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The Utilization of Cocoa Pod Husk-Based Compost Inoculated with Arbuscular Mycorrhizal Fungi on Soil Chemical Properties and Nutrient Uptake of Coffee Plants

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Abstract

Sustainable waste management and the preservation of soil health represent critical challenges in intensive coffee and cocoa plantation. Composting offers an effective approach for sustainable waste management by enhancing soil health, while arbuscular mycorrhizal fungi (AMF) optimize nutrient uptake (NU) efficiency in coffee plants. This research aimed to investigate the effect of cocoa pod husk-based compost inoculated with AMF on soil chemical properties and NU in coffee plants. This research employed a completely randomized design with two factors. Factor I consisted of three compost doses: K0 (no compost), K1 (15% compost, w/w), and K2 (30% compost, w/w). Factor II comprised three levels of AMF: F0 (no AMF), F1 (15 g polybag^{-1}), and F2 (30 g polybag^{-1}). Compost application significantly enhanced soil nutrient levels of N, P, K, C-organic, and CEC, as well as improved the uptake of N, P, and K by coffee plants. Similarly, AMF significantly increased soil P levels and P uptake by coffee plants. The combined application of compost and AMF further contributed to an increase in soil P availability. The K1F1 treatment (15% compost and 15 g AMF polybag^{-1}) was the most effective in optimizing nutrient turnover, as indicated by the highest uptake of N (33.48 g plant^{-1}) and P (1.37 g plant^{-1}), which contributed to enhance plant performance. According to nutrient availability classification, this treatment supplied sufficient soil N (0.36%) and soil organic C (SOC) (2.54%). However, excessive N and SOC induces antagonistic interactions, compromising the efficient uptake of P and K, while deficiencies constrain overall nutrient acquisition.

Keywords: Compost, arbuscular mycorrhizal fungi, soil

INTRODUCTION

Intensive cocoa cultivation produces large quantities of residual agricultural biomass. Cocoa pod husks (CPH) are one of the remaining biomass from cocoa plantations. During the initial processing of cocoa, 70-80% of the fresh fruit is biomass residue, including CPH (Porto de Souza Vandenberghe *et al.*, 2022). Wise management of this huge quantity of waste must be considered, in order to achieve a sustainable agricultural system which is one of the 2030 Sustainable Development Goals (SDGs) agenda.

The simplest use of CPH waste is as compost (Lü *et al.*, 2018) to increase soil organic matter (Damanik *et al.*, 2013). Returning nutrients in the form of organic material as a soil amandement is a step towards sustainable use of agricultural waste by paying attention to economic and environmental values (Poulsen *et al.*, 2013). Apart from improving the chemical properties of the soil, CPH-based compost also contributes to changes in the physical properties of the soil in the form of increasing the availability of soil water content and biological properties in the form of increasing the activity of microorganisms (Oswaldo *et al.*, 2022). However, these supportive soil conditions can be utilized optimally by plants with the assistance of soil microorganisms that can increase the effectiveness of nutrient absorption, one of which is fungi with external mycelium.

Utilization of Arbuscular Mycorrhizal Fungi (AMF) is an effective organic step to increase the productivity of cultivated plants (Koda *et al.*, 2018). Arbuscular mycorrhizal fungi are soil microorganisms that form a mutualistic symbiosis with vascular plants, where the plants provide substrate energy through photoassimilates for AMF, while AMF use their external mycelium to capture nutrients and transfer them to the main plant (Gomes Júnior *et al.*, 2018). Plant roots infected with AMF have a superior ability to absorb macro and micro nutrients (Yunedi & Perdana, 2023), accelerate the mineralization process of organic matter, and reduce mobilization of P and Zn nutrients, thereby increasing soil fertility (Gomes Júnior *et al.*, 2018). Therefore, the use of compost made from CPH inoculated with AMF is considered effective as an organic fertilizer.

Basically, many organic fertilizers have been produced on the market, but their effectiveness has not been optimized by utilizing fungi and the nutrient content in them, which should still be improved. The nutrient content of organic fertilizers on the market is around 15% C-organic, 15–25 C:N ratio, and 4% N+ P_2O_5+K_2O. Meanwhile, the nutrient content of CPH-based compost reaches 33.71% C-organic, 30 C:N ratio, and 7% N+P_2O_5 +K_2O (Away, 2004). Therefore, CPH-based compost inoculated with AMF is expected to be able to become a more optimal organic fertilizer in improving soil and plant health.

The application of CPH-based compost as an organic material inoculated with AMF can be applied to seedlings and adult plants in the field. However, the seeding period is one of the factors that determines the success of cultivation. This is due to the limited availability of quality planting media and nematode attacks are a threat at the seedling stage, especially for coffee plants. One of the obstacles in breeding is the lack of availability of nutrients in the planting media used (Riyanto *et al.*, 2023). In addition, AMF inoculation will produce plants that are resistant to various soil pathogens (Djenatou *et al.*, 2020).

Therefore, the use of compost made from CPH inoculated with AMF is considered to be an alternative solution in handling cocoa waste, providing quality planting media, and preventing nematode infection attacks. However, its effectiveness still needs to be studied further. Therefore, it is important to conduct research on the effect of CPH-based compost with AMF inoculation as a mixture of planting media on soil nutrients and nutrient uptake of coffee plant seeds (*Coffea* sp.).

MATERIALS AND METHODS

Research Location and Time Description

This research was carried out at Experimental Field of 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 °C and relative humidity of 75–90%. The annual rainfall of study sites is 2,114 mm/year with 4 dry months; therefore, the climate type of research location is type D (moderate) based on the classification of Schmidt-Ferguson.

This research had been conducted for five months, starting from February to July

2024. The research began with the preparation of composting materials, the composting process, analysis of the quality and success rate of the composting process carried out, application of compost and FMA to coffee plants, and analysis the soil and plant performance.

Experimental Design and Statistical Analysis

The experiment was consist of two factors, as follows: (1) Compost (K): without compost (K0), 15% compost (K1), 30% compost (K2); and (2) FMA (F): without FMA (F0), FMA 6 g polybag^{-1} (F1), FMA 12 g polybag^{-1} (F2).

The research was analyzed using a factorial Completely Randomized Design (CRD). The combination of these two factors had 9 treatment combinations which were repeated 3 times, there were 27 experimental units in total. Each experimental unit had three plants, so there were 81 polybags in total. Observation data was analyzed using three-ways ANOVA at a significance level of 5%. If the results are significant, they will be tested further using the Duncan Multiple Range Test (DMRT) at a significance level of 5%. Correlation test also carried out to determine the relationship between the three variables.

Materials and Tools

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

Compost Making Process

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 paralon (pvc) pipe placed in the middle of the compost pile to be made. The CPH sprayed by insecticide before composting process. Insecticide (active ingredient: cypermethrin 50 g/L) was applied in 2 L of solution with a concentration of 4 ml/L.

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. The 250 kg 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 (comparison 1 g *Trichoderma* and for 1 kg of compost material).

The second and third layers of compost to be made consist of 60 kg of CPH, 90 g *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 week. 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. The compost temperature is measured every day. The composting process lasts for 55 days.

Analysis of compost nutrient content

Compost nutrient content analysis consists of initial analysis of the material, weekly and at the end of the composting process. Initial material analysis consists of analysis of N, P, K, Ca, Mg, S, B, C-organic content, C:N ratio, CEC, and pH. Weekly analysis consists of analysis of N content, C-organic, C:N ratio, pH, and water content. The final analysis consists of analysis of N, P, K, Ca, Mg, S, B, C-organic content, C:N ratio, CEC, and pH. Compost nutrient content analysis was carried out to determine the quality of the CPH-based compost that has been produced.

Inoculation of AMF

The AMF used was consist of *Gigaspora margarita*, *Acaulospora tuberculate, Acaulospora scrobiculata,* and *Colombian acaulospora* inoculated in a mixture of sterilized sand and vermiculite media as a carrier medium.

Treatment application to coffee plant seeds

The treatment application is carried out on the coffee plant in the early stage, inside 30×40 cm polybag. The planting medium used in each treatment is the soil that is given inorganic fertilizer in accordance with the recommended dose used in the Kaliwining Experimental Field. The control treatment still receives additional livestock dung in accordance with the treatment carried out at the Kaliwining Experimental Field, but the other treatments adhere the experimental plan. The treatment is implemented on a hole made next to the coffee plant.

Soil analysis

Soil analysis will be carried out two times, consisting of an initial soil analysis and a final soil analysis. The initial soil analysis is carried out to determine the initial nutrient content of the soil to be used, while the final soil analysis is to determine the effectiveness of the treatment given to increase soil nutrition. Soil analysis consists of analysis of N, P, K, Ca, Mg, S, B, C-organic content, C:N ratio, CEC, and pH.

Analysis of coffee plant performance

Analysis of the performance of coffee plant seeds was carried out during the growth period and also at the final stage of the research. During the growth period, observations were made regarding the height of the coffee plant seeds, the number of shoots, and the number of leaves. At the end of the research period, plant performance observations were made in the form of plant height, number of shoots, number of leaves, root weight and dry weight of plant biomass.

Analysis of nutrient uptake of coffee plant

Analysis of coffee plant nutrient uptake was carried out to determine the ability of coffee plant seeds to absorb the nutrients provided by the given treatment, especially to determine the effectiveness of AMF capabilities. Nutrient analysis of coffee plants was carried out at the final stage of the research. Plant nutrient analysis consists of N, P, K, Ca, Mg, and S.

RESULTS AND DISCUSSION

1. Composting Phases

Based on the daily temperature observations (Figure 1), the composting process followed the typical thermal progression described in composting theory. Specifically, the decomposition of cocoa pod husks proceeded through a series of well-defined stages—mesophilic, thermophilic, cooling, and maturation—each

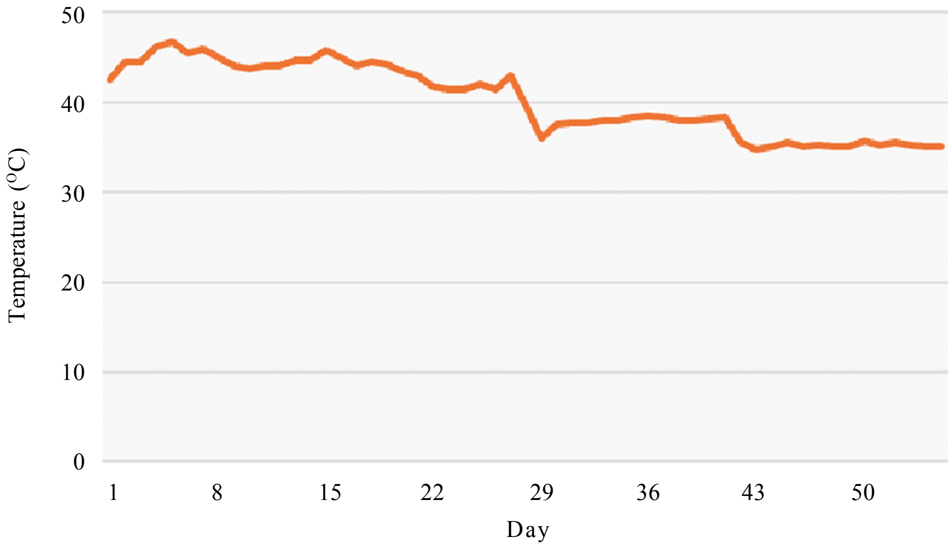

Figure 1. Temperatur changes during composting process

characterized by distinct microbial communities adapted to specific temperature ranges and environmental conditions.

The initial phase of composting is the mesophilic stage (days 1–7), when the tempe-rature rapidly increased, peaking above 45 °C. This initial rise reflects the onset of microbial activity, particularly the metabolism of easily degradable substrates such as simple carbohydrates and proteins.

Between days 8 and 22, the temperature remained relatively stable within the thermophilic range (40–45 °C), suggesting sustained microbial activity and effective degradation of more resistant organic compounds like cellulose and hemicellulose.

A sudden drop in temperature was observed around day 23, marking the transition from the thermophilic back to the mesophilic phase, signaling the start of the cooling phase. This shift likely corresponds to the depletion of readily available nutrients and the succession of microbial populations.

From day 24 onwards, the temperature stabilized around 35–38 °C, entering the maturation phases. A smaller drop near day 36 further confirms the compost's progression toward stabilization. From days 40 to 55, exhibited a consistent temperature range close to ambient mesophilic levels (approximately 33–36 °C), indicating reduced microbial activity and the approach of compost maturity.

Overall, the temperature dynamics observed confirm that the cocoa pod husk underwent a complete composting cycle, including active degradation and stabilization, which is essential for producing mature and phytotoxin-free compost. The observed thermal profile aligns with standard composting benchmarks, demonstrating that cocoa pod husk is a suitable substrate for aerobic composting processes.

2. Produced Compost Quality

Table 1 demonstrete the comparison of the physicochemical properties of the produced compost, the raw cocoa pod husk (CPH) material, and the technical standards set by the Indonesian Ministry of Agriculture.

The comparison between raw cocoa pod husk (CPH), established technical standards, and the final compost product demonstrates a substantial improvement in nutrient content and compost maturity, affirming the effectiveness of the composting process. The compost produced not only meets but surpasses the established technical standards for organic fertilizers in terms of nutrient content and C-organic, while C:N ratio and pH value also falls within the acceptable reference range. Moreover, it represents a substantial upgrade over the raw CPH material, proving its potential as a high-quality organic amendment for sustainable agriculture.

3. The Influence of CPH-Based Compost and AMF on Soil Chemical Properties

Table 2 illustrates the effects of varying doses of compost derived from cocoa pod husk (CPH) and inoculation with arbuscular mycorrhizal fungi (AMF) on several chemical properties of the soil. The data show significant improvements in key soil fertility parameters, with notable interactions between compost and AMF treatments.

Soil nitrogen content (%)

Soil nitrogen content showed a marked increase with higher compost doses. A significant increase in soil nitrogen content was observed at the 30% compost dose (0.58%), which was significantly higher than the 0% and 15% compost levels. This suggests that compost application at higher doses contributes substantially to improving nitrogen availability. However, no significant effect of AMF and its interaction were observed on nitrogen levels.

The application of CPH compost has been found to enhance soil nitrogen levels. Kayode and Adeoye (2021) reported that CPH-based compost produced a higher buildup of total nitrogen compared to control treatments, demonstrating its potential as a nutrient source in the soil (Kayode & Adeoye, 2021). Ayeni *et al.* (2024) also noted that organic amendments like CPH can significantly influence nutrient uptake and soil properties, ensuring adequate N levels for plant growth (Ayeni *et al.*, 2024).

Soil phosphorus content (ppm)

Soil phosphorus content was significantly influenced by compost, AMF, and its interaction. The 30% compost dose resulted in the highest phosphorus level (1003.6 ppm), significantly greater than the 0% and 15% treatments. The 6 g polybag^{-1} dose yielded the highest phosphorus concentration (819.3 ppm), which was significantly higher than the 0 g dose. The combination of 30% compost with 6 g AMF per polybag yielded the highest phosphorus concentration (1075.7 ppm), significantly greater than other treatments. This demonstrates a synergistic effect, where organic matter serves as a substrate for microbial activity and AMF enhances nutrient solubilization and uptake.

CPH compost has been demonstrated to increase soil available P effectively. Research by Dogbatse *et al.* highlighted that CPH compost improved plant growth and boosted phosphorus availability in the soil compared to other organic treatments (Dogbatse *et al.*, 2019). These improvements are crucial because

Table 1. Comparison of chemical properties of the produced compost, CPH raw material, and technical standards

Material quality	N (%)	P (%)	K (%)	N+P+K (%)	C:N ratio	C-organic	pH
Cocoa pod husk (CPH)	1.58	0.15	0.4	2.13	28	44.19	8.54
Technical standard*		Min. 2		2.00	<25	Min. 15.00	4-9
Compost produced	↑ 2.55	↑ 2.50	↑ 2.95	↑ 8.00	✓ 14	↑ 36.37	✓ 8.78

Notes: The asterisk (*) indicates the standard established by the Indonesian Ministry of Agriculture (Decree No. 261/KPTS/SR.310/M/4/2019). The term "increased" refers to values exceeding the reference standard, while "compliant" denotes conformity within the reference range.

Table 2. The effect of CPH-based compost inoculated with AMF on soil chemical characteristics

CPH-basedcompost dose (%)	AMF dose (g)			Average
	0	6	12	
Nitrogen (%)				
0				0.38 b
15				0.35 b
30				0.58 a
Average	0.45	0.44	0.42	
Phosphorus (ppm)				
0				762.86 b
15				521.42 c
30				1003.6 a
Average	694 b	819.3 a	774.6 ab	
Potassium (cmol(+)/kg)				
0				3.74 b
15				4.27 b
30				9.46 a
Average	5.93	5.79	5.77	
C-organic (%)				
0				2.65 b
15				2.48 b
30				4.31 a
Average	3.16	3.30	2.98	
CEC (cmol(+)/kg)				
0				28.1 c
15				30.3 b
30				32.4 a
Average	29.7	29.6	31.4	

Note: Numbers followed by the same letter in the same column are not significantly different according to the DMRT test at the 5% level.

phosphorus is vital for plant energy transfer and root development.

The symbiotic relationship between coffee plant roots and AMF plays a significant role in nutrient acquisition and soil stabilization. AMF colonize the root system and extend their hyphal networks into the surrounding soil, effectively increasing the absorptive surface area for water and nutrient uptake, particularly in nutrient-poor or phosphorus-fixing soil (Ait-El-Mokhtar *et al*., 2020). This symbiosis is known to facilitate the slow release of nutrients from organic amendments, which in turn supports a sustained release of nutrients to the host plant (Ait-El-Mokhtar *et al*., 2020).

Futhrermore, the combination of 30% compost with 6 g AMF per polybag resulted the highest phosphorus concentration. Its due to the elevated soil phosphorus in the treatment of 30% compost. In nutrient-enriched soils, particularly where P is abundant, the symbiotic relationship between AMF and plant roots can diminish. Studies indicate that as available soil phosphorus increases, the extent of AMF colonization can decrease significantly due to reduced necessity for plants to rely on these fungi for P uptake (Ceulemans *et al*., 2019; Ma *et al*., 2025).

This dual approach between CPH-based compost and AMF, therefore, holds promise as a cost-effective and sustainable alternative to chemical fertilizers, especially in tropical regions where soil fertility is often constrained by high phosphorus fixation and low organic matter content (Medina & Azcón, 2010).

Soil potassium content (cmol(+)/kg)

Soil potassium content was significantly increased by compost application, with the 30% compost level showing the highest potassium concentration (average 9.46 cmol(+)/kg), significantly different from the 0% and 15% compost treatments. AMF application and its interaction with compost did not cause a statistically significant difference.

Potassium levels in the soil benefit from the application of CPH compost. The work by Koné *et al.* emphasized that CPH, rich in potassium, can be effectively utilized to enhance the mineral nutrition of cocoa plants, thereby addressing potassium depletion in soils (Koné *et al.*, 2020). Lü *et al.* indicated that CPH serves as an organic fertilizer that replenishes soil nutrients, including potassium, which is vital for crops (Lü *et al.*, 2018).

C-organic (%)

C-organic content was positively correlated with increasing compost doses. A significant increase in organic carbon content was observed with the 30% compost treatment (4.31%), which was significantly higher than the 0% and 15% treatments. This highlights the positive role of compost in improving soil organic matter status. AMF and its interaction; however, did not significantly affect organic carbon levels.

Organic carbon content in soils is also significantly affected by CPH compost based on several fundings. Research by Ogunlade and Orisajo documented that the incorporation of CPH into soils leads to increased organic matter, crucial for improving soil structure and stability (Ogunlade & Orisajo, 2020). The higher organic carbon content improves various soil properties, including water retention and microbial activity, although a direct reference validating this claim could not be found (Adeleye *et al.*, 2021).

Cation Exchange Capacity (CEC)

Cation Exchange Capacity (CEC) followed a similar trend, increasing significantly with compost dose. The 30% compost treatment produced the highest CEC (average 32.4 cmol(+)/kg), which was significantly greater than the 0% and 15% compost levels. AMF and its interaction; however, did not significantly affect organic carbon levels.

The cation exchange capacity (CEC) of the soil is positively influenced by the application of CPH compost. Studies, including those by Vitinaqailevu and Rao, highlight that organic amendments, including CPH compost, enhance soil CEC, thus promoting better nutrient retention (Vitinaqailevu & Rao, 2019).

The overall results through soil chemical properties demonstrate that CPH-based compost, particularly at 30% dose, significantly improves soil chemical properties, including N, P, K, organic carbon, and CEC. AMF inoculation further enhances phosphorus availability, particularly at moderate doses (6 g), but has limited influence on other soil chemical parameters. These findings support the integrated use of compost and AMF as a sustainable strategy to restore soil fertility and promote nutrient retention.

4. The Influence of CPH-Based Compost and AMF on Nutrient Uptake

Table 3 illustrates the effects of cocoa pod husk (CPH)-based compost inoculated with varying doses of arbuscular mycorrhizal fungi (AMF) on the uptake of essential macronutrients—namely nitrogen (N), phosphorus (P), and potassium (K)—by coffee plants.

Nitrogen uptake (%)

Nitrogen uptake in coffee plants was significantly influenced by the compost dose. On average, 15% compost resulted in significantly greater nitrogen uptake (29.1%) than 30% (15.8%). This suggests that moderate levels of organic input optimize nitrogen mineralization and uptake, while higher doses may lead to reduced availability. AMF alone and its interaction; however, did not significantly affect nitrogen uptake.

CPH compost has been shown to enhance total nitrogen and soil organic carbon initially; however, excessive applications can lead to nutrient imbalances. Kayode & Adeoye reported that CPH-based compost enriched total nitrogen and soil organic constituents but cautioned that excessive addition could inhibit nutrient accessibility due to potential over-saturation of the soil with organic matter, affecting microbial dynamics and nutrient release patterns (Kayode & Adeoye, 2021b).

In addition, vegetation competition plays a significant role. When CPH is applied in excessive amounts, it may induce nutrient immobilization, leading to an increased carbon-to-nitrogen ratio in the soil. This condition could limit the effectiveness of microbial decomposition of organic matter necessary for N and P mineralization (Setyowati *et al*., 2024). Studies have indicated that appropriate quantities of compost, aligning with crop needs, support microbial activity and nutrient release (Kekong, 2023), which is essential for effective nutrient uptake.

Phosphorus uptake (%)

Phosphorus uptake was significantly affected by both compost and AMF. The significant P uptake (1.07%) occurred in the 15% compost treatment comparet to 0 and 30% compost treatment. Average values indicated a significant effect of AMF as a single factor: P uptake increased from 0.58% (control) to 0.97% with 6 g AMF per polybag. These findings confirm the critical role of AMF in enhancing P acquisition, likely through hyphal extension into the soil and improved mobilization of P from organic matter.

Soil chemical property shifts can further compound issues associated with excessive CPH compost application. Research indicates that fluctuations in soil pH and changes in microbial diversity resulting from unbalanced organic inputs can hinder P solubility and availability. Enhanced microbial activity under moderate CPH application has been shown to correlate positively with improved phosphorus uptake (Séry *et al*., 2024). Hence, larger compost applications could disrupt this relationship, resulting in limited bioavailable P for plant needs. Such conditions may hinder the direct availability of P during critical plant uptake periods, as suggested by Dunsin *et al*., who noted that excess organic inputs, without balance, could negatively impact the bioavailability of these nutrients to plants (Dunsin *et al*., 2018).

Table 3. The effect of CPH-based compost inoculated with AMF on nutrient uptake of coffee plants

CPH-based compost dose (%)	AMF dose (g)			Average
	0	6	12	
Nitrogen (%)				
0				22.9 ab
15				29.1 a
30				15.8 b
Average	18.8	25.7	23.3	
Phosphorus (%)				
0				0.70 b
15				1.07 a
30				0.58 b
Average	0.58 b	0.97 a	0.81 ab	
Potassium (%)				
0				9.30 c
15				11.4 b
30				15.7 a
Average	12.6	12.5	11.4	

Note: Numbers followed by the same letter in the same column are not significantly different according to the DMRT test at the 5% level.

Potassium uptake (%)

The highest K uptake (15.7%) was observed at 30% compost and increased steadily from 9.30% (0% compost). AMF alone and its interaction; however, did not significantly affect K uptake. Therefore, compost application rate becomes the dominant factor influencing potassium nutrition in this system.

While excessive CPH-based compost might reduce N and P uptake, it can enhance potassium (K) uptake by coffee plants. This effect is partly due to the high inherent K content in CPH itself, which can contribute to an increase in K concentrations in the soil (Agbotui *et al*., 2024; Mboua *et al*., 2023). CPH not only serves as a K source but can also alter soil structure and cation exchange capacity, thereby facilitating K availability even when applied in higher quantities (Mboua *et al*., 2023). Increased microbial activity from high organic matter may also encourage the mineralization of K, making it more readily available to plants despite the detrimental effects observed with other nutrients (Mboua *et al*., 2023; Setyowati *et al*., 2024).

Thus, the application rates of CPH-based compost exert a differential effect on nutrient uptake in coffee plants. Moderate applications seem to provide an optimal balance where N and P remain available while simultaneously enhancing K uptake, indicating that careful management of organic fertilizers is critical for sustainable coffee production (Jiang *et al*., 2023; Yardani *et al*., 2021).

5. The Influence of CPH-Based Compost and AMF on Plant Performance

Table 4 and Figure 2 demonstrates the effects of cocoa pod husk (CPH)-based compost and arbuscular mycorrhizal fungi (AMF) on the vegetative performance of coffee plants, specifically on plant height, leaf number, and stem diameter. The results indicate that AMF inoculation and its interaction with CPH-based compost had a significant influence on all three parameters, while compost alone did not significantly affect coffee plants performance.

Plant height (cm)

Plant height was significantly affected by AMF dose and its interaction with CPH-based compost. Inoculation with 6 g AMF per polybag resulted in the highest average plant height (18.20 cm), which was significantly greater than the 12 g AMF treatment (10.31 cm). The combination of 15% compost and 6 g AMF resulted in the highest plant height (20.42 cm).

A clear relationship was observed between the nutrient uptake (Table 3) and the resulting plant growth response (Table 4). The combination of 15% compost and 6 g AMF resulted in the highest nitrogen (33.5%) and phosphorus (1.37%) uptake, which corresponded with the highest plant height. Higher nitrogen uptake has been associated with increased height in coffee plants, linked to enhanced metabolic activity during key growth phases (Rodrigues *et al*., 2021). Additionally, adequate P levels facilitate enhanced root architecture and shoot development in coffee, which translates to plant height (Jaitieng *et al*., 2020).

Furthermore, based on the classification of nutrient availability, this treatment provided adequate levels of soil nitrogen (0.36%) and soil organic carbon (SOC) (2.54%) (Table 2) to support optimal growth of coffee plants. However, while sufficient N and SOC are essential for plant development, their excessive presence may lead to antagonistic interactions that hinder the efficient uptake of other essential nutrients, particularly phosphorus (P) and potassium (K). Conversely, nutrient deficiencies can significantly limit overall nutrient acquisition and, consequently, plant performance.

Leaf number (leaves)

Leaf number also responded significantly to AMF application and its interaction with CPH-based compost. The treatment with 6 g AMF per polybag produced the highest average leaf count (8.11 leaves), significantly greater than the 12 g AMF treatment (5.15 leaves). The combination of 15% compost and 6 g AMF resulted in the highest leaves number (8.44 leaves). No significant differences were observed among compost levels.

The highest average observed in the 6 g AMF treatment and its interaction with 15% compost, aligning with superior nitrogen and phosphorus availability as seen in Table 3. Phosphorus plays a vital role in metabolic processes within the plant, facilitating energy transfer and photosynthesis, which also reflects in leaf number and plant height (Hifnalisa *et al*., 2018). As with plant height, excessive AMF may negatively affect aboveground growth due to potential carbon drain from the host plant.

Stem diameter (cm)

Stem diameter showed significant effects from AMF treatment and its interaction with CPH-based compost as well. The largest diameter (2.46 cm) was observed in plants inoculated with 6 g AMF, while the smallest (1.53 cm) occurred with 12 g AMF. The combination of 15% compost and 6 g AMF resulted in the widest stem diameter (2.93 cm). This trend is consistent with the other growth parameters and emphasizes the importance of balanced AMF inoculation.

Stem diameter was also influenced by the nutrient dynamics. The 15% compost + 6 g AMF treatment produced the widest stems (2.93 cm), consistent with enhanced nutrient availability—particularly phosphorus, which is critical for meristem development and structural growth. Research indicates that adequate N and P fertilization promotes not only leaf expansion but also contributes to greater stem diameter, indicating robust growth (Salamanca-Jiménez *et al*., 2017). Additionally, increased P uptake has been connected with improved physiological responses in coffee plants, reinforcing growth parameters such as stem diameter (Covre *et al*., 2018).

Table 4. The effect of CPH-based compost inoculated with AMF on coffee plants performance

CPH-based compost dose (%)	AMF dose (g)			Average
	0	6	12	
Plant height (cm)				
0	15.04 a	16.60 a	8,63 b	13.42 a
15	16.63 a	20.42 a	11.56 b	16.20 a
30	16.39 a	17.58 a	10.76 b	14.91 a
Average	16.02 a	18.20 a	10.31 b	
Leaves number (leaves)				
0	6.89 a	8.33 a	3.22 b	6.15 a
15	8.17 a	8.44 a	6.22 a	7.61 a
30	7.33 a	7.56 a	6.00 a	6.96 a
Average	7.46 a	8.11 a	5.15 b	
Stem diameter (cm)				
0	2.22 b	2.14 b	1.24 c	1.87 a
15	2.34 a	2.93 a	1.68 b	2.32 a
30	2.50 a	2.31 a	1.67 b	2.16 a
Average	2.36 a	2.46 a	1.53 b	

Note: Numbers followed by the same letter in the same column are not significantly different according to the DMRT test at the 5% level.

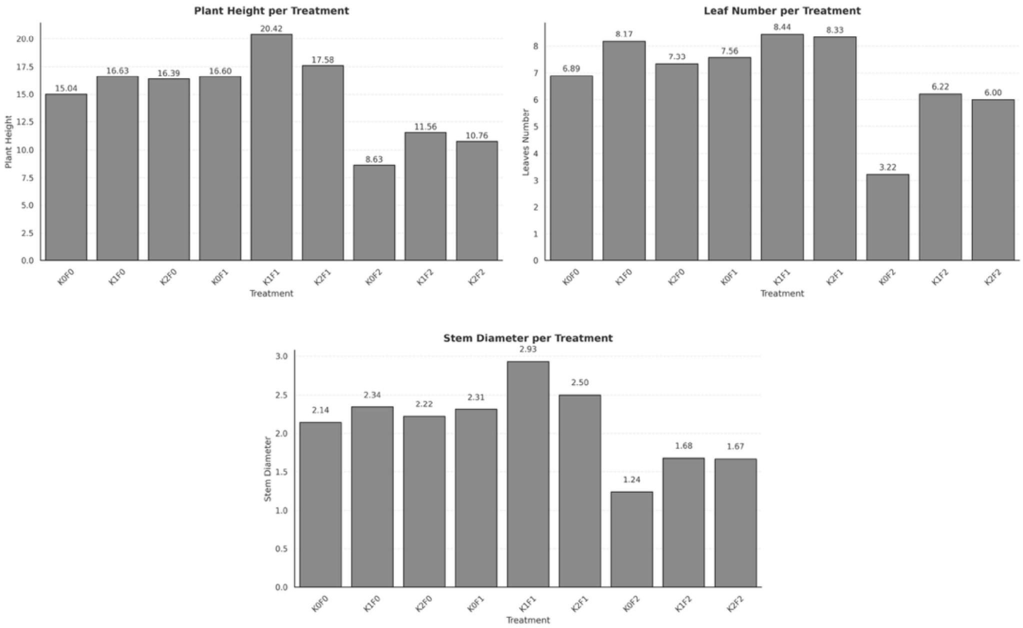

Figure 2. The effect of CPH-based compost inoculated with AMF on coffee plants performance

CONCLUSIONS

The application of compost significantly improved soil nutrient status, including nitrogen (N), phosphorus (P), potassium (K), organic carbon (C-organic), and cation exchange capacity (CEC), while also enhancing N, P, and K uptake by coffee plants. Similarly, the inoculation of arbuscular mycorrhizal fungi (AMF) resulted in a notable increase in soil P availability and P uptake. The combined application of compost and AMF further augmented soil P availability. Among the treatments, K1F1 (15% compost combined with 15 g AMF per polybag) was the most effective in optimizing nutrient cycling, as reflected by the highest N uptake (33.48 g plant^{-1}) and P uptake (1.37 g plant^{-1}). This improvement in nutrient acquisition was associated with enhanced plant growth parameters, including plant height, number of leaves, and stem diameter.

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