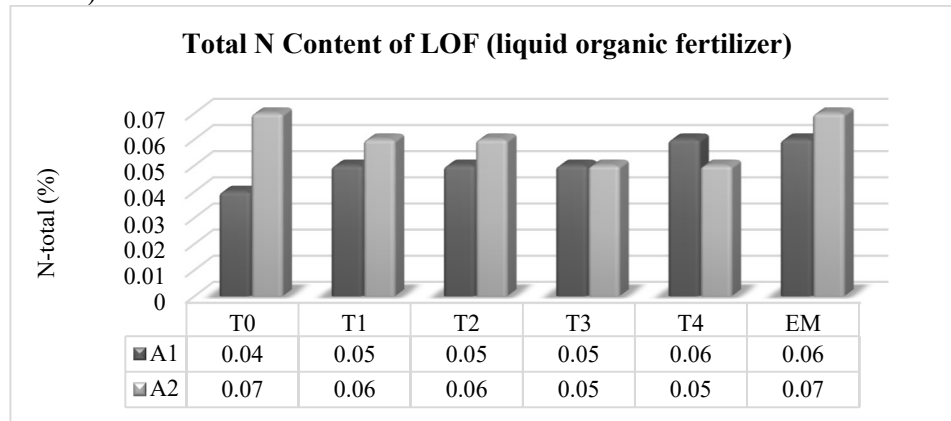


Figure 3. Diagram of Total N Content in LOF from Organic Waste

In liquid organic fertilizer (LOF), the total N content was relatively low (around 0.04–0.07%). The aerobic condition (A₂) generally produced higher values compared to the anaerobic condition (A₁). For example, in the control (T₀), total N in A₂ reached 0.07% compared to 0.04% in A₁. Treatments with *Trichoderma* (T₁–T₄) showed variation, with total N tending to range around 0.05–0.06%, while EM4 (0.06–0.07%) was relatively higher than some *Trichoderma* treatments. This indicates that the aerobic system (A₂) better supports N stability in dissolved forms that are readily available for plants.

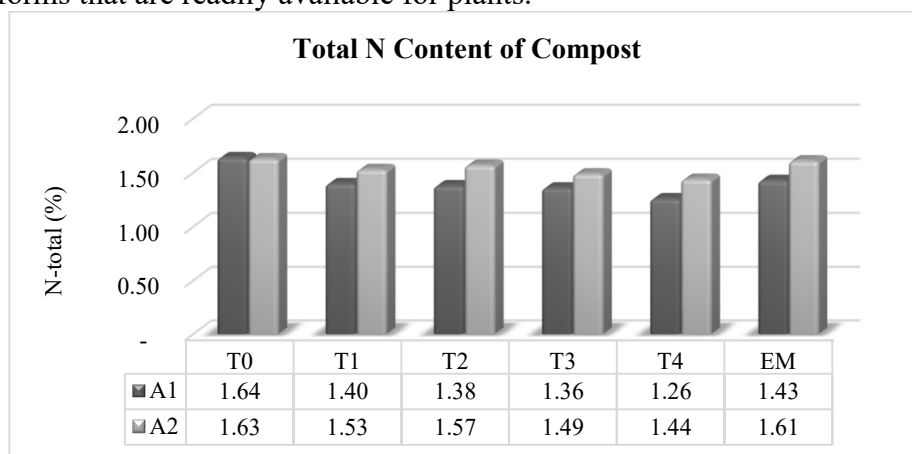


Figure 4. Diagram of Total N Content in Compost from Organic Waste

In compost, the total N content was higher than in LOF, ranging from 1.26–1.64%. The trend showed that the control (T₀) produced the highest total N (1.63–1.64%), while the addition of *Trichoderma* (T₁–T₄) tended to reduce total N levels to the range of 1.26–1.57% due to accelerated decomposition and possible volatilization losses. EM4 produced intermediate values (1.43–1.61%), higher than some *Trichoderma* treatments, particularly under aerobic conditions.

Trichoderma (T₁–T₄) can enhance microbial N cycling and accelerate ammonification/nitrification; however, in some cases, the final compost total N was slightly

lower (12.61%) compared to T_0 due to conversion and volatilization losses during the process. EM4 often showed higher total N in LOF (17.31%) than several *Trichoderma* doses, while in compost its relative performance (6.0%) depended on the substrate and process control. This phenomenon is related to the role of *Trichoderma* and EM consortia in modulating N dynamics through increased enzymatic activity and microbial competition (Maciag et al., 2023; Poveda et al., 2020). To improve total N in LOF, A_2-T_1/T_2 was the preferred choice, while A_1-T_1/T_2 was more suitable for reducing volatilization losses in LOF.

Table 2. Effect of Bioactivators on Total N Content of LOF and Compost from Organic Waste

Comparison	LOF: % Total N			Compost: % Total N		
	Significance	Difference		Significance	Difference	
		-	%		-	%
(A ₁) vs (A ₂)	**	-0,01	-13,89	**	-0,13	-8,63
T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	ns	-0,001	-2,27	**	-0,21	-12,61
T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	**	-0,01	-17,31	**	-0,09	-6,00
T ₁ ,T ₂ vs T ₃ ,T ₄	ns	0,003	4,76	**	0,08	5,95
T ₁ vs T ₂	ns	0,00	0,00	ns	-0,01	-0,68
T ₃ vs T ₄	ns	-0,01	-9,09	**	0,08	5,56
A ₁ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	**	0,01	31,25	**	-0,29	-17,68
A ₁ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	**	-0,01	-12,50	**	-0,08	-5,59
A ₁ : T ₁ ,T ₂ vs T ₃ ,T ₄	*	-0,01	-9,09	**	0,08	6,11
A ₁ : T ₁ vs T ₂	*	0,00	0,00	ns	0,02	1,45
A ₁ : T ₃ vs T ₄	**	-0,01	-16,67	**	0,10	7,94
A ₂ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	**	-0,02	-21,43	**	-0,12	-7,52
A ₂ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	**	-0,02	-21,43	**	-0,10	-6,37
A ₂ : T ₁ ,T ₂ vs T ₃ ,T ₄	**	0,01	20,00	**	0,09	5,80
A ₂ : T ₁ vs T ₂	*	0,00	0,00	*	-0,04	-2,55
A ₂ : T ₃ vs T ₄	ns	0,00	0,00	**	0,05	3,47

Notes: ns = not significant; * = $p < 0.05$; ** = $p < 0.01$; anaerobic condition (A₁); aerobic condition (A₂); *Trichoderma* sp. 0 mL/L (T₀); 15 mL/L (T₁); 20 mL/L (T₂); 25 mL/L (T₃); 30 mL/L (T₄); EM4 30 mL/L (E_m). Negative (–) differences indicate that the group on the right-hand side had higher values; percentage differences are calculated relative to the value of the group on the right-hand side.

C/N Ratio Values

The C/N ratio values of LOF and compost are presented in Figures 5 and 6. On average, the C/N ratio of compost (20.37) was higher than that of LOF (14.51). The orthogonal contrast test of C/N ratio data (Table 3) showed significant differences among treatments, especially in compost. The C/N ratio is primarily used as an indicator of compost maturity (SNI target ≈ 10 –20). The C/N ratio of LOF varied, but it is not a primary legal reference. A₂ (aerobic) consistently reduced the C/N ratio (indicating higher maturity) compared to A₁ in LOF (40.93%) and compost (19.52%). The results indicated that the combination of A₂–T₁/T₂ most often approached or fell within the 10–20 range.

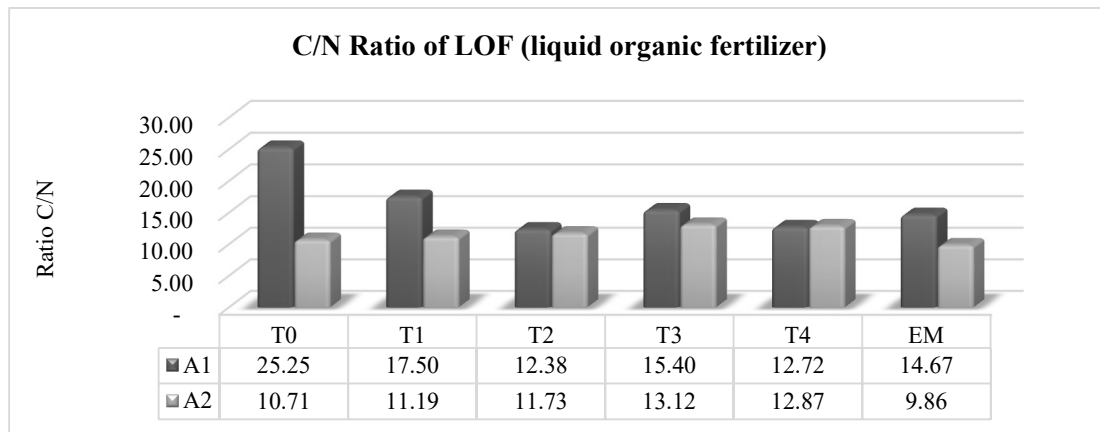


Figure 5. Diagram of C/N Ratio in LOF from Organic Waste

Figure 5 shows the variation in C/N ratio of liquid organic fertilizer (LOF) under different treatments (T₀–T₄, EM) in A₁ (anaerobic) and A₂ (aerobic) conditions. The C/N ratio values in A₁ were generally higher than in A₂, for example in T₀ (25.25 vs 10.71). This pattern indicates that aerobic conditions (A₂) accelerate carbon decomposition, resulting in LOF with a lower C/N ratio (more mature). The combinations A₂–T₁ and A₂–T₂ produced C/N values approaching the optimal range (10–20) for maturity standards, with A₂–T₁ (11.19) being one of the best results.

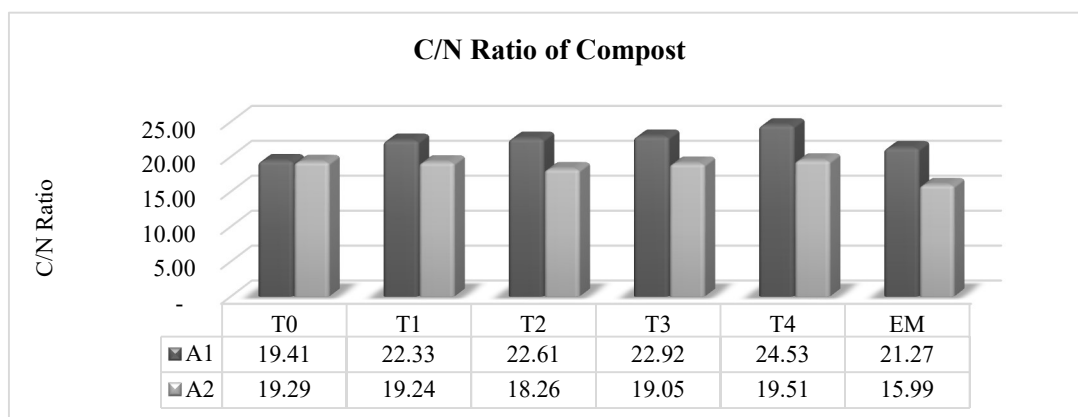


Figure 6. Diagram of C/N Ratio in Compost from Organic Waste

Figure 6 shows the C/N ratio in compost, which was generally higher than in LOF. The average C/N ratio in compost was above 18, ranging from 15.99 to 24.53. Similar to LOF, the A₂ (aerobic) treatment tended to lower the C/N ratio compared to A₁, for example in EM (15.99 vs 21.27). This indicates that the aerobic system (A₂) more consistently produced compost with a maturity level that meets the standard range (10–20), especially in the A₂–T₁ and A₂–T₂ combinations, which were more stable.

Trichoderma reduced the C/N ratio in compost (8.82%) compared to T₀, reflecting accelerated carbon decomposition relative to microbial N accumulation. The decrease in C/N ratio by T₁–T₄ was generally comparable to EM, particularly in LOF; in some cases EM worked slightly faster, while in others *Trichoderma* was sufficient. To achieve a C/N ratio of 10–20 in compost, A₂–T₁ was the most consistent. In LOF, A₂–T₁ produced the lowest C/N ratio (more stable) without drastically reducing nutrient content. These results occurred because aeration accelerates C oxidation, while *Trichoderma* enzymes accelerate lignocellulose breakdown, thereby lowering the C/N ratio (Lima et al., 2024; Yang et al., 2021).

Table 3. Effect of Bioactivators on the C/N Ratio of LOF and Compost

Comparison	LOF: C/N Ratio			Compost: C/N Ratio		
	Significance	Difference		Significance	Difference	
		-	%		-	%
(A ₁) vs (A ₂)	**	4,74	40,93	**	3,62	19,52
T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	**	-4,62	-25,67	**	1,71	8,82
T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	ns	1,10	8,96	**	2,43	13,02
T ₁ ,T ₂ vs T ₃ ,T ₄	ns	-0,33	-2,42	**	-0,89	-4,15
T ₁ vs T ₂	ns	2,29	19,00	Ns	0,35	1,71
T ₃ vs T ₄	ns	1,47	11,45	**	-1,04	-4,70
A ₁ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	**	-10,75	-42,57	**	3,69	19,00
A ₁ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	ns	-0,17	-1,16	**	1,83	8,59
A ₁ : T ₁ ,T ₂ vs T ₃ ,T ₄	ns	0,88	6,26	**	-1,26	-5,29
A ₁ : T ₁ vs T ₂	*	5,12	41,36	Ns	-0,28	-1,24
A ₁ : T ₃ vs T ₄	ns	2,68	21,07	**	-1,61	-6,56
A ₂ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	ns	1,52	14,17	Ns	-0,27	-1,43
A ₂ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	ns	2,37	24,01	**	3,03	18,92
A ₂ : T ₁ ,T ₂ vs T ₃ ,T ₄	ns	-1,54	-11,81	**	-0,53	-2,75
A ₂ : T ₁ vs T ₂	ns	-0,54	-4,60	**	0,98	5,37
A ₂ : T ₃ vs T ₄	ns	0,25	1,94	Ns	-0,46	-2,36

Notes: ns = not significant; * = $p < 0.05$; ** = $p < 0.01$; anaerobic condition (A₁); aerobic condition (A₂); *Trichoderma sp.* 0 mL/L (T₀); 15 mL/L (T₁); 20 mL/L (T₂); 25 mL/L (T₃); 30 mL/L (T₄); EM₄ 30 mL/L (E_m). Negative (–) differences indicate that the group on the right-hand side had higher values; percentage differences are calculated relative to the value of the group on the right-hand side.

Total P and Total K Content

The total P₂O₅ and K₂O contents in LOF from organic waste fermented under anaerobic and aerobic conditions with *Trichoderma sp.* bioactivator showed variation among treatments (Figures 7 and 8). In this study, total P and total K were evaluated only in LOF. The orthogonal contrast test (Table 4) indicated that A₂ generally produced LOF with higher P₂O₅ (14.81%) compared to A₁, due to more controlled mineralization and solubilization; in contrast, K₂O was higher in A₁ (19.82%) than in A₂.

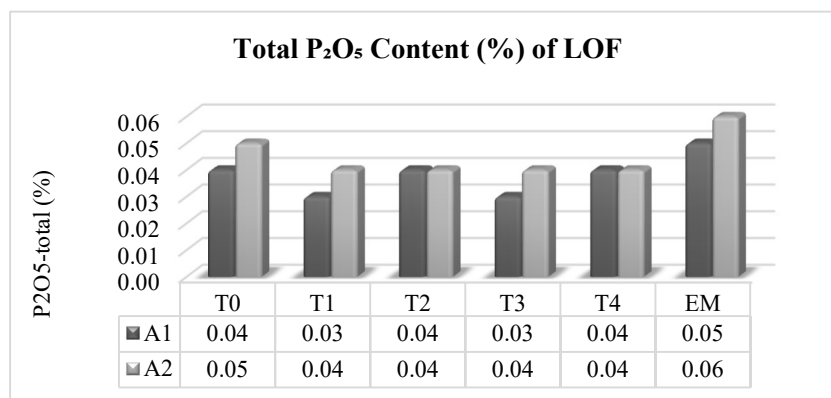

Figure 7. Diagram of Total P₂O₅ Content in LOF

Figure 7 shows the total P₂O₅ content in LOF resulting from fermentation under various treatments. In general, the A₂ (aerobic) condition produced higher P₂O₅ compared to A₁

(anaerobic), for example in T₃ and T₄, where the values were close to EM. This pattern confirms that phosphorus mineralization is more optimal under aerobic conditions, as the solubilization process and P availability are better controlled, thereby increasing the total P₂O₅ content in LOF.

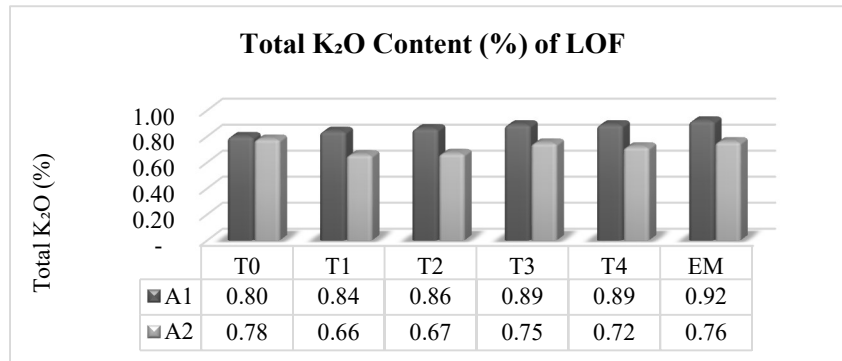


Figure 8. Diagram of Total K₂O Content in LOF from Organic Waste

Figure 8 shows the total K₂O content in LOF, with a trend different from that of P₂O₅. In this parameter, the A₁ (anaerobic) condition actually produced higher K₂O values compared to A₂. This is presumed to be due to the enzymatic activity and organic acids of *Trichoderma* under anaerobic conditions, which can solubilize bound potassium and thereby increase K availability. Although EM still showed the highest overall P and K values, the A₂–T₃/T₄ combinations were able to approach EM results, particularly for P₂O₅.

Under A₁ conditions, *Trichoderma* can increase K availability through the solubilization of bound potassium (via organic acid/enzymatic activity). EM produced higher P₂O₅ and K₂O values in LOF compared to T₁–T₄; however, T₃–T₄ under A₂ conditions came close to matching EM. These results are strongly influenced by the fact that *Trichoderma* has the potential to solubilize P and improve root access to K, while EM relies on a consortium of fermentative microbes to increase dissolved nutrient content (Lima et al., 2024). To maximize P and K elements in LOF without sacrificing stability, the A₂–T₃/T₄ combinations are recommended, although the values remain well below the Ministry of Agriculture's requirements (C-organic $\geq 10\%$; (N+P₂O₅+K₂O) 2–6% w/v).

Table 4. Effect of Bioactivators on Total P₂O₅ and Total K₂O in LOF

Comparison	Total P ₂ O ₅ (%)			Total K ₂ O (%)		
	Significance	Difference		Significance	Difference	
		-	%		-	%
(A ₁) vs (A ₂)	**	-0,01	-14,81	**	0,14	19,82
T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	**	-0,01	-16,67	ns	-0,01	-0,63
T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	**	-0,02	-31,82	**	-0,06	-6,55
T ₁ ,T ₂ vs T ₃ ,T ₄	ns	0,00	0,00	**	-0,06	-6,77
T ₁ vs T ₂	ns	-0,01	-12,50	ns	-0,02	-1,96
T ₃ vs T ₄	ns	-0,01	-12,50	ns	0,02	1,86
A ₁ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	ns	-0,01	-12,50	**	0,07	8,75
A ₁ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	**	-0,02	-30,00	**	-0,05	-5,43
A ₁ : T ₁ ,T ₂ vs T ₃ ,T ₄	ns	0,00	0,00	*	-0,04	-4,49
A ₁ : T ₁ vs T ₂	ns	-0,01	-25,00	ns	-0,02	-2,33

Comparison	Total P ₂ O ₅ (%)			Total K ₂ O (%)		
	Significance	Difference		Significance	Difference	
		-	%		-	%
A ₁ : T ₃ vs T ₄	ns	-0,01	-25,00	ns	0,00	0,00
A ₂ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	*	-0,01	-20,00	**	-0,08	-10,26
A ₂ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	**	-0,02	-33,33	**	-0,06	-7,89
A ₂ : T ₁ ,T ₂ vs T ₃ ,T ₄	ns	0,00	0,00	**	-0,07	-9,52
A ₂ : T ₁ vs T ₂	ns	0,00	0,00	ns	-0,01	-1,49
A ₂ : T ₃ vs T ₄	ns	0,00	0,00	ns	0,03	4,17

Notes: ns = not significant; * = $p < 0.05$; ** = $p < 0.01$; anaerobic condition (A₁); aerobic condition (A₂); *Trichoderma* sp. 0 mL/L (T₀); 15 mL/L (T₁); 20 mL/L (T₂); 25 mL/L (T₃); 30 mL/L (T₄); EM4 30 mL/L (E_m). Negative (–) differences indicate that the group on the right-hand side had higher values; percentage differences are calculated relative to the value of the group on the right-hand side.

Heavy Metal Content

The heavy metal content in compost was evaluated for Pb and Cu, while in LOF it was evaluated for Pb and Cd (Table 5). Based on SNI 19-7030-2004 and Regulation of the Ministry of Agriculture No. 112/2020, the permissible limits for heavy metals are as follows: for compost, Pb must not exceed 50 mg/kg and Cu not more than 100 mg/kg; while for LOF, Pb is allowed up to 5 mg/L and Cd up to 1 mg/L. In general, the measured values in both materials were far below the limits set by SNI/Ministry of Agriculture, indicating that both are safe for application. The Pb and Cu contents in compost are shown in Figures 9 and 10, indicating that heavy metal content in compost was generally higher than in LOF, yet still within the safe limits defined by the standards.

Table 5. Results of Heavy Metal Content Analysis in LOF and Compost

Treatment	LOF		Compost	
	Pb-total (mg/L)	Cd-total (mg/L)	Pb-total (mg/kg)	Cu-total (mg/kg)
A ₁ T ₀ = Anaerobic without bioactivator	0,082	<0,027	0,16	4,11
A ₁ T ₁ = Anaerobic <i>Trichoderma</i> 15 mL/L	<0,034	<0,027	1,06	4,35
A ₁ T ₂ = Anaerobic <i>Trichoderma</i> 20 mL/L	0,05	<0,027	1,97	4,65
A ₁ T ₃ = Anaerobic <i>Trichoderma</i> 25 mL/L	0,09	<0,027	2,04	4,28
A ₁ T ₄ = Anaerobic <i>Trichoderma</i> 30 mL/L	<0,034	<0,027	2,15	3,94
A ₁ E _m = Anaerobic EM4 30 mL/L	0,048	<0,027	1,15	4,81
A ₂ T ₀ = Aerobic without bioactivator	<0,034	<0,027	3,83	5,06
A ₂ T ₁ = Aerobic <i>Trichoderma</i> 15 mL/L	0,164	<0,027	2,39	5,11
A ₂ T ₂ = Aerobic <i>Trichoderma</i> 20 mL/L	0,17	<0,027	0,97	5,18
A ₂ T ₃ = Aerobic <i>Trichoderma</i> 25 mL/L	0,12	<0,027	5,38	5,25
A ₂ T ₄ = Aerobic <i>Trichoderma</i> 30 mL/L	0,215	<0,027	9,87	5,36
A ₂ E _m = Aerobic EM4 30 mL/L	<0,034	<0,027	0,70	5,23

Note: “<” indicates not detected by ICP-OES instrument.

Table 5 shows the results of the analysis of heavy metal content, Pb and Cd in LOF, as well

as Pb and Cu in compost. In general, all treatments produced values well below the thresholds of SNI 19-7030-2004 and Regulation of the Ministry of Agriculture No. 112/2020. Pb in LOF ranged from 0.048–0.215 mg/L with Cd undetected (<0.027 mg/L), while in compost Pb ranged from 0.16–9.87 mg/kg and Cu from 3.94–5.36 mg/kg. These values confirm that both LOF and compost products remain safe for agricultural application.

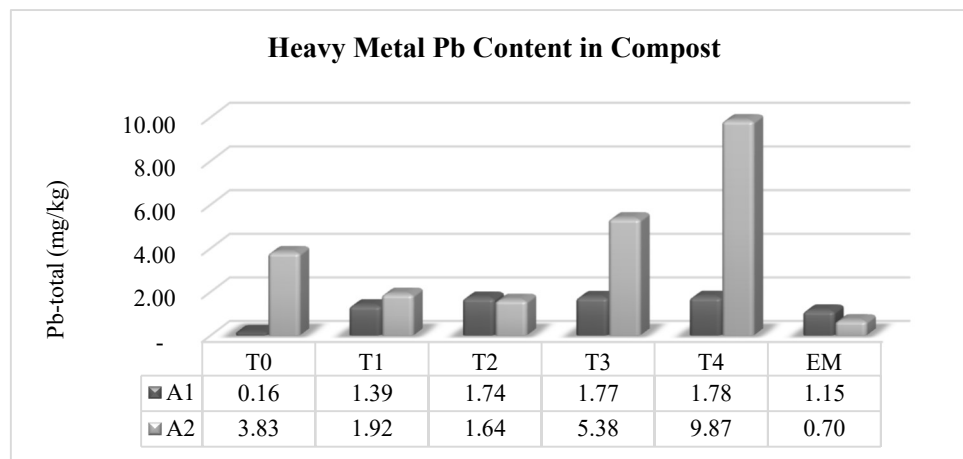


Figure 9. Diagram of Pb Content in Compost from Organic Waste

Figure 9 shows the variation in total Pb content (mg/kg) in compost under different treatments. In general, the aerobic condition (A2) produced higher Pb content compared to the anaerobic condition (A1). The T₄–A₂ treatment reached the highest value (9.87 mg/kg), while the lowest value was observed in A₁T₀ (0.16 mg/kg). Despite the variation, all results remained far below the maximum threshold of 50 mg/kg.

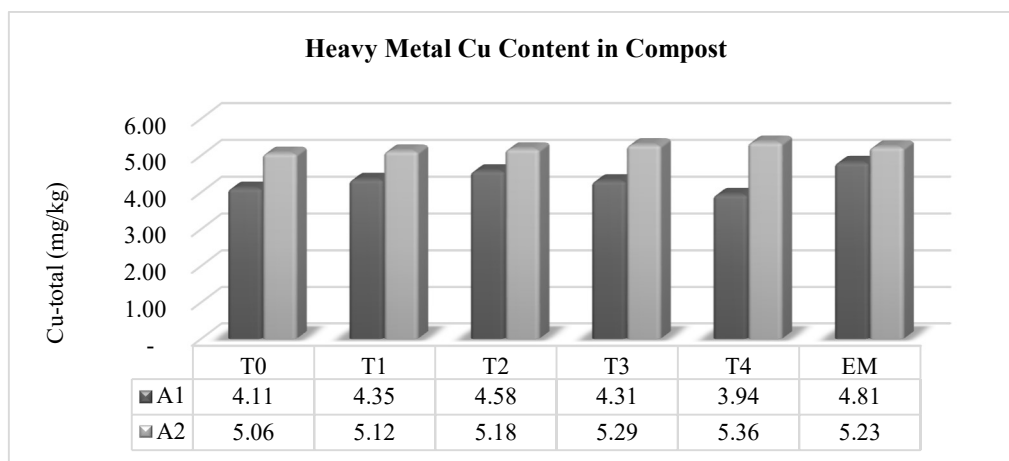


Figure 10. Diagram of Cu Content in Compost from Organic Waste

Figure 10 shows the total Cu content (mg/kg) in compost. Under both anaerobic (A₁) and aerobic (A₂) conditions, Cu values were relatively uniform, ranging from 3.94–5.36 mg/kg. A₂ tended to produce slightly higher Cu compared to A₁, with values ranging from 5.06–5.36 mg/kg. All these values remained far below the maximum threshold of 100 mg/kg according to SNI/Ministry of Agriculture standards.

Table 6. Effect of Bioactivators on Heavy Metal Pb and Cu Content in Compost

Comparison	Pb-total (mg/kg)			Cu-total (mg/kg)		
	Significance	Difference		Significance	Difference	
		-	%		-	%
(A ₁) vs (A ₂)	**	-2,56	-65,8	**	-0,86	-16,45
T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	**	1,19	59,7	**	0,18	3,95
T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	**	2,26	244,5	**	-0,25	-5,05
T ₁ ,T ₂ vs T ₃ ,T ₄	**	-3,03	-64,4	**	0,08	1,75
T ₁ vs T ₂	ns	-0,04	-2,1	**	-0,15	-2,97
T ₃ vs T ₄	**	-2,25	-38,6	**	0,15	3,23
A ₁ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	**	1,51	943,8	**	0,19	4,50
A ₁ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	ns	0,52	45,2	**	-0,52	-10,71
A ₁ : T ₁ ,T ₂ vs T ₃ ,T ₄	ns	-0,21	-11,8	**	0,34	8,24
A ₁ : T ₁ vs T ₂	ns	-0,35	-20,1	**	-0,23	-5,02
A ₁ : T ₃ vs T ₄	ns	-0,01	-0,6	**	0,37	9,39
A ₂ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs T ₀	**	0,87	22,8	**	0,18	3,51
A ₂ : T ₁ ,T ₂ ,T ₃ ,T ₄ vs E _m	**	4,00	571,8	ns	0,01	0,14
A ₂ : T ₁ ,T ₂ vs T ₃ ,T ₄	**	-3,13	-81,7	**	-0,18	-3,29
A ₂ : T ₁ vs T ₂	ns	-5,85	-76,7	ns	-0,06	-1,16
A ₂ : T ₃ vs T ₄	**	0,28	17,1	ns	-0,07	-1,31

Notes: ns = not significant; * = $p < 0.05$; ** = $p < 0.01$; anaerobic condition (A₁); aerobic condition (A₂); *Trichoderma* sp. 0 mL/L (T₀); 15 mL/L (T₁); 20 mL/L (T₂); 25 mL/L (T₃); 30 mL/L (T₄); EM4 30 mL/L (E_m). Negative (–) differences indicate that the group on the right-hand side had higher values; percentage differences are calculated relative to the value of the group on the right-hand side.

The results of the orthogonal contrast test (Table 6) show that heavy metal content in compost (Pb and Cu) was higher under aerobic (A₂) conditions compared to anaerobic (A₁). *Trichoderma* is not specifically intended to reduce heavy metals; however, by accelerating humification, it can lower metal bioavailability (through binding to humic complexes).

The performance of *Trichoderma* and EM on heavy metals was generally comparable; there was no indication of significant increases in metal content due to *Trichoderma* or EM. If the priority is to minimize Pb/Cu (in compost) or Pb/Cd (in LOF), the A₂–T₁/T₂ combination is recommended, as it promotes better humification and stabilization. However, since the values are already low, dosage selection should be more strongly guided by maturity indicators (C/N ratio) and macronutrients. This outcome is related to aerobic humification, which is associated with the adsorption of metals onto humic/fulvic functional groups, thereby reducing the mobility of heavy metals (Feszterová et al., 2024; M. Wang et al., 2024).

Discussion

Trichoderma (T₁–T₄) had a significant effect on the quality of LOF and compost, although the impact was not always favorable. In compost, *Trichoderma* increased organic C content compared to EM, but both were still lower than T₀. For total N, both *Trichoderma* and EM tended to be lower than T₀. This indicates that the addition of inoculants accelerates decomposition, but is followed by reductions in total C and N due to mineralization or volatilization during fermentation. In LOF, *Trichoderma* effectively reduced the C/N ratio, indicating improved maturity, with results comparable to EM. However, the average contents of N, P₂O₅, and K₂O were higher in EM than in *Trichoderma*, while T₁–T₄ were not consistently

higher than T_0 . Thus, the primary role of *Trichoderma* in LOF lies more in improving maturity through C/N ratio reduction, rather than increasing total macronutrients.

The addition of *Trichoderma* was able to increase organic C content in compost compared to Effective Microorganisms (EM). This relates to the enzymatic ability of *Trichoderma* to decompose complex organic materials such as lignin and cellulose into simpler compounds (Bohacz & Kowalska, 2020; Hemati et al., 2022). However, although organic C increased compared to EM, the values were still lower than the control (T_0) without inoculant. This phenomenon shows that both EM and *Trichoderma* accelerate decomposition, causing some carbon to be lost through respiration in the form of CO_2 (Elbasiouny et al., 2022; Zhu et al., 2024). A similar decrease was observed in total nitrogen (N-total), where both *Trichoderma* and EM treatments were lower than T_0 . This decline may be due to rapid nitrogen mineralization during fermentation, or nitrogen losses in gaseous forms such as NH_3 through volatilization (Lima et al., 2024; Sossa et al., 2024).

In the context of LOF, *Trichoderma* played a more prominent role in lowering the C/N ratio, an important indicator of organic fertilizer maturity and stability (Liu et al., 2020). A lower C/N ratio indicates that organic matter has decomposed more thoroughly, making LOF more readily available for plant use. These results were comparable to the effectiveness of EM in lowering the C/N ratio. However, in terms of macronutrients such as nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O), EM treatments tended to produce higher values than *Trichoderma* treatments (Abdelghany et al., 2025). This can be attributed to the more diverse microbial composition of EM, which enriches solubilization and nutrient transformation processes in organic materials (Hidalgo et al., 2022). Meanwhile, T_1 – T_4 (*Trichoderma*-based) treatments did not always show higher nutrient contents compared to T_0 , indicating that the main function of *Trichoderma* lies more in organic matter decomposition rather than direct nutrient enrichment. Thus, *Trichoderma* is more effective at accelerating decomposition and improving LOF maturity through C/N reduction, but less effective in enhancing macronutrient content compared to EM.

A comparison of bucket systems (A_1) and aerobic bucket systems (A_2) showed that A_2 consistently produced compost with lower final C/N ratios, in line with SNI maturity standards (≈ 10 – 20), such as in A_2 – T_4 , which reached around 19.5. In contrast, A_1 tended to increase C/N ratios above 20 when treated with *Trichoderma*. This confirms that aeration in A_2 facilitates better C oxidation and N stabilization compared to A_1 . In compost, organic C content in A_1 was higher than A_2 , but indicators of maturity and stability were better in A_2 . In LOF, A_1 tended to maintain slightly higher organic C, while A_2 was superior in some nutrients, such as P_2O_5 , and supported the maturity of compost solids used as raw materials for LOF.

A high C/N ratio indicates incomplete decomposition and unstable compost (Yang et al., 2021). A lower C/N ratio in A_2 showed that aeration in this system played an important role in supporting carbon oxidation and nitrogen stabilization, thereby accelerating organic matter decomposition (Sun et al., 2025). Aeration also prevented the formation of anaerobic conditions that can cause the accumulation of toxic compounds and nitrogen loss as ammonia gas (NH_3) (Y. Wang et al., 2021). Although organic C content in compost from A_1 was higher than A_2 , this did not necessarily indicate better compost quality. High C content may indicate that most organic material had not decomposed optimally (Huang et al., 2021). Conversely, in A_2 , even though organic C was slightly lower, this indicated that decomposition had progressed further, producing more stable and mature compost (Sahu et al., 2020). LOF in A_1 tended to maintain slightly higher organic C due to limited oxidation and volatilization. However, A_2 showed advantages in certain nutrients, particularly P_2O_5 , which plays a key role in root growth and flowering (Waheed & Zeng, 2020). In addition, A_2 's superiority in producing mature solid compost also positively affected the stability and nutrient content of LOF. Thus, the A_2

(aerobic) system was more effective in achieving maturity and final quality of compost and LOF, although A₁ maintained higher organic C.

The best *Trichoderma* doses (T₁–T₄) varied depending on the desired outcome. In compost, A₂–T₄ most consistently met maturity criteria with C/N ratios of 10–20 while maintaining good organic C levels. In A₁, however, increasing doses raised C/N above the ideal threshold, making it less recommended. If the specific goal was to maintain the highest organic C, A₁–T₁ was the best among T₁–T₄, although the maturity index (C/N) is generally more important for application-ready compost. In LOF, medium to high doses (T₃–T₄) in A₂ tended to yield lower C/N ratios with better stability, although N, P₂O₅, and K₂O values in EM were generally higher than in T₁–T₄. Practically, A₂–T₃ or A₂–T₄ combinations are recommended if the main objective is LOF maturity and stability, while A₂–T₁ or A₂–T₂ can be considered for reducing risks of heavy metal accumulation.

The optimal *Trichoderma* inoculant dose (T₁–T₄) depends heavily on production goals, whether for enhancing compost maturity or maintaining organic C and LOF stability. In the aerobic bucket system (A₂), the highest dose (T₄) consistently produced compost with C/N ratios that met maturity standards (10–20), while maintaining adequate organic C. This shows that optimal aeration in A₂ supports effective carbon oxidation and nitrogen stabilization, resulting in mature, high-quality compost (Zhao et al., 2025). Conversely, in the closed bucket system (A₁), higher *Trichoderma* doses raised C/N ratios above the ideal threshold, indicating suboptimal decomposition and low compost maturity. If the goal is maximizing organic C, A₁–T₁ showed the highest C among T₁–T₄, although maturity (C/N) is more important for ready-to-use compost.

For LOF, medium to high doses (T₃–T₄) in A₂ tended to yield lower C/N ratios and better stability, indicating more efficient fermentation and products ready for use. However, in terms of macronutrients such as nitrogen (N), phosphorus (P₂O₅), and potassium (K₂O), EM-based products consistently had higher values compared to *Trichoderma* (T₁–T₄). This highlights the advantage of EM microbes in nutrient enhancement, while *Trichoderma* focused more on maturity and stability (Zhao et al., 2025). In practice, A₂–T₃ or A₂–T₄ are highly recommended if maturity and stability are the main targets, which are important for fertilization effectiveness and reducing phytotoxicity risks. Meanwhile, A₂–T₁ or A₂–T₂ can be considered for more cautious applications, especially when heavy metal accumulation is a concern (Zhao et al., 2025). The heavy metal contents of Pb and Cu in compost across all treatments were far below the thresholds set by SNI and the Ministry of Agriculture. Differences in average Pb and Cu across systems and doses did exist, such as Cu levels decreasing with increasing doses in A₁ and increasing in A₂, but all values were within safe limits. Thus, dosage decisions should be guided more by compost maturity and nutrient content rather than heavy metals.

Although average Pb and Cu levels varied across systems and doses, these variations were not significant in terms of product safety. For instance, Cu tended to decrease with higher doses in A₁, while in A₂ it tended to increase. Nevertheless, all values remained safe and well below thresholds that could pose environmental or health risks (BSN, 2004; Permentan, 2011). Therefore, *Trichoderma* dosage selection should prioritize compost maturity and macronutrient content (N, P₂O₅, K₂O), which directly affect fertilizer quality and plant productivity. Since heavy metal levels were consistently safe, dosage does not need to be restricted solely due to concerns about heavy metal accumulation, provided raw materials and fermentation processes are well managed (Munir et al., 2022).

This study shows that *Trichoderma* plays an important role in accelerating decomposition and improving the maturity of both LOF and compost, mainly through lowering the C/N ratio, although it does not always increase macronutrients such as N, P₂O₅, and K₂O, which were more pronounced in EM. The aerobic bucket system (A₂) proved superior in producing mature

and stable products in line with SNI standards, while the closed system (A₁) maintained higher organic C but less optimal maturity. The optimal *Trichoderma* dose was medium to high (T₃–T₄) in A₂, producing mature, high-quality compost and LOF safe from heavy metal accumulation. Thus, *Trichoderma* is better positioned as a bioactivator for accelerating maturity and stabilizing organic matter, while macronutrient enhancement remains more effective with EM or microbial enrichment strategies.

This study has advantages over previous works because it directly tested the effectiveness of *Trichoderma* as a bioactivator in organic waste fermentation under both aerobic and anaerobic bucket systems, with comprehensive chemical parameter measurements (C-organic, N-total, C/N ratio, P₂O₅, K₂O, and heavy metals). These findings are more applicable and contextual for LOF and compost production, compared to Zhang et al. (2022), which focused only on biochar for seed coating; Lima et al. (2024), which reviewed the role of *Trichoderma* in waste bioconversion theoretically; or Sani et al. (2020) and Alias et al. (2022), which emphasized biofertilizers and solid-state fermentation with specific agronomic outputs. This study also complements Sarah et al. (2023), which optimized fermentation conditions for LOF from vegetable waste, by adding a comparison between *Trichoderma* and EM₄ as bioactivators. Thus, this study aligns with previous research emphasizing the role of *Trichoderma* in waste bioconversion and soil fertility, but contributes novel, applied experimental approaches for identifying optimal doses and fermentation systems to produce more mature, nutrient-rich, and environmentally safe organic fertilizers.

The findings indicate that *Trichoderma sp.* is a viable alternative bioactivator to EM₄ for accelerating the maturity and stabilization of LOF–compost at household/community scale. The operational implication is that aerobic bucket systems (A₂) should be prioritized, as they consistently reduce C/N ratios to the SNI maturity range; medium–high doses ($\approx 25\text{--}30\text{ mL/L}$; T₃–T₄) were the most effective for this purpose. Since EM tends to yield higher N, P₂O₅, and K₂O levels, nutrient enhancement could be pursued through co-inoculation (*Trichoderma*+EM) or substrate enrichment, while *Trichoderma* should focus on maturity and stability to reduce phytotoxicity risks. The consistently low heavy metal values well below SNI/Ministry thresholds highlight opportunities for safe, low-cost, and applicable replication of local organic waste management programs, provided process controls (aeration, pH, residence time, material hygiene) and simple lab quality checks (C-organic, N-total, C/N, P, K, Pb/Cd/Cu) are ensured before distribution. For local governments and extension workers, these results can be translated into technical SOPs and training packages for waste banks/farmer groups; for researchers, they provide a basis for agronomic field trials, microbial co-culture evaluations, and economic and supply chain scale-up analyses for compost–LOF production within a circular economy framework.

CONCLUSION

This study demonstrates that *Trichoderma sp.* can serve as an alternative bioactivator to replace EM₄ in the production of mature and stable compost and liquid organic fertilizer (LOF) through a tiered bucket system. The findings show that the aerobic configuration (A₂) with medium–high inoculum doses ($\pm 25\text{--}30\text{ mL L}^{-1}$; T₃–T₄) consistently reduced the C/N ratio and accelerated maturity, while maintaining heavy metal contents well below national thresholds. These results expand previous knowledge by simultaneously evaluating fermentation conditions (aerobic and anaerobic) and variations in *Trichoderma* doses, comparing them with EM₄, and assessing the quality of both liquid and solid fractions based on chemical parameters (C, N, C/N, P₂O₅, K₂O) as well as safety indicators (Pb, Cd, Cu). Theoretically, this study reinforces the primary role of *Trichoderma* as a maturation catalyst that accelerates humification and stabilizes nitrogen, while EM₄ is relatively more effective in increasing

macronutrient content. Practically, these results support the application of the tiered bucket system at household or community scales as a low-cost, practical organic waste management strategy aligned with circular economy principles.

This study is still limited to laboratory scale, with specific substrate types, relatively short fermentation duration, and the absence of field agronomic trials or in-depth microbial community analysis. As a direction for future development, this research recommends agronomic field trials to link maturity levels and nutrient content with plant responses and soil health, exploration of co-inoculation between *Trichoderma* and EM4, optimization of the fermentation process using statistical and microbial approaches, as well as environmental, economic, and life cycle (LCA) analyses to ensure that the application of this technology can be implemented consistently, safely, and sustainably.

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