Pelita Perkebunan 41(2) 2025, 86–100
DOI: 10.22302/iccri.jur.pelitaperkebunan.v41i2.659

ISSN: 0215-0212 / e-ISSN: 2406-9574

The Potential of *Trichoderma* sp. as a Decomposer of Cocoa Pod Husk-Based Compost on Degradation of Herbicide and Insecticide Residues

Andrian Perdana[1*)] and Niken Puspita Sari[1)]

[1)]Indonesian Coffee and Cocoa Research Institute (ICCRI), Jl. PB Sudirman 90, Jember, Indonesia
*)Corresponding author: andrianperdanaap@gmail.com
Received: March 12, 2025 / Accepted: July 6, 2025

Abstract

Compost, a final product of composting as a sustainable waste management strategy, contains a wide range of organic pollutants penetrating by deliberate input such as pesticide application in feedstock materials. The involvement of Trichoderma in composting processes is expected to degrade pesticide compounds and enhance compost quality. The study employed four treatments: P1D0 (herbicide without *Trichoderma* sp.), P1D1 (herbicide with *Trichoderma* sp.), P2D0 (insecticide without *Trichoderma* sp.), and P2D1 (insecticide with *Trichoderma* sp.). The results of pesticide residue and compost quality were analyzed descriptively by comparing the effects of *Trichoderma* sp. n degrading the herbicide and insecticide residue through the composting process. Compost quality was monitored through initial, biweekly, and final analyses. All compost fulfilled the minimum standards set by the Indonesian Ministry of Agriculture. Incorporation of *Trichoderma* sp. enhanced compost quality by increasing N content (up to 37.23%) and pH (up to 5.28%), while reducing the C:N ratio (up to 50%). Moreover, it effectively degraded glyphosate and cypermethrin residues by up to 99.96% and 99.48%, respectively. These findings highlight the dual role of *Trichoderma*-enriched compost in improving compost quality and remediating pesticide residues, supporting sustainable and environmentally friendly agricultural practices.

Keywords: *Trichoderma, glyphosate, cypermethrin*

INTRODUCTION

Composting is a prominent sustainable waste management strategy. The final product, compost, can be used as a soil amendment and organic fertilizer. Thereby, recycling nutrients back to agriculture and increasing soil health by enhancing physical, biological, and chemical soil properties. However, compost contains a wide range of organic pollutants (Brändli *et al*., 2005). The organic pollutants penetrate the compost by deliberate input such as pesticide application.

Chemical pesticides, predominantly organic compounds, are widely used in developing countries to safeguard crop yields, including in cocoa plantations. However, intensive pesticide application—particularly herbicides (47.5%), insecticides (29.5%), and fungicides (17.5%)—has led to significant plant and soil contamination (Sharma *et al*., 2019). While essential for plant protection, their persistent and bioaccumulative nature poses serious environmental risks (Chen *et al*., 2020; Liu *et al*., 2016).

Due to the large-scale application of pesticides, it becomes considerably related to the composting process. Pesticide compounds are potentially present in initial feedstock materials that are routinely composted (Brändli *et al*., 2005; Cai *et al.*, 2007). It can be found in every plant material of the cocoa plantation, such as cocoa pod husk, cocoa tree pruning waste, and shade tree pruning waste.

Based on the Decree of the Minister of Agriculture of the Republic of Indonesia No. 261/KPTS/SR.310//M/4/2019 concerning minimum technical requirements for organic fertilizers, biological fertilizers, and soil amendment, the organic fertilizer must not contain chemical composition in its processes. Therefore, the presence of organic pollutants in pesticide compounds is prohibited according to the criteria for organic fertilizer.

It is considerably important that the pesticide compounds do not persist in the compost produced. It is not only because of the possible toxicity of the pesticides to people handling the compost but also, pesticides may migrate from the compost to the environment. Additionally, some compounds, particularly herbicides, may be harmful to the plants where the compost is applied or animals ingesting the compost (Büyüksönmez *et al.,* 1999).

The involvement of vigorous biological activity in composting processes is expected to accelerate the decomposition of pesticide compounds and reduce pollutant bioavailability. Specifically, *Trichoderma* sp. were identified as key degraders of pesticides, with significant changes in microbial diversity (C *et al*., 2024). *Trichoderma* sp. is used to degrade toxic substances and convert them into less toxic substances through the secretion of enzymes or metabolic processes (Šašek *et al*., 2003; Vidali, 2001). Additionally, Trichoderma isolates have been documented to possess strong cellulase activity, aiding in organic matter decomposition, which is essential for composting efficacy (Lakshmi *et al*., 2024; Thuy & TRAI, 2025). Therefore, it is a promising approach to enrich the microorganism activity by adding Trichoderma in the composting process to reduce pesticide residues.

The utilization of composting strategies in the biodegradation of organic pollutants has been seriously adopted recently. However, there is still a lack of general information provided regarding the residue status of pesticides through the composting process. Therefore, the finding about the potential of *Trichoderma* sp. as a decomposer in the degradation of pesticide residue is considerably needed to support sustainable agriculture and waste management solutions.

MATERIALS AND METHODS

Research location and time description

This research was carried out at the Kaliwining Experimental Station of the Indonesian Coffee and Cocoa Research Institute (ICCRI), Jember, East Java, Indonesia. It is located at an altitude of 45 m above sea level with an average temperature of 25-30 ^{o}C and relative humidity of 75-90%. The climate type of the research location is type D based on the classification of Schmidt-Ferguson.

This research was conducted for five months, starting from April to September 2024. The research began with the preparation of composting materials, the composting process, and the analysis of the quality and success rate of the composting process carried out.

Experimental design and treatments

This research involved the initial feedstock materials with pesticide application (herbicide or insecticide) in cocoa pod husk (CPH) and the presence of a decomposer (*Trichoderma* sp.). Therefore, this research consisted of four treatments, namely: P1D0 (initial feedstock material with herbicide application and without *Trichoderma* sp.), P1D1 (initial feedstock material with herbicide application and *Trichoderma* sp.), P2D0 (initial feedstock material with insecticide application and without *Trichoderma* sp.), and P2D1 (initial feedstock material with insecticide application and *Trichoderma* sp.).

The results of pesticide residue and compost quality were analyzed descriptively by comparing the effects of *Trichoderma* sp. in degrading the herbicide and insecticide residue by conducting the composting process in every given treatment.

Materials and tools

The material used consists of cocoa pod husk (CPH), livestock dung, *Leucaena leucocephala* leaves, *Trichoderma* sp., insecticide (active ingredient: cypermethrin 50 g/l), herbicide (active ingredient: glyphosate 486 g/l), and water. The tool used is a PVC pipe (length 1.5–2 m, diameter 7–10 cm) which has holes in the sides, tarpaulin (3–4 m) made of flexible plastic, *portable digital scales*, manual scales, shovels, pots, buckets, *thermometer liquid-in-glass, thermohygrometer digital*, and plastic samples.

Composting process and treatment application

The initial stage of making CPH-based compost is done by selecting cocoa pod material that is still fresh (has not changed color or blackened). The aerobic technique uses a PVC pipe placed in the middle of the compost pile to be made. The CPH is sprayed with insecticide and herbicide before the composting process. Insecticide (active ingredient: cypermethrin 50 g/L) and herbicide (active ingredient: glyphosate 486 g/L) were applied at a dosage of 8 mL/kg (2 L per 250 kg of compost), with a solution concentration of 4.000 ppm.

Cocoa pod husk that will be composted is mixed with livestock dung, *L. leucocephala* leaves, and *Trichoderma* sp. Compost is made in one mound consisting of three layers with an aeration pipe. Each layer consists of all compost materials arranged from bottom to top in the form of CPH, *Trichoderma* sp., livestock dung, and *L. leucocephala* leaves to cover each layer. Two hundred and fifty kilograms of compost was made, consisting of 165 kg of CPH, mixed with 82.5 kg of livestock dung (ratio 2:1), and 2.5 kg of *L. leucocephala* leaves. *Trichoderma* sp. added as much as 250 g (10^8cfu/g) (comparison 1 g *Trichoderma* and 1 kg of compost material).

The second and third layers of compost to be made consist of 60 kg of CPH, 90 g of *Trichoderma*, 27.5 kg of livestock dung, and 1 kg of *L. leucocephala* leaves. The third layer consists of 45 kg of CPH, 70 g of *Trichoderma* sp., 27.5 kg of livestock dung, and 0.5 kg of *L. leucocephala* leaves. The mixture of ingredients is then added with water to each layer until the humidity reaches around 50–60% and then covered with tarpaulin.

The compost turning process is conducted every two weeks. Every time it is turned over, water is added to the compost until it reaches a water content of 50–60% to maintain compost moisture.

Data collection

Compost nutrient content analysis consists of initial analysis of the feedstock materials, biweekly analysis, and final analysis at the end of the composting process. Compost nutrient content analysis was carried out to determine the quality of the CPH-based compost that has been produced. Insecticide and herbicide residue analysis consists of initial analysis before the composting process and final analysis at the end of composting process.

Initial samples of compost material are analyzed to determine the initial nutrient content of all compost materials used. Initial feedstock material analysis consists of analysis of N, P, K, Ca, Mg, S, B, C-organic content, C:N ratio, CEC, pH, initial insecticide, and herbicide residue.

Compost samples are taken biweekly along with the compost turning schedule to determine the progress of the composting process that has been carried out. Biweekly analysis consists of analysis of N content, C-organic, C:N ratio, pH, and water content.

The final sample of mature compost is analyzed to determine the nutrient content, the quality level of the compost that has been made, and to compare the quality level of the compost between the treatments given. The final analysis consists of analysis of N, P, K, Ca, Mg, S, B, C-organic content, C:N ratio, CEC, pH, final insecticide, and herbicide residue.

The compost temperature is measured every two days. Temperature measurements were carried out at four different points on the compost pile using a thermometer. Temperature measurements are carried out before the weekly turning schedule of the compost because the temperature of the compost will change drastically after the compost turning process. The ambient temperature is also observed using a digital thermohygrometer which has been installed in accordance with the compost temperature observation schedule. The composting process takes 55 days.

RESULTS AND DISCUSSION

Phase of the composting process

Based on the daily temperature observations (Figure 1), the composting that has been conducted adheres to the theory of temperature changes during the composting process. Whereas the composting of CPH is a dynamic process that transitions through distinct phases—mesophilic, thermophilic, cooling, and maturation—dominated by various microorganisms with specific environmental conditions.

The initial phase of composting is the mesophilic stage, which typically occurs at temperatures between 20 °C and 45 °C. In this research, the mesophilic stage temperatures range between 40–45 °C. During this stage, mesophilic microorganisms become active and decompose easily degradable organic matter found in the CPH. This phase lasts several days and wasmarked by moisture retention and the breakdown of proteins and sugars, which are abundant in CPH due to the presence of polysaccharides and nitrogenous materials (Ogunlade *et al.*, 2019). Previous research indicates that the incorporation of additional materials such as manure enhances microbial colonization and degradation rates, optimizing the mesophilic phase in CPH composting (Ogunlade *et al.*, 2019; Praveena *et al.*, 2018).

Following the mesophilic phase, a significant temperature rise indicates the onset of the thermophilic phase, where temperatures exceed 45 °C and can reach up to 70 °C (Nartey *et al.*, 2017; Vitinaqailevu & Rao, 2019). During this phase, thermophilic micro–organisms, which thrive in hot conditions, take over the decomposition process. This phase is particularly important for pathogen and weed seed destruction, as the increased temperatures can lead to effective sanitation of the compost (Nartey *et al*., 2017). The thermophilic phase is characterized by a rapid decrease in organic matter as it is converted to heat and microbial biomass. CPH, when composted with nitrogen-rich materials or co-composted with other agricultural wastes, such as shade tree pruning waste, can sustain these high temperatures and optimize the breakdown of lignocellulosic compounds (Nartey *et al*., 2017; Ogunlade & Orisajo, 2020).

As the readily available substrates are depleted, the temperature in the compost begins to decline, signaling the start of the cooling phase. This phase sees a transition back to mesophilic conditions as thermophilic microorganisms die off or become dormant due to cooling. The activity during this phase is primarily from mesophilic bacteria and fungi, which continue to break down more resistant organic materials, including lignin and cellulose present in the CPH. This phase is critical for enhancing the compost's microbial diversity and improving its overall quality as it matures (Praveena *et al*., 2018).

The final phase is the maturation phase, also known as the curing phase, during which further decomposition occurs at relatively low temperatures (below 40 °C). This phase occurred from the 29th day to the last day of composting process, with the temperature below 40 °C. The biochemical changes in this stage lead to the stabilization of compost as microbial activity slows down significantly. The resulting material is rich in nutrients and has a fine texture, which is ideal for agricultural applications. This maturation process allows for the development of complex organic structures and the enhancement of humic substances, which are crucial for soil fertility (Ogunlade & Orisajo, 2020; Praveena *et al*., 2018). Furthermore, maturity can be assessed by measuring the C:N ratio; a mature compost typically has a C:N ratio

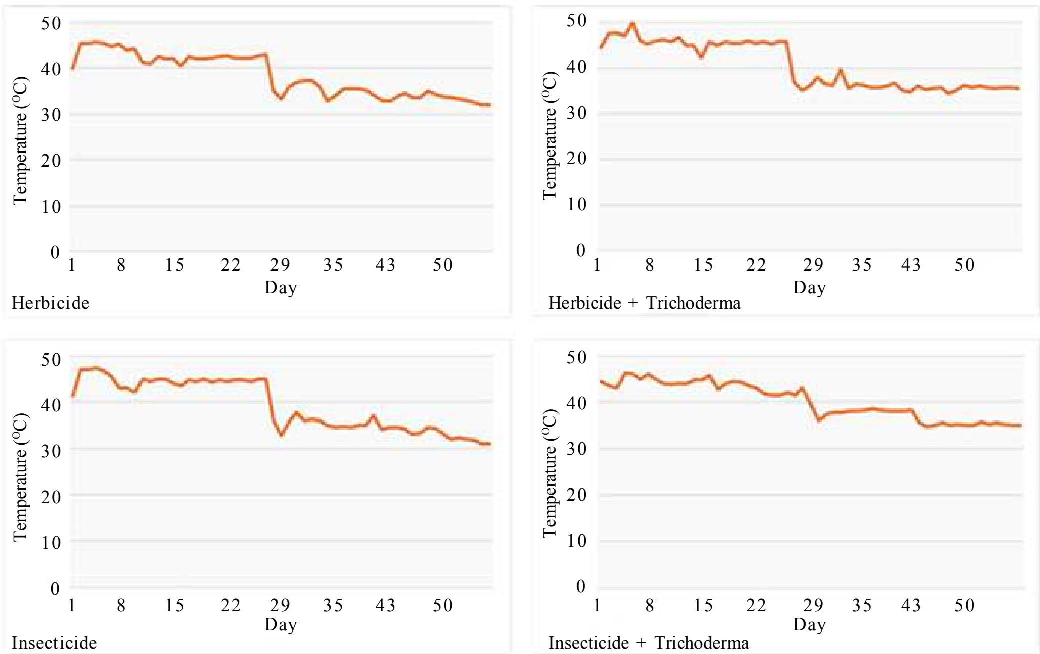

Figure 1. Daily temperature observations of composting process

below 20, indicating that it has reached a stable state suitable for agricultural use (Ogunlade & Orisajo, 2020).

Effect of *Trichoderma* sp. on glyphosate residue (herbicide)

Trichoderma species have been recognized for their ability to facilitate composting and potentially degrade glyphosate residues in organic waste. Based on the result of residue analysis, compost with Trichoderma capable to degrade the glyphosate up to 99.96% (Figure 2).

Among various microorganisms, the genus Trichoderma has emerged as a viable candidate for degrading glyphosate (Sviridov *et al.*, 2015). The introduction of Trichoderma into composting processes offers multiple benefits, including accelerated decomposition rates and the detoxification of harmful substances such as glyphosate (Arfarita *et al.*, 2016). This dual role has significant implications for organic waste management and ecological sustainability.

Research has identified several pathways through which *Trichoderma* sp species can enzymatically break down glyphosate, often utilizing it as a source of carbon and phosphorus. When *Trichoderma* sp. were incorporated into compost with glyphosate residues, they exhibited the ability to utilize glyphosate as a carbon source, indicating their potential in bioremediation (Asitok & Ekpenyong, 2019).

Trichoderma sp. exhibits a unique ability to degrade glyphosate via mechanisms that involve the cleavage of the carbon-phosphorus (C-P) bond, which is pivotal in the degradation pathways described in studies involving other microorganisms. For instance, it has been shown that *Trichoderma harzianum* can effectively utilize glyphosate as a nutritional source, converting it into less harmful metabolites such as aminomethylphosphonic acid (AMPA) (Espinoza-Montero *et al.*, 2020). *Trichoderma harzianum* has been documented to possess significant AMPA-degrading activity, achieving up to 69% degradation efficiency of AMPA within 10 days under controlled conditions (Espinoza-Montero *et al.*, 2020).

Further insights reveal that the enzymatic activities can include glyphosate oxidoreductase and C-P lyase, driving the cleavage of glyphosate into metabolites that are less toxic or can be further utilized by the organism (Ezaka *et al.*, 2019). The metabolic processes of *Trichoderma* sp. not only degrade glyphosate but can also mitigate ecological risks posed by its residues through microbial bioremediation (Asitok & Ekpenyong, 2019). In addition, the presence of Trichoderma can stimulate microbial populations in compost, leading to enhanced biodegradation mechanisms (Ros *et al.*, 2017).

Other studies corroborate these findings, suggesting that different strains of Trichoderma, including *T. viride* and *T. asperellum*, can adapt and exhibit tolerance to varying concentrations of glyphosate, thus facilitating their role in composting processes that may involve herbicide-laden residues (Asitok & Ekpenyong, 2019; Carro Huerga *et al.*, 2023). These strains often rely on their enzymatic capabilities, including cellulases and chitinases, which not only assist in degrading glyphosate but also contribute to the overall decomposition process in compost systems (Mukesh *et al.*, 2015).

Effect of *Trichoderma* sp. on cypermethrin residue (insecticide)

The potential of *Trichoderma* sp, particularly in the biodegradation of pesticide residues such as cypermethrin in compost production, has drawn considerable attention. Based on residue analysis of compost produced, compost with Trichoderma was capable to degrade the cypermethrin up to 99.48% (Figure 2).

The degradation of cypermethrin residues during the composting process is influenced by the activity of *Trichoderma*. *Trichoderma* sp. has demonstrated effectiveness in the bio-remediation of pesticide residues. Studies have indicated that certain strains, such as *Trichoderma harzianum* and *Trichoderma viride*, possess the ability to degrade various pesticides, suggesting a mechanism through which they can contribute to the detoxification of cypermethrin residues in compost (Ros *et al*., 2017; Sun *et al*., 2019).

The mechanism by which *Trichoderma* degrades cypermethrin in compost primarily involves its lignocellulolytic enzymes, such as cellulases and hemicellulases, which facilitate the breakdown of various organic materials. Furthermore, studies have shown that *Trichoderma* can enhance the production of enzymes like chitinases, which may aid in breaking down complex organic structures, including those found in pesticide residues (Brzezinska *et al*., 2023). The enzymatic pathways employed by *Trichoderma* in the degradation of these chemical compounds often involve oxidative enzymes that facilitate the breakdown of complex pesticide molecules into less toxic or non-toxic byproducts (Sun *et al.*, 2019).

H±ng *et al*. reported that *Trichoderma* contributes to the breakdown of lignin-rich materials, thus enhancing the bioavailability of nutrients and promoting microbial activity essential for degrading complex organic pollutants like cypermethrin (H±ng *et al*., 2018; H±ng *et al*., 2020). Furthermore, Bohacz discussed the potential of *Trichoderma* species in degrading aromatic compounds, including pesticide residues, highlighting its potential in bioremediation, particularly for compounds like cypermethrin that have a complex aromatic structure (Bohacz, 2020).

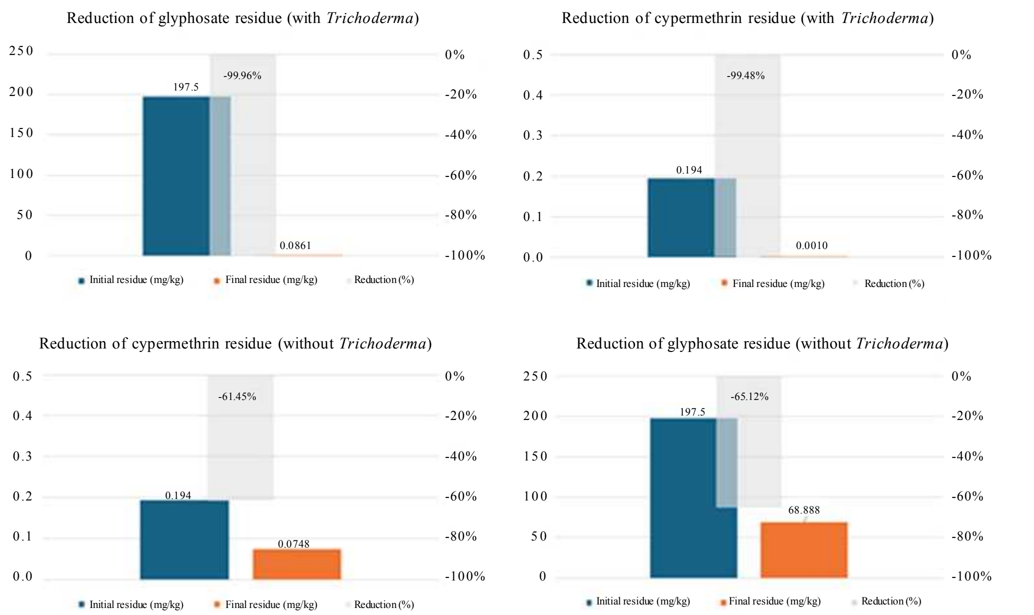

Figure 2. The effect of *Trichoderma* on glyphosate and cypermethrin residue

Moreover, the research by Nguyen *et al.* indicates that the introduction of *Trichoderma* into compost can enhance the mineralization of nitrogen compounds, thus creating conditions favorable for the microbial degradation of contaminants such as cypermethrin during composting (Nguyen *et al.*, 2021). Mazen emphasized that combining compost with *Trichoderma* can increase microbial activity against plant pathogens, which may also apply to pesticide degradation, indicating a broader role of *Trichoderma* in enhancing the microbial ecological balance necessary for effective bioremediation during composting (Mazen, 2021).

Additionally, *Trichoderma* has demonstrated the ability to biotransform pesticides and similar compounds, as reported by Wu *et al.* (2018) emphasizing its potential in degrading synthetic compounds, including cypermethrin. This highlights the importance of *Trichoderma* in not only improving the conditions in compost but also in impacting the integrity of problematic residues, facilitating their degradation under optimized composting conditions (El-Tahlawy *et al.*, 2022).

The influence of *Trichoderma* sp. on nitrogen content

The role of *Trichoderma* as a composting decomposer influences the nitrogen content in the resulting compost (Figure 3). Compost with *Trichoderma* as decomposer resulted in higher nitrogen content in compost produced. *Trichoderma* in compost with insecticide and herbicide application produces compost with N content of 2.58% and 2.2%, respectively. While compost without Trichoderma with insecticide and herbicide application produces compost with N content of 2.15% and 1.88%, respectively. Thus, *Trichoderma* enhances the N content up to 37.23%.

Trichoderma sp., known for their enzymatic capabilities, enhance the decomposition of organic materials, facilitating the release of nutrients including nitrogen. *Trichoderma* sp. actively participate in the composting process by degrading complex organic compounds, which improves microbial efficiency in mineralizing nitrogen. Studies have shown that *Trichoderma* sp., through their decomposition mechanisms, enhance compost quality and foster biological nitrification processes; this results in increased availability of nitrate nitrogen ($N\text{-}NO_3$) in the compost (Komolafe *et al.*, 2020; Nguyen *et al.*, 2021). This enhancement is crucial since nitrates are one of the most readily absorbable forms of nitrogen for plants, thereby improving growth when such compost is utilized.

When *Trichoderma* sp. is employed synergistically with compost materials, it promotes more rapid nutrient release. The presence of *Trichoderma* sp. accelerates the breakdown of organic matter and enhances the overall nutrient dynamics within the soil ecosystem (Komolafe *et al.*, 2020; Komolafe *et al.*, 2021). Research has indicated that the application of *Trichoderma* sp. can improve nitrogen mineralization rates and increase humic acid content in mature compost which typically correlates with higher nitrogen retention (H±ng *et al.*, 2018; Mazen, 2021).

The influence of *Trichoderma* sp. on C:N ratio

Trichoderma sp. as a decomposer in composting processes influences the carbon to nitrogen (C:N) ratio, which is a critical parameter for the efficiency of compost as a soil amendment. Compost with Trichoderma has lower C:N ratio compared to compost without *Trichoderma* sp. (Figure 3). Trichoderma in compost with insecticide and herbicide application produces compost with C:N ratio of 14. While compost without *Trichoderma* with insecticide and herbicide application produces compost with N content of 16 and 21, respectively. Therefore, *Trichoderma* sp. reduces the C:N ratio up to 50%. The ideal C:N ratio should be maintained between 10 and 20; ratios below this threshold can lead to nitrogen loss through volatilization, while higher ratios can inhibit microbial activity and lead to nitrogen immobilization (Wang & Liang, 2021).

The effectiveness of *Trichoderma* sp. in enhancing compost quality is primarily attributed to its ability to accelerate the decomposition of organic matter and improve nutrient availability, thus affecting the dynamics of the C:N ratio during composting. *Trichoderma* sp. wasknown for their capacity to decompose organic materials efficiently through the production of enzymes that break down cellulose and lignin, which are complex organic compounds (Gaind et al., 2005). This enzymatic activity promotes the degradation of carbon-rich materials, thereby lowering the C:N ratio while also increasing nitrogen availability.

Studies have shown that the incorporation of *Trichoderma asperellum* into compost increases the rate at which organic materials are broken down, resulting in a more rapid decline in the C:N ratio compared to uninoculated compost (Komolafe *et al.*, 2020). This is particularly important for achieving a desirable C:N ratio for mature compost, which is essential for optimizing nutrient release for plant uptake.

The influence of *Trichoderma* sp. on C-organic

The application of *Trichoderma* sp. as composting decomposers influences the composition of organic carbon in the produced compost. Compost with *Trichoderma* sp. has lower C-organic compared to compost without *Trichoderma* sp. (Figure 3). *Trichoderma* sp. in compost with insecticide and herbicide application produces compost with C-organic content of 33.37% and 28.29%, respectively. While compost without *Trichoderma* sp. with insecticide and herbicide application produces compost with C-organic content of 34.33% and 39.16%, respectively.

During composting, *Trichoderma* sp. mineralizes organic matter, which may result in altered C-organic levels. Juwanda *et al.* indicate that organic C content tends to decrease during composting as microbial activity rises, suggesting that carbon serves as a vital energy source for these microorganisms (Juwanda *et al.*, 2022). The faster mineralization process that *Trichoderma* fosters suggests a quicker breakdown of organic matter, potentially resulting in lower organic carbon concentrations in the final compost product.

Nguyen *et al.* noted that the use of *Trichoderma* in composting can enhance biological nitrification, contributing to higher nitrogen availability while facilitating the decomposition of organic carbon (Nguyen *et al.*, 2021a). This relationship illustrates the trade-offs that occur during composting when *Trichoderma* was introduced; while nutrient retention may improve, the carbon content may decline.

Furthermore, analyses on thermal dynamics during composting have shown that increased temperatures can enhance organic matter breakdown (Juwanda *et al.*, 2022). The ability of *Trichoderma* sp. to promote temperature-induced decomposition could lead to even lower organic carbon levels when included in the compost mixture.

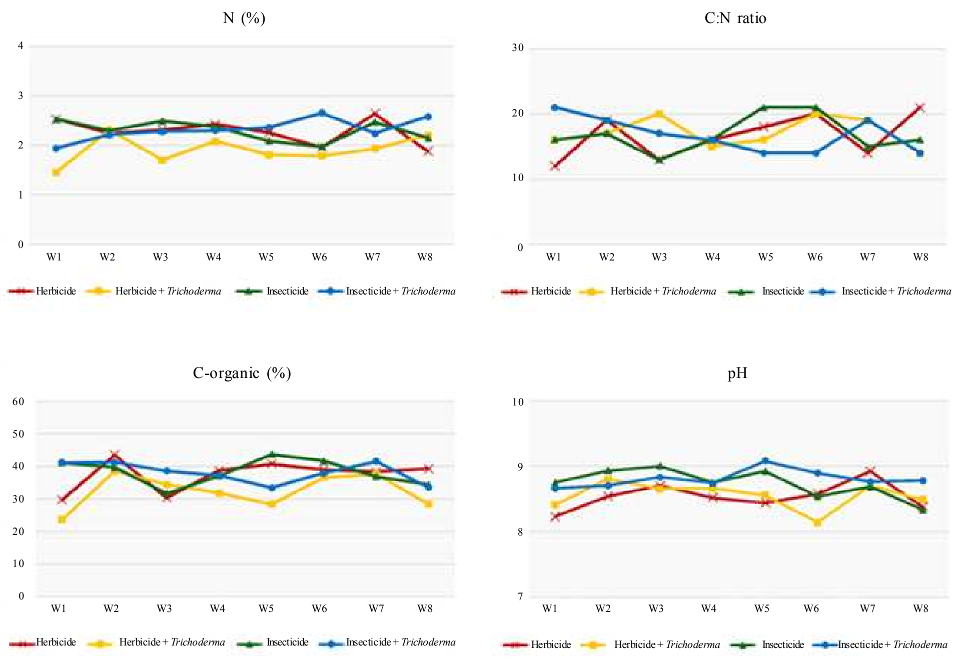

Figure 3. N content, C:N ratio, C-organic, and pH of compost produced

The influence of *Trichoderma* sp. on pH

The role of Trichoderma as a decomposer in composting processes impacts the pH of the compost produced. Compost with *Trichoderma* has higher pH compared to compost without *Trichoderma* (Figure 3). *Trichoderma* sp. in compost with insecticide and herbicide application produces compost with a pH of 8.78 and 8.49, respectively. Compost without Trichoderma with insecticide and herbicide application produces compost with pH of 8.34 and 8.38, respectively. Thus, *Trichoderma* sp. increases the pH up to 5.28%.

Initial composting tends to lead to the production of organic acids due to microbial activity, resulting in a decrease in pH. However, as composting progresses, particularly with the activity of *Trichoderma*, mineralization processes can lead to a gradual increase in pH, often stabilizing at neutral levels indicative of mature compost. Studies reveal that during early decomposition stages, the growth of microorganisms like *Trichoderma* leads to acid accumulation, contributing to a drop in pH (Liu *et al*., 2022). However, as composting proceeds, *Trichoderma's* enzyme activity, particularly the production of cellulases, tends to enhance the mineralization of nitrogen, which can stabilize and increase pH levels over time (Kumar *et al*., 2008).

The neutralization process observed in several studies correlates well with the maturity of compost. A study found that compost treated with *Trichoderma* exhibited a neutral pH, thus indicating a mature and stable compost suitable for use as an organic fertilizer (Alfadlli *et al*., 2018). Furthermore, the ability of *Trichoderma* to improve soil dynamics, such as enhancing nutrient availability, appears to be linked with the pH stabilization during composting (Komolafe *et al*., 2020).

Comparison of the quality of compost produced and standard minimum of organic fertilizer

Based on the results of the analysis that has been conducted, all the compost produced has fulfill the minimum technical requirements (Figure 4 and Table 1). This standard refers to the Decree of The Minister of Agriculture of The Republic of Indonesia No. 261/KPTS/SR.310//M/4/2019 concerning minimum technical requirements for organic fertilizers, biological fertilizers, and soil amendment.

The N+P+K content in the minimum technical standard is 2% at the lowest, while the N+P+K content of the compost produced ranges from 4.79–8.03%. Compost with *Trichoderma* sp. has a higher N+P+K content compared to compost without *Trichoderma* sp. Minimum technical standard stipulates that the C:N ratio is a minimum of 25, while the compost produced has a C:N ratio ranging from 14–21. The lowest C:N ratio resulted from compost with *Trichoderma* sp. compared to compost without *Trichoderma* sp. The C-organic content specified by the minimum technical standard is a minimum of 15%,

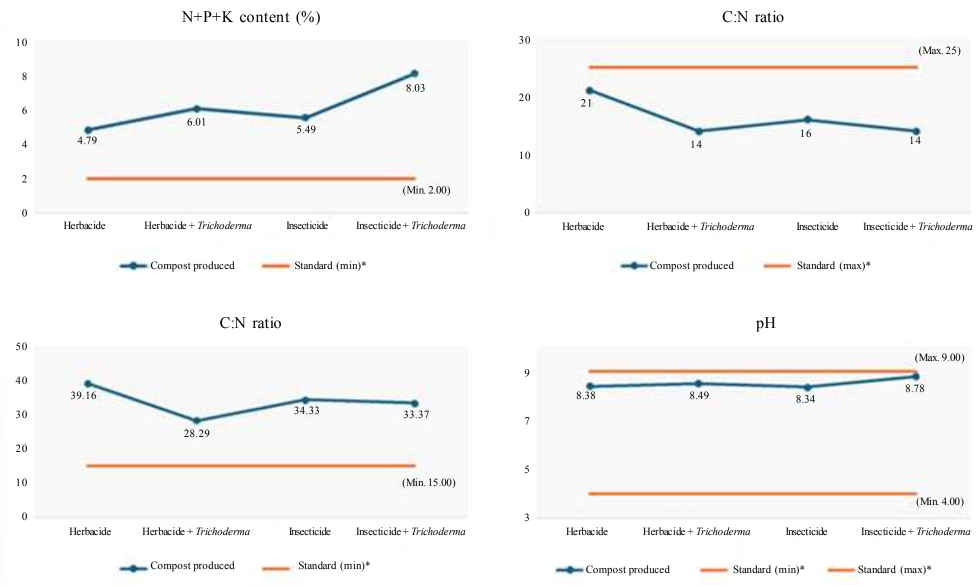

Figure 4. Comparison of the quality of compost produced and minimum technical standard of organic fertilizer

Table 1. Comparison of compost quality between the minimum technical standards and produced compost

Parameter	Minimum technical standard	Compost without *Trichoderma*	Compost with *Trichoderma*	Remarks
N + P + K (%)	≥ 2.00	4.79-6.10	6.52-8.03	Both exel standard; higer with *Trichoderma*
C:N ratio	≤ 25	18-21	14-17	Both meet standard; lower (better) with *Trichoderma*
C-organic (%)	≥15.00	35.12-39.16	28.29-34.57	All exceed standard; slightly lower with *Trichoderma*
pH	4.0-9.0	8.34-8.60	8.62-8.78	All within range; slightly higher with *Trichoderma*

while the C-organic content of the compost produced ranges from 28.29"39.16%. Although the C-organic content of compost with *Trichoderma* sp. is lower than compost without *Trichoderma* sp., the C-organic content still exceeds the established minimum technical standards. Technical standards stipulate a minimum pH of 4 and a maximum of 9, while the compost produced has a pH ranging from 8.34"8.78. The highest pH is produced from compost with *Trichoderma* sp than compost without *Trichoderma* sp.

CONCLUSIONS

Incorporating *Trichoderma* sp. into the composting process presents a promising biological strategy for addressing glyphosate and cypermethrin residues, with the reduction up to 99.96% and 99.48%, respectively. Through their enzymatic activity and enhancement of microbial dynamics, *Trichoderma* sp. can facilitate the breakdown of complex organic contaminants.

The involvement of *Trichoderma* sp. simultaneously enhances N content (up to 37.23%) and pH (up to 5.28%), while reducing C:N ratio (up to 50%), thus promoting improved compost quality. This multifaceted role in degrading pesticide residue and enhancing compost quality is critical for sustainable agricultural practices and contributing to environmentally friendly waste management practices.

REFERENCES

Alfadlli, N.S.; S. Noor; B.S. Hertanto & M. Cahyadi (2018). The effect of various decomposers on quality of cattle dung compost. *Buletin Peternakan*, 42(3). https://doi.org/10.21059/buletinpeternak.v42i3.25865.

Asitok, A. & M. Ekpenyong (2019). Comparative analysis of determination methods of glyphosate degradation by *Trichoderma asperellum* strain JK-28: A multivariate statistical approach. *Journal of Agriculture and Ecology Research International*, 1–14. https://doi.org/10.9734/jaeri/2019/v19i130070.

Bohacz, J. (2020). *Archives of Environmental Protection*. https://doi.org/10.24425/aep.2020.133470.

Brändli, R.C.; T.D. Bucheli; T. Kupper; R. Furrer; F.X. Stadelmann & J. Tarradellas (2005). Persistent organic pollutants in source separated compost and its feedstock materials—A review of field studies. *Journal of Environmental Quality*, 34(3), 735–760. https://doi.org/10.2134/jeq2004.0333.

Brzezinska, M.S.; B. Kaczmarek; G.B. Dabrowska; M. Michalska Sionkowska; K. Dembiñska; A. Richert; M. Pejchalová; S.B. Kumar & A. Kalwasiñska (2023). Application potential of *Trichoderma* in the degradation of phenolic acid-modified chitosan. *Foods*, 12(19), 3669. https://doi.org/10.3390/foods12193669

Büyüksönmez, F.; R. Rynk; T.F. Hess & Bechinski, E. (1999). Occurrence, degradation and fate of pesticides during composting. *Compost Science & Utilization*, 7(4), 66–82. https://doi.org/10.1080/1065657X.1999.10701986

Cai, Q.-Y.; C.-H. Mo; Q.-T. Wu; Q.-Y. Zeng & A. Katsoyiannis (2007). Quantitative determination of organic priority pollutants in the composts of sewage sludge with rice straw by gas chromatography coupled with mass spectrometry. *Journal of Chromatography A*, *1143*(1–2), 207–214. https://doi.org/10.1016/j.chroma.2007.01.007.

Carro Huerga, G.; S. Mayo Prieto; Á. Rodríguez González; R.E. Cardoza; S. Gutiérrez & P.A. Casquero (2023). Vineyard management and physicochemical parameters of soil affect native *Trichoderma* populations, sources of biocontrol agents against *Phaeoacremonium minimum*. *Plants*, 12(4), 887. https://doi.org/10.3390/plants12040887.

Chen, S.; Y. Yan; Y. Wang; M. Wu; Q. Mao; Y. Chen; J. Ren; A. Liu; X. Lin & G.J. Ahammed (2020). *Trichoderma asperellum* reduces phoxim residue in roots by promoting plant detoxification potential in *Solanum lycopersicum* L. *Environmental Pollution*, 259, 113893. https://doi.org/10.1016/j.envpol.2019.113893

El-Tahlawy, Y.A.; S. Hassanen & A. Mostafa (2022). Compost fortification with lignocellulolytic fungi for heat cultivation using fewer mineral fertilizers amount in sandy soil. *Egyptian Journal of Agricultural Research*, *100*(4), 591–607. https://doi.org/10.21608/ejar.2022.163540.1284.

Espinoza-Montero, P.J.; C. Vega-Verduga; P. Alulema-Pullupaxi; L. Fernández & J.L. Paz (2020). Technologies employed in the treatment of water contaminated ith glyphosate: A review. *Molecules*, 25(23), 5550. https://doi.org/10.3390/molecules25235550.

Ezaka, E.; A.K. Akintokun; P.O. Akintokun; L.B. Taiwo; A.C.O. Uthman; A.O. Oyedele & O.I. Aluko (2019). Glyphosate degradation by two plant growth promoting bacteria (PGPB) isolated from rhizosphere of maize. *Microbiology Research Journal International*, 1–11. https://doi.org/10.9734/mrji/2018/v26i630081.

Gaind, S.; A.K. Pandey & L. Lata (2005). Biodegradation study of crop residues as affected by exogenous inorganic nitrogen and fungal inoculants. *Zeitschrift Für Allgemeine Mikrobiologie*, *45*(4), 301–311. https://doi.org/10.1002/jobm.200410483.

H±ng, P.T.; N.T. Minh; T.T.Y. Nhi; N.T. Hoanh & D.H.D. Khoa (2020). Diversity of microfungi associated ith aerobic composting process of organic astes. *Vietnam Journal of Biotechnology*, 18(2), 385–392. https://doi.org/10.15625/1811-4989/18/2/15641.

H±ng, P.T.; L.T.Q. Tram; T.P. Anh; H.T.T.K. Mui; D.N. Thao & D.H.D. Khoa (2018a). Isolation and identification of fungi associated with composting process of municipal biosolid waste. *Vietnam Journal of Biotechnology*, 15(4), 763–770. https://doi.org/10.15625/1811-4989/15/4/13421.

H±ng, P.T.; L.T.Q. Tram; T.P. Anh; H.T.T.K. Mui; D.N. Thao & D.H.D. Khoa (2018b). Isolation and identification of fungi associated with composting process of municipal biosolid waste. *Vietnam Journal of Biotechnology*, 15(4), 763–770. https://doi.org/10.15625/1811-4989/15/4/13421.

Juwanda, M.; Sakhidin; Saparso & Kharisun (2022). The long composting period effect of leaf shallots on the compost quality. *IOP Conference Series Earth and Environmental Science*, 1097(1), 012045. https://doi.org/10.1088/1755-1315/1097/1/012045.

Komolafe, A.F.; C.O. Adejuyigbe; A.A. Soretire & I.O.O. Aiyelaagbe (2020). Maturity indices of composting plant materials with *Trichoderma asperellum* as activator. *Agricultura Tropica Et Subtropica*, 53(1), 19–27. https://doi.org/10.2478/ats-2020-0003.

Komolafe, A.F.; C.O. Kayode; D.T. Ezekiel–Adewoyin; O.E. AyanfeOluwa; D. Ogunleti & A.I. Makinde (2021). Soil properties and performance of Celosia (*Celosia argentea*) as affected by compost made with *Trichoderma asperellum*. *Eurasian Journal of Soil Science* (EJSS), 10(3), 199–206. https://doi.org/10.18393/ejss.880541.

Kumar, R.; S. Singh & O.V. Singh (2008). Bioconversion of Lignocellulosic biomass: Biochemical and molecular perspectives. *Journal of Industrial Microbiology & Biotechnology*, 35(5), 377–391. https://doi.org/10.1007/s10295-008-0327-8.

Liu, S.; Z. Che & G. Chen (2016). Multiple-fungicide resistance to carbendazim, diethofencarb, procymidone, and pyrimethanil in field isolates of *Botrytis cinerea* from tomato in Henan Province, China. *Crop Protection*, 84, 56–61. https://doi.org/10.1016/j.cropro.2016.02.012.

Liu, X.; X. Li; Y. Hua; A. Sinkkonen; M. Romantschuk; Y. Lv; Q. Wu & N. Hui (2022). Meat and bone meal stimulates microbial diversity and suppresses plant pathogens in Asparagus straw composting. *Frontiers in Microbiology*, 13. https://doi.org/10.3389/fmicb.2022.953783.

Mazen, M. (2021a). Combined effects of compost and *Trichoderma* spp. on reducing damping-off and root rot diseases of Lentil plants. *Egyptian Journal of Phytopathology*, 49(2), 29–40. https://doi.org/10.21608/ejp.2021.80911.1037.

Mukesh, S.; M. Shahid; P. Sonika; K. Vipul; A. Singh; T. Shubha; Y.K. Srivastava & Shivram (2015). *Trichoderma*: A scientific approach against soil borne pathogens. *African Journal of Microbiology Research*, 9(50), 2377–2384. https://doi.org/10.5897/ajmr2015.7788.

Nartey, E.; P. Amoah; G.K. Ofosu-Budu; A. Muspratt & Pradhan S.K. (2017). Effects of co-composting of faecal sludge and agricultural wastes on tomato transplant and growth. *International Journal of Recycling of Organic Waste in Agriculture*, 6(1), 23–36. https://doi.org/10.1007/s40093-016-0149-z.

Nguyen, T.V.; V.M. Tran & B.P.K. Huynh (2021a). Assessment of seafood processing sludge after composting on growth of *Tagetes patula* L. *Scientific Journal of Tra Vinh University*, 1(42), 102–108. https://doi.org/10.35382/18594816.1.42.2021.697.

Ogunlade, M.O.; O.S. Bello; S.O. Agbeniyi & D.O. Adeniyi (2019). Microbiota assay of cocoa pod husk–based compost as organic fertilizer. *International Journal of Current Microbiology and Applied Sciences*, 8(06), 3182–3192. https://doi.org/10.20546/ijcmas.2019.806.380.

Ogunlade, M.O. & S.B. Orisajo (2020). Integrated soil fertility management for small holder cocoa farms using combination of cocoa pod husk based compost and mineral fertilizers. *International Journal of Plant & Soil Science*, 68–77. https://doi.org/10.9734/ijpss/2020/v32i230250.

Praveena, C.; J. Suresh; V. Jegadeeswari; J. Kannan & S. Karthikeyan (2018). Studies on composting of cocoa (*Theobroma cacao* L.) pod husk. *International Journal of Advanced Research*, 6(9), 1081–1085. https://doi.org/10.21474/ijar01/7616.

Ros, M.; I. Rãut; A.B. Santísima Trinidad & J.A. Pascual (2017). Relationship of microbial communities and suppressiveness of *Trichoderma* fortified composts for pepper seedlings infected by *Phytophthora nicotianae*. *Plos One*, 12(3), e0174069. https://doi.org/10.1371/journal.pone.0174069.

Šašek, V.; J.A. Glaser & P. Baveye (2003). *The utilization of bioremediation to reduce soil contamination: Problems and solutions*. Springer Netherlands. https://doi.org/10.1007/978-94-010-0131-1.

Sharma, A.; V. Kumar; B. Shahzad; M. Tanveer; G.P.S. Sidhu; N. Handa; S.K. Kohli; P. Yadav; A.S. Bali; R.D. Parihar; O.I. Dar; K. Singh; S. Jasrotia; P. Bakshi; M. Ramakrishnan; S. Kumar; R. Bhardwaj & A.K. Thukral (2019). Worldwide pesticide usage and its impacts on ecosystem. *SN Applied Sciences*, 1(11), 1446. https://doi.org/10.1007/s42452-019-1485-1.

Sun, J.; Y. Xu; Y. Li; X. Wang & J. Chen (2019). The pathway of 2,2-dichlorovinyl dimethyl phosphate (DDVP) degradation by *Trichoderma atroviride* strain T23 and characterization of a paraoxonase-like enzyme. *Applied Microbiology and Biotechnology*, 103 (21–22), 8947–8962. https://doi.org/10.1007/s00253-019-10136-2.

Vidali, M. (2001). Bioremediation. An overview. *Pure and Applied Chemistry*, 73(7), 1163–1172. https://doi.org/10.1351/pac200173071163.

Vitinaqailevu, R. & B.K.R. Rao (2019). The Role of Chemical Amendments on modulating ammonia loss and quality parameters of co-composts from aste cocoa pods. *International Journal of Recycling of Organic Waste in Agriculture*, 8(S1), 153–160. https://doi.org/10.1007/s40093-019-0285-3.

Wang, W.-K. & C. Liang (2021). Enhancing the compost maturation of swine manure and rice straw by applying bio-augmentation. *Scientific Reports*, 11(1). https://doi.org/10.1038/s41598-021-85615-6

Wu, Q.; M. Ni; G. Wang; Q. Liu; M. Yu & J. Tang (2018). Omics for understanding the tolerant mechanism of *Trichoderma asperellum* TJ01 to organophosphorus pesticide dichlorvos. *BMC Genomics*, 19(1). https://doi.org/10.1186/s12864-018-4960-y.

Zhang, T.; J. Tang; J. Sun; C. Yu; Z. Liu & J. Chen (2015). Hex1-related transcriptome of *Trichoderma atroviride* reveals expression patterns of ABC transporters associated with tolerance to dichlorvos. *Biotechnology Letters*, *37*(7), 1421–1429. https://doi.org/10.1007/s10529-015-1806-4.