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Enhancing Cocoa Pod Husk Decomposition Through a Microbial Consortium of *Trichoderma harzianum*, *Pleurotus ostreatus* and Mikrobat

Fitrianti[1], Tutik Kuswinanti[2], Melina[2], Jayadi[3]

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ABSTRACT

Background: Cocoa (*Theobroma cacao* L.) is a major global commodity, with Indonesia ranking among the top producers. However, cocoa pod husks which account for about 73% of the fruit mass-remain largely underutilized, creating significant agricultural waste and environmental concerns. These husks are rich in nutrients and lignocellulosic compounds, making them suitable for conversion into compost. This study aimed to evaluate the effectiveness of *Trichoderma harzianum*, *Pleurotus ostreatus* and a microbial consortium (Mikrobat) as bio-decomposers for enhancing the composting of cocoa pod husks and to assess their impact on compost physicochemical quality and lignocellulose degradation.

Methods: The experiment was conducted using a randomized block design with seven treatments (single and combined inoculations) and three replications, resulting in 63 experimental units. Composting parameters observed included temperature dynamics, mycelial growth, color, texture, odor, weight loss, nutrient content (C-organic, N, P, K) and lignocellulolytic composition (NDF, ADF, cellulose, hemicellulose, lignin).

Result: The results showed that microbial treatments significantly accelerated the composting process, as indicated by elevated early-phase temperatures, rapid mycelial colonization and improved physical maturity (darker color, finer texture). The combination of *T. harzianum* and Mikrobat yielded the highest C-organic (17.90%), total N (1.01%) and K (0.82%) contents with an optimal C/N ratio (~18), while the triple combination produced the highest P (1.08%). Lignocellulolytic analysis revealed that *T. harzianum* + *P. ostreatus* effectively reduced fiber and lignin contents, whereas *T. harzianum* + Mikrobat promoted the transformation of lignin into stable humic compounds.

Key words: Cocoa pod husk, Composting, Microbial consortium, *Pleurotus ostreatus, Trichoderma harzianum.*

INTRODUCTION

Cocoa (*Theobroma cacao* L.) is a major global export commodity that plays a vital role in the rural economies of producing countries. Currently, Ivory Coast, Ghana and Indonesia dominate global cocoa production, each contributing over 400,000 tons annually (ICCO, 2016). In Indonesia, approximately 75% of the national cocoa output originates from Sulawesi, particularly Central Sulawesi, South Sulawesi and other regions such as Lampung and Sumatra (Hapsari, 2023). Among the agricultural by-products of cocoa cultivation, *Cocoa Pod Husks* (CPH) remain significantly underutilized. A cocoa fruit typically consists of 73.63% husk (pod), 24.37% seeds (containing about 30-40 beans per pod) and 2% placenta (bean wrapper) (El Kiyat *et al.,* 2018). This implies that for every ton of cocoa beans harvested, around 3-4 tons of cocoa pod waste are generated. This waste is often discarded or incinerated, contributing to environmental issues and representing a missed opportunity for economic valorization (Djali *et al.,* 2018; Panak *et al.,* 2018). Cocoa husk, which is rich in nutrients, contains 1.81% N, 26.61% C-organic and other minerals and can be processed into organic fertilizer, animal feed, or industrial raw materials (Kuswinanti *et al.,* 2012). Research indicates that cocoa husk compost can enhance cocoa plant productivity by 19.48% (Hartatik *et al.*, 2015) and improve soil fertility (Marius *et al.,* 2020).

[1]Post Graduate Student of the Agriculture Faculty, Hasanuddin University, Jl. Perintis Kemerdekaan KM. 10, Makassar 90245, South Sulawesi, Indonesia.
[2]Plant Protection Study Program, Faculty of Agriculture, Hasanuddin University, Jl. Perintis Kemerdekaan KM. 10, Makassar 90245, South Sulawesi, Indonesia.
[3]Soil Science Study Program, Faculty of Agriculture, Hasanuddin University, Jl. Perintis Kemerdekaan KM. 10, Makassar 90245, South Sulawesi, Indonesia.

Corresponding Author: Tutik Kuswinanti, Plant Protection Study Program, Faculty of Agriculture, Hasanuddin University, Jl. Perintis Kemerdekaan KM. 10, Makassar 90245, South Sulawesi, Indonesia. Email: tkuswinanti@gmail.com
ORCIDs: https://orcid.org/0000-0003-2960-2841, https://orcid.org/0009-0005-1202-3853, https://orcid.org/ 0009-0008-1863-1499, https://orcid.org/0000-0002-0765-9743

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The combination of cocoa skin with bran can increase the protein content of compost by 14.6% (Kamelia and Fathurohman, 2017). With this great potential, the utilization

of cocoa husk waste not only reduces environmental impacts but also supports sustainable agriculture. Therefore, innovation in cocoa waste processing is a strategic solution to increase economic value while maintaining the agricultural ecosystem. CPH is the largest waste product from cocoa fruit (70-80% of fruit weight) and can cause environmental problems. However, CPH contains bioactive compounds and is a high-potential source of cellulose that can be utilized in various sustainable material industries (Meza-Sepulveda *et al*., 2025; Anatachodwanit *et al*., 2025).

One method of processing cocoa shell husk biologically is by utilizing microorganisms that can produce cell wall-degrading enzymes, such as cellulase, hemicellulase and lignin-degrading enzymes, considering that cocoa shells contain lignin and hemicellulose (Akinjokun *et al.,* 2021; Herrera-Barrios *et al.,* 2022). Microorganisms capable of producing enzymes such as cellulase, endoglucanase, xylanase and laccase are known to be effective in decomposing lignocellulosic compounds (Sarangi *et al.,* 2021). Microbial degradation of lignocellulose, involving bacteria and fungi, results in the production of several lignocellulolytic enzymes, including cellulase, hemicellulase and laccase, through the method of decomposing lignocellulosic constituents (Chen *et al*., 2025). Fungi are one group of microbes that are reported to have the ability to degrade lignin, cellulose and hemicellulose. For example, *Pleurotus* sp. and *Trichoderma* sp. are reported to be able to degrade lignin by up to 76.46% and hemicellulose by 6.22% (Fitrianti, 2016). *Trichoderma* spp. possess the capability to break down lignocellulose and include essential genes for these enzymes (Awad-Allah *et al*., 2023; Zhu *et al*., 2025).

Beyond enhancing the decomposition process, these microorganisms also act as antagonistic agents against plant pathogens, serving as natural biofungicides (Kuswinanti, 2006). A microbial consortium such as Mikrobat, comprising *Bacillus subtilis*, *Pseudomonas fluorescens* and *Lactobacillus* sp., not only accelerates the decomposition process but also reduces unpleasant odors through the production of lactic acid (Baharuddin and Zaenab, 2005). Bacteria like *Bacillus* spp. can produce cellulase and aid in the degradation of lignocellulose (Wang *et al*., 2024). The research findings of Pan *et al*. (2025) elucidate the potential of microbial consortia, comprising filamentous fungi and bacteria, that collaboratively break down lignocellulose. The presence of actinomycetes in the formulation enhances its functionality by suppressing plant pathogens through antibiotic production. The application of such decomposer microbes has been shown to promote plant growth in crops such as shallots (Karim *et al*., 2019) and coffee (Yakup, 2021), while also offering a sustainable alternative to reduce reliance on chemical fertilizers.

Considering that *Trichoderma harzianum* and *Pleurotus ostreatus* are among the most active decomposers capable of producing lignocellulose-degrading enzymes, it is essential to investigate their potential in decomposing cocoa pod waste. The final product of this process can serve as an organic fertilizer, contributing to the increased availability of compost for sustainable agriculture. The application of *T. harzianum* and *P. ostreatus*, whether separately or together, is anticipated to markedly expedite the decomposition of cocoa pod waste by increasing lignocellulolytic activity. Their enzymatic synergy is expected to enhance the degradation of cellulose, hemicellulose and lignin, therefore reducing the composting duration and advancing compost maturity. Moreover, the integration of these fungi is presumed to augment nutrient accessibility by promoting organic carbon stability and the liberation of vital macronutrients. As a result, the compost produced is anticipated to have enhanced physicochemical properties and comply with agronomic criteria for application as an organic fertilizer. This method is expected to promote sustainable agriculture by transforming CPH into a beneficial soil supplement.

The purpose of this study was evaluate the effect of applying *T. harzianum*, *P. ostreatus* and a microbial consortium (Mikrobat), both separately and in combination, on the pace of lignocellulose degradation and the quality of CPH waste compost. This study aims to find the most effective bio-decomposer treatment for expediting the composting process, improving nutrient content and producing mature compost that meets organic fertilizer standards to support sustainable agriculture.

MATERIALS AND METHODS

This study was conducted from June to November 2024 at the Research Center's Agricultural Biotechnology Laboratory and the Department of Plant Pests and Diseases, Faculty of Agriculture, Hasanuddin University in Makassar. CPH was employed as the primary composting substrate, broken into small pieces to enhance surface area, then homogenized before composting. *T. harzianum*, *P. ostreatus* and a microbial consortium (Mikrobat) that included *Bacillus subtilis*, *Pseudomonas fluorescens*, *Lactobacillus* spp. and actinomycetes were used as decomposer agents.

The decomposers were used at a rate of 1-2 kg per ton of organic waste, depending on the substrate type. For substrates with low lignin content, a dosage of 0.5 kg^{-1} kg per ton was used. To achieve uniform dispersion, decomposers were administered directly or diluted in water first. Composting was done aerobically and piles were covered in dark-colored plastic sheets to keep the temperature and moisture stable while also increasing microbial activity. Moisture content was maintained at approximately 55-65% during the composting process by periodic watering and stirring.

The experiment used a randomized block design (RBD) with 7 treatments: control (no decomposer), *T. harzianum*

(25 g L^{-1}), *P. ostreatus* (25 g L^{-1}), Mikrobat (25 g L^{-1}), *T. harzianum* + *P. ostreatus*, *T. harzianum* + Mikrobat and *T. harzianum* + *P. ostreatus* + Mikrobat. Each treatment had 3 experimental units and was repeated 3 times, for a total of 63 experimental units.

Observation parameters

Composting performance was tested using physical, chemical and biological criteria. Compost temperature was recorded weekly with a digital thermometer to track microbiological activity and composting processes. Color, texture, odor and mycelial development were visually analyzed to determine compost maturity. The percentage of compost weight reduction was estimated by comparing the initial and final compost weights.

Chemical analyses included the Walkley-Black method for determining organic carbon (C-organic), the Kjeldahl method for total nitrogen (N), spectrophotometry for available phosphorus (P) and flame photometry for potassium. The C/N ratio was estimated as a measure of compost maturity. To assess lignocellulose breakdown efficiency, the Van Soest technique was applied to the lignocellulosic composition, which included neutral detergent fiber (NDF), acid detergent fiber (ADF), cellulose, hemicellulose and lignin.

Statistical analysis

To investigate the impact of decomposer treatments on composting parameters, all quantitative data underwent analysis of variance (ANOVA) using a RBD. When significant differences were found at $p<0.05$, mean comparisons were performed using Duncan's multiple range test (DMRT) at the 5% significance level. Statistical analyses were carried out using conventional statistical software. Data are reported as mean values and differences between treatments were judged statistically significant at $p<0.05$.

RESULTS AND DISCUSSION

Effectiveness test of *Trichoderma harzianum* and *Pleurotus ostreatus* biodecomposers

Based on the research results, the effectiveness of decomposers can be seen from the compost temperature measured every week and physical characteristics such as color, texture and odor. The following is the compost temperature data for 3 weeks (Table 1). This study revealed that the use of *Trichoderma harzianum* and *Pleurotus ostreatus* decomposers significantly affected the composting temperature from the first to the third week. The high temperature at the beginning of the process indicates that composting is taking place optimally. In the first week, a sharp increase in temperature indicates intensive microorganism activity in degrading organic matter. The heat generated comes from the metabolic energy of decomposer bacteria during the decomposition process. In the early phase (first week), the highest peak in *Pleurotus ostreatus* (46.2°C), was statistically significantly different from the combination of *T. harzianum* + *P. ostreatus* (45.9°C). Meanwhile, treatments *T. harzianum*, *P. ostreatus*, Mikrobat and *T. harzianum* + *P. ostreatus* showed a decrease in temperature. This indicates that decomposer activity is starting to decline and the composting process is entering the maturation stage. In contrast, treatments *T. harzianum*+Mikrobat and *T. harzianum* + *P. ostreatus*+Mikrobat experienced an increase in temperature in the second and third weeks, indicating that decomposition had only just begun at this stage. Especially in *T. harzianum*+*P. ostreatus*+Mikrobat treatment, the temperature continued to increase until the third week, indicating the ineffectiveness of decomposer activity in this treatment.

The findings of this study suggest that microbial treatment influences the temperature profile during the composting process. This study's findings are consistent with those of Faesal *et al*. (2020), who discovered that using a combination of bacteria and fungi as decomposers can increase biological activity during composting, as evidenced by an increase in initial temperature and accelerated degradation of organic matter. Wang *et al*. (2026) found that using lignocellulolytic microbial consortia at specified phases can increase the peak composting temperature and speed the temperature rise. These findings are also pertinent to the study conducted by Tahsini *et al*. (2025), who discovered that adding microbial to compost increased temperatures and lengthened the thermophilic phase while also enhancing microbial activity and compost quality. Microbial inoculation not only

Table 1: Weekly compost temperature profiles under various decomposer treatments during composting of CPH.

Treatment	Temperature (°C)		
	Week 1	Week 2	Week 3
Control	41.5^{cd}	41.0^{d}	34.8^{b}
T. harzianum	42.3^{d}	37.4^{c}	31.6^{a}
P. ostreatus	46.2^{e}	36.5^{c}	36.5^{c}
Mikrobat	40.7^{c}	36.9^{bc}	38.3^{d}
T. harzianum + *P. ostreatus*	45.9^{e}	34.9^{a}	38.3^{d}
T. harzianum + Mikrobat	22.2^{a}	36.6^{b}	34.3^{b}
T. harzianum + *P. ostreatus* + Mikrobat	34.8^{b}	34.9^{a}	36.1^{c}

Source: Processed data, 2025.

accelerates organic matter decomposition, but it also promotes an increase in compost temperature and speeds up the composting maturation process by increasing microbial activity (Salih *et al*., 2025).

Physical properties of compost

The following are the results of observations made in the field based on the physical properties of compost in the decomposition process (Table 2). Based on the research conducted, the effectiveness of the cocoa shell waste composting process can be assessed through the compost maturity structure, which includes visual characteristics (color) and biological development (the presence of mycelium) in decomposing organic materials. As shown in the observation results table, there is a significant variation in development between the observations of the first week and the 4th week after the application of the decomposer. Changes in texture and color can serve as markers of compost maturity. According to Xu *et al*. (2025), particle size and color/texture changes in compost have a substantial impact on the humification process and the role of organic matter in humus production. During the composting process, the color darkens and other physical property measures are significantly connected with increasing compost maturity and humification, indicating increased microbial activity and improved nutrient retention in the final product (Xie *et al*., 2025).

During the initial phase (first week), the control, *T. harzianum* and *P. ostreatus* treatments exhibited early signs of mycelial growth, whereas Mikrobat treatments to *T. harzianum*+*P. ostreatus*+Mikrobat treatments had already achieved approximately 50% colonization of the substrate. After 30 days, distinct differences in mycelial development were observed among the treatments. Mycelial growth in *T. harzianum* and *P. ostreatus* treatments progressed to around 50% substrate coverage, while Mikrobat and *T. harzianum*+*P. ostreatus* treatments showed minimal further development. Notably, *T. harzianum*+Mikrobat treatment exhibited nearly complete mycelial colonization of the cocoa pod waste, indicating strong fungal activity. In contrast, *T. harzianum*+ *P. ostreatus*+Mikrobat treatments showed no further mycelial growth beyond the first week. In addition to biological parameters (mycelium growth), physicochemical aspects such as color, aroma and texture are also important indicators of the success of the composting process. According to Bernal *et al*. (2017), color changes in compost occur due to oxidation reactions during the transformation of organic matter into inorganic compounds and the formation of humus. This was observed in *P. ostreatus*, *T. harzianum*+Mikrobat and *T. harzianum* +*P. ostreatus*+Mikrobat treatments containing the microorganism *Pleurotus ostreatus*, where the yellowish-white mycelium oxidized to blackish and brownish characteristics that were considered as indicators of mature compost. According to Setyaningsih *et al*. (2017), compost that appears blackish-brown is typically associated with a relatively high moisture content, whereas a lighter color indicates lower water content.

In terms of texture, *T. harzianum*+*P. ostreatus* treatment showed optimal development with a softness level of 71-100%, indicating almost perfect material decomposition. The *T. harzianum*, *P. ostreatus*, Mikrobat and *T. harzianum* +Mikrobat treatments were in the range of 36-70% softness, indicating an intermediate decomposition stage. This finding is consistent with the statement of Syukur *et al*. (2006), who noted that compost maturity is directly proportional to the reduction in particle size. Similarly, recent studies also emphasize that color and texture are reliable indicators of compost maturity, where darker color and finer particle size reflect higher humification and microbial activity (Bernal *et al.,* 2017; Witasari *et al*., 2022).

As organic matter decomposes, complex lignocellulosic compounds are gradually broken down into simpler forms, which increases the softness and reduces particle size, while microbial biomass contributes to the dark coloration through the formation of stable humic substances (Gabhane *et al*., 2020; Tandy *et al*., 2022). Therefore, the observed increase in softness and darkening in *T. harzianum* + *P. ostreatus* treatment can be considered

Table 2: Visual qualities of CPH compost (color, texture and odor) at the end of the composting process.

Treatment	Parameters observed 1 week after application				Parameters observed 3 weeks after application			
	Growth	Color	Odor	Texture	Growth	Color	Odor	Texture
Control	+	Brownish	Fragrant	x	+	Brownish	Fragrant	x
T. harzianum	+	Black	Fragrant	xx	+	Black	Fragrant	xxx
P. ostreatus	+	White	Fragrant	xx	++	Black	Fragrant	xxx
Mikrobat	++	Brownish	Fragrant	xxx	++	Brownish	Fragrant	xxx
T. harzianum + *P. ostreatus*	++	Black	Fragrant	xxxx	++	Black	Fragrant	xxxx
T. harzianum + Mikrobat	++	White	Fragrant	xx	+++	Brownish	Fragrant	xx
T. harzianum + *P. ostreatus* + Mikrobat	++	Black	Fragrant	x	-	Black	Fragrant	xxx

Description: (-) no mycelium growth and no color change; (+) mycelium has formed but is still small in the baglog section; (++) mycelium has formed half in the baglog section; (+++) mycelium has formed almost covering the entire baglog; (x) Hard; (xx) Soft texture 1%-35%; (xxx) Soft texture 36%-70%; (xxxx) Soft texture 71%-100%.

a sign of advanced compost stabilization and readiness for agronomic use. The analysis revealed significant differences in compost weight loss among the biodecomposer treatments (Fig 1). The control and *T. harzianum* + Mikrobat treatment exhibited the highest percentage of weight loss, suggesting intense microbial activity in breaking down organic matter. This aligns with findings by Witasari *et al*. (2022), who stated that high mass loss reflects the efficiency of organic matter mineralization into volatile compounds during composting. Similarly, Rahman *et al*. (2023) reported that vigorous microbial metabolism accelerates carbon loss as CO_2 and water vapor, leading to greater weight reduction.

However, interestingly, treatments with lower weight loss, such as *T. harzianum* alone, *P. ostreatus* alone, Mikrobat, *T. harzianum*+*P. ostreatus* and *T. harzianum* +*P. ostreatus*+Mikrobat treatments demonstrated a more efficient composting mechanism. In these treatments, organic matter was not only decomposed but also more effectively converted into microbial biomass and stable humic substances, thereby retaining greater mass and nutrient content in the final compost product. This is supported by Zhao *et al*. (2021) and Sari *et al*. (2024), who found that the incorporation of lignocellulolytic fungi can enhance humification, stabilize organic carbon and reduce excessive mass loss, ultimately improving compost quality and nutrient retention.

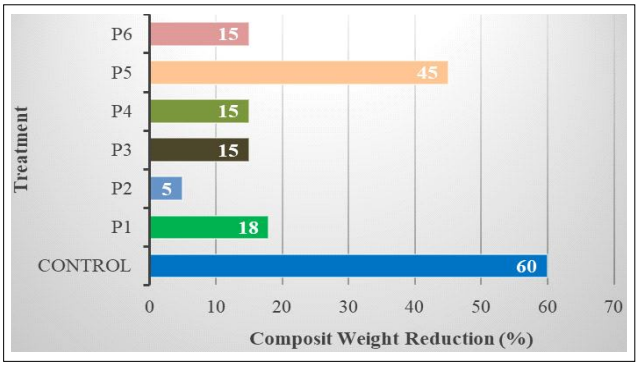


Fig 1: The percentage of compost weight reduction impacted by various decomposer treatments.

Micro and macro nutrient content

Based on the data in Table 3, there are significant variations in the chemical properties of compost resulting from various bio-decomposer treatments. The C-organic content ranged from 14.38 to 17.90%, with the highest value observed in the combination of *Trichoderma harzianum* and Mikrobat (17.90%). This indicates the effectiveness of this combination in maintaining and stabilizing organic matter during the decomposition process. The role of *T. harzianum* in accelerating the degradation of lignocellulosic material has been reported to enhance organic matter stabilization and humus formation (Shanmugaiah *et al*., 2023). Similarly, the addition of biofertilizer consortia is known to support microbial activity and improve compost organic carbon content (Saputra *et al.,* 2024). Microbial activity is critical for nutrient recovery during composting. This is consistent with Wang *et al*. (2025) research findings, which showed that aeration and microbial treatment may maintain organic carbon levels while increasing total nitrogen, phosphate and potassium in compost compared to the control. According to Zhou *et al*. (2025), the inclusion of lignocellulolytic inoculants greatly improved compost maturity by lowering the C/N ratio and boosting total N, total P and total K in the finished compost.

In terms of nitrogen, the highest total N content (1.01%) was found in the treatments with *T. harzianum* alone and its combination with Mikrobat, which far exceeded the SNI 19-7030-2004 minimum standard of 0.40%. The increase in nitrogen content is associated with microbial-mediated protein mineralization, where complex proteins are transformed into amino acids, ammonium and subsequently nitrates (Hastuti *et al*., 2017; Kumar *et al*., 2022). In contrast, *Pleurotus ostreatus* exhibited the lowest nitrogen content (0.55%), which may be due to its preferential utilization of nitrogen during lignin degradation, yet it still met the compost quality standards (Rahman *et al*., 2023b).

Another crucial parameter is the C/N ratio, which varied between 16 and 27 across treatments. The *T. harzianum* treatment recorded the lowest ratio (16), indicating optimal compost maturity. According to Mawar *et al*. (2022), compost maturity is achieved when the C/N ratio is below 20,

Table 3: Effects of various decomposer treatments on the chemical characteristics of CPH compost.

Treatment	Chemical properties of compost				
	C-Organic	N Total	C/N	P	K
Control	14.38^{ab}	0.75^{bc}	19^{a}	0.24^{a}	0.35^{ab}
T. harzianum	15.98^{ab}	1.01^{c}	16^{b}	0.49^{b}	0.29^{a}
P. ostreatus	14.93^{ab}	0.55^{a}	27^{a}	0.38^{b}	0.55^{cd}
Mikrobat	16.49^{ab}	0.87^{bc}	19^{a}	0.64^{c}	0.67^{d}
T. harzianum + *P. ostreatus*	15.89^{ab}	0.94^{c}	17^{a}	1.05^{d}	0.48^{bc}
T. harzianum + Mikrobat	17.90^{b}	1.01^{c}	18^{a}	0.71^{c}	0.82^{e}
T. harzianum + *P. ostreatus* + Mikrobat	15.68^{ab}	0.85^{bc}	18^{a}	1.08^{d}	0.66^{d}

Source: Processed data, 2025.

as lower values reflect sufficient organic carbon decomposition relative to nitrogen content. A low C/N ratio is desirable as it promotes microbial efficiency and nutrient mineralization (Gao *et al.,* 2024). Conversely, the high ratio observed in the *P. ostreatus* treatment suggests slower decomposition, possibly linked to its primary role as a lignin degrader rather than a nitrogen fixer (Khan *et al.,* 2024).

Phosphorus (P) content also varied considerably among treatments, ranging from 0.24 to 1.08%, all exceeding the SNI minimum standard (0.10%). The highest P content (1.08%) was recorded in the combined treatment of *T. harzianum*, *P. ostreatus* and Mikrobat. The increase in phosphorus availability has been attributed to microbial solubilization of inorganic phosphate through the production of organic acids and phosphatase enzymes (Du *et al.,* 2021; Marra *et al*., 2023). This suggests that the synergistic activity of multiple decomposer species enhances the release of P from organic matter and mineral sources during composting.

Potassium (K) content ranged from 0.29 to 0.82%, with all treatments exceeding the SNI standard (0.20%). The highest value (0.82%) was found in the combination of *T. harzianum* and Mikrobat. The release of potassium during composting is facilitated by the formation of humic and fulvic acids, which chelate and mobilize potassium ions, thereby increasing their availability (Ratriyanto *et al*., 2023). Additionally, microbial enzymatic activity enhances cell wall breakdown and the liberation of intracellular potassium, further contributing to K enrichment in compost (Prasetyo *et al*., 2024).

Overall, the combination of *T. harzianum* and Mikrobat demonstrated the best performance, showing optimal chemical parameters: the highest C-organic (17.90%), maximum total N (1.01%), ideal C/N ratio (~18) and the highest K (0.82%). Meanwhile, the combination of three decomposers (*T. harzianum*, *P. ostreatus* and Mikrobat) excelled in phosphorus content (1.08%). This highlights the potential of integrating multiple bio-decomposers to enhance the chemical quality of compost, thus improving its agronomic value and nutrient content for sustainable soil fertility management (Hasibuan *et al*., 2024).

Lignocellulolytic test

The results of the study indicated that the effectiveness of lignocellulose decomposition in compost was significantly affected by the formulation of the decomposer applied (Table 4). *T. harzianum* demonstrated limited efficacy in lignin degradation, as evidenced by elevated levels of crude fiber (ADF and NDF) and remaining lignin residues. Mikrobat proved to be more effective in decomposing hemicellulose, although it still left significant amounts of lignin. The combination of *T. harzianum* with *P. ostreatus* produced a balanced performance in reducing ADF, NDF and lignin levels, indicating good enzymatic synergy between the two microorganisms. Meanwhile, the combination of *T. harzianum* with Mikrobat produced high lignin levels but with low ATL values, indicating the transformation of lignin into more stable humic compounds. These findings confirm that the success of the decomposition process is not only determined by the ability to reduce lignin levels but also by the capacity of microbes to modify lignin into compounds that are beneficial for the stability and maturity of the compost. Given that cocoa shells contain relatively high levels of lignin (18.6%) and cellulose (13.7%), each biodecomposer treatment encounters specific challenges in degrading this material. The study (Djali *et al*., 2021) further noted that most *Trichoderma* species produce polyphenol oxidase enzymes involved in the lignin degradation process, although their effectiveness remains limited.

The decomposition of lignocellulosic materials during composting is a complex process influenced by microbial communities and their enzymatic activities. Recent studies have shown that combinations of microorganisms, such as *Trichoderma harzianum* and *Phanerochaete chrysosporium*, can synergistically degrade lignin and enhance humification, resulting in more mature compost products (Muteab *et al*., 2025; Zhai *et al*., 2025). White-rot fungi like *Pleurotus ostreatus* are especially effective in breaking down lignin and cellulose due to their ligninolytic enzymes, including laccase and lignin peroxidase, which improve the overall composting process and increase the nutritive value of the final compost (Yu *et al*., 2024; Olagunju *et al*., 2023). Microbial inoculation with targeted agents has also been demonstrated to accelerate lignocellulose degradation and improve compost quality by enhancing microbial diversity and enzymatic activity. For example, two-stage inoculation of lignocellulose-degrading microbes can enhance the decomposition of cattle manure and bagasse, optimizing both nutrient release and compost maturity (Zhang *et al*., 2025). The addition of biochar along with microbial agents has been reported to further optimize microbial community dynamics and promote efficient

Table 4: Effects of decomposer treatments on the lignocellulosic components (Cellulose, hemicellulose and lignin) of CPH compost.

Treatment	NDF	ADF	Cellulose	Hemicellulose	Lignin	ATL
T. harzianum	66.86	59.27	35.67	7.59	23.67	26.73
Microbat	62.93	48.47	25.26	14.46	23.21	24.70
T. harzianum + *P. ostreatus*	65.84	56.22	31.38	9.62	24.84	24.84
T. harzianum + *Microbat*	63.21	57.27	27.76	5.94	29.51	18.64
Control	61.90	49.83	29.70	26.68	23.15	17.35

Source: Processed data, 2025.

degradation of lignocellulosic substrates (Li *et al*., 2024; Yang *et al*., 2023).

Environmental factors, particularly temperature and moisture, significantly influence the degradation process. Optimal temperature conditions enhance microbial activity and lignocellulose breakdown, while microbial community succession determines which species dominate at various composting stages, affecting the rate and efficiency of lignocellulose decomposition (Wang *et al.,* 2025; Martín *et al*., 2023). Cocoa shells, a byproduct of cocoa processing, present specific challenges due to their high lignin and cellulose content. Studies have shown that using specialized microbial inoculants and optimized composting techniques can significantly enhance the degradation of lignocellulosic components in cocoa shells, producing high-quality compost suitable for agricultural use (Arini *et al*., 2021; Djali *et al*., 2021; Sánchez *et al*., 2023).

Overall, these findings indicate that the success of lignocellulose decomposition in compost is not determined solely by the reduction of lignin content but also by the microorganisms' ability to transform lignin into stable, beneficial compounds. The utilization of bio-decomposers based on *Trichoderma harzianum, Pleurotus ostreatus* and microbial consortia is critical for optimizing the composting process of CPH waste. The temperature dynamics and changes in the physical features of the compost show that the effectiveness of decomposition is determined by the kind and combination of decomposers used. As a result, this strategy has the potential to be a long-term solution for agricultural waste management while simultaneously promoting the use of high-quality organic fertilizer in ecologically friendly farming systems.

CONCLUSION

This study shows that applying bio-decomposers significantly improved the composting of CPH. Treatments with *Trichoderma harzianum*, *Pleurotus ostreatus* and Mikrobat enhanced temperature dynamics, mycelial growth and physical changes, indicating faster decomposition and compost maturity. The combination of *T. harzianum* and Mikrobat produced the best overall chemical quality (high C-organic, N, K and ideal C/N), while the triple combination achieved the highest phosphorus content. Lignocellulolytic analysis revealed that combining *T. harzianum* and *P. ostreatus* effectively degraded fiber and lignin, while *T. harzianum* + Mikrobat promoted lignin transformation into stable humic compounds. Overall, integrating these decomposers accelerates lignocellulose breakdown, enhances nutrient content and produces high-quality compost, offering a sustainable solution for utilizing cocoa shell waste.

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Disclaimers

This research was conducted for academic and scientific purposes and the results obtained are dependent on the condition of the materials, the environment and the methods used; thus, the application of the research results in the field must be tailored to local conditions and carried out with appropriate technical considerations.

Informed consent

Not available.

Conflict of interest

The authors state that there are no conflicts of interest related to the publication of this work.

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