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Regional Case Study

Starbo-AFE Compost and Volcanic Ash Improve Coffea liberica Growth in Tropical Peat Soils

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Abstract

Coffee liberica is an economically important yet under-researched coffee species in Indonesia. This study evaluated the individual and combined effects of Starbo-AFE compost and volcanic ash on vegetative growth and physiological performance of C. liberica in Jambi, Indonesia. A two-factor factorial experiment arranged in a randomized complete block design tested three compost rates (0, 250, and 500 g plant^{-1}) and three volcanic ash rates (0, 250, and 500 g plant^{-1}) with three replications. Measured variables included leaf area, primary branch diameter, number of fruiting branches, chlorophyll content, and soil chemical properties. Starbo-AFE compost significantly increased leaf area and branch diameter ($p < 0.05$), with the highest values at 500 g plant^{-1}, increasing by 54.6% and 17.5%, respectively, compared with the control. Volcanic ash alone showed no short-term effect; however, its combination with compost resulted in the highest chlorophyll content, indicating a synergistic response. Compost improved soil total N and organic carbon, while volcanic ash enhanced potassium availability and potential pH buffering. Overall, applying 500 g Starbo-AFE compost per plant effectively promotes early vegetative growth of C. liberica on peat soils, with volcanic ash contributing to longer-term soil fertility improvement.

Keywords: Chlorophyll; Coffea liberica ; compost; peat soil; vegetative growth; volcanic ash

1. Introduction

Tambak Coffee is one of the most economically important commodities worldwide, with global production exceeding 10 million tonnes annually, supporting the livelihoods of over 125 million people (Krishnan, 2017). While *Coffea arabica* and *Coffea canephora* dominate global markets, *Coffea liberica* has gained increasing interest due to its high adaptability to marginal soils, unique flavor profile, and potential to diversify coffee production systems. However, productivity of *C. liberica* remains low, especially on tropical peatlands, which are widely cultivated in Southeast Asia. Peat soils present significant agronomic challenges due to their high acidity (pH < 4.5), low nutrient availability, high C/N ratios, and susceptibility to nutrient leaching (Idoko et al., 2025; Vroom et al., 2022).

Indonesia is one of the largest coffee producers in the world and the only major producer of *C. liberica*, with Jambi Province as a leading production center (Rosyani et al., 2019). In Tanjung Jabung

Barat, smallholder farmers cultivate *C. liberica* predominantly on peat soils. Despite its adaptability, yields remain suboptimal due to poor soil fertility, slow vegetative growth, and delayed onset of the reproductive phase. Addressing soil limitations is crucial not only for improving yields but also for sustaining the economic viability of *C. liberica* farming in rural communities. Amelioration techniques, such as the addition of organic and mineral amendments, have been shown to improve the physical and chemical properties of peat soils (Larney and Angers, 2012; Maswar et al., 2021). Organic composts can enhance nutrient content and microbial activity, while volcanic ash is rich in silica, potassium, and polyvalent cations that can neutralize acidity and improve phosphorus retention. However, most existing studies on peatland amelioration focus on food crops such as rice and maize, with very limited data on perennial plantation crops like coffee. Furthermore, the combined application of organic compost derived from oil palm empty fruit bunches inoculated with Starbo-AFE biostarter and volcanic ash has never been systematically tested for *C. liberica* under field conditions.

To date, there is no published factorial field study evaluating the synergistic effects of Starbo-AFE compost and volcanic ash on *C. liberica* growth and early productivity in peatland systems. Previous research has investigated these amendments separately or in different crops yields (Celestina et al., 2019), but their interactive effects on key growth parameters such as leaf area index, chlorophyll content, and primary branch development in *C. liberica* remain unknown. This lack of empirical evidence limits the formulation of precise, location-specific recommendations for smallholder coffee farmers managing peat soils. This study aims to evaluate the individual and combined effects of Starbo-AFE compost and volcanic ash application on the vegetative growth of *C. liberica* in peat soils of Jambi, Indonesia. We hypothesize that integrating organic and mineral ameliorants will produce complementary effects by improving nutrient availability, enhancing chlorophyll content, and accelerating canopy development, ultimately leading to improved plant vigor and earlier transition to the reproductive stage

2. Methods

2.1. Study Area and Plants

Green The The field experiment was conducted from April to October 2023 in Mekar Jaya Village, Betara Subdistrict, Tanjung Jabung Barat Regency, Jambi Province, Indonesia (01°08′S, 103°12′E; altitude: 5–8 m a.s.l.) (Figure 1). The area has a tropical humid climate, with long-term averages of 2,200–2,500 mm annual rainfall, mean daily temperatures between 21–34 °C, and relative humidity ranging from 75–90% (BMKG, 2023). Soils are classified as tropical peat (Histosol), characterized by high acidity (pH < 4.5), low bulk density, high C/N ratio, and poor nutrient availability. The site is managed by smallholder coffee farmers practicing rainfed cultivation. The experimental crop was *Coffea liberica* var. Tungkal, approximately three years old, planted at a spacing of 3 × 3 m, and not yet at the productive stage.

The study site's monthly climate conditions for 2023 are shown in **Table 1**. Maximum temperatures ranged from 33.0 °C (December) to 35.0 °C (May), while minimum temperatures remained between 21.4 °C and 23.0 °C. Maximum relative humidity was consistently high (98–100%), while minimum relative humidity varied from 49% (November) to 66% (June). Annual rainfall totaled 3,036.6 mm, with July (135.9 mm) and September (175.1 mm) representing relatively drier months, and October recording the highest rainfall (505.6 mm) across 24 rainy days.

Table 1. Environmental condition in study area according to Indonesian Meteorological, Climatological, and Geophysical Agency

Climate elements	January	February	March	April	May	June	July	August	September	October	November	December
Maximum Temperature (celcius)	33.4	33.8	34.6	34	35	33.6	34.4	34.2	34.7	34.2	34.6	33
Minimum Temperature (celcius)	22.2	21.8	21.8	21.4	23	22.6	22	21.4	22.4	22.4	22.6	22

Climate elements	January	February	March	April	May	June	July	August	September	October	November	December
Maximum humidity (%)	98	98	98	98	100	100	100	98	98	98	98	98
Minimun humidity (%)	51	55	52	56	60	66	55	50	50	54	49	59
Number of Precipitation (mm)	294.1	225.2	431.1	206.6	268.5	227.5	135.9	307.9	175.1	505.6	316.2	243.9
Number of Rainy Days (days)	20	21	23	19	17	21	19	18	18	24	19	21

While monthly averages provide a general climatic profile, short-term fluctuations such as consecutive dry or wet days can have disproportionate impacts on perennial crops like *C. liberica*. Therefore, daily climate data were also monitored throughout the experimental period. These records showed, for example, a late-August dry spell (four consecutive days with < 2 mm rainfall) that coincided with early nutrient incorporation, and a mid-October wet spell (six consecutive days > 25 mm rainfall) that could accelerate nutrient leaching from peat soils. Recognizing these events is crucial because extreme short-term conditions, rather than monthly means alone, often determine immediate plant physiological responses, such as reduced photosynthetic activity during waterlogging or leaf wilting during temporary drought.

Figure 1. Location of study

For statistical analyses, including factor analysis, we did not rely solely on monthly averages. Instead, for each climatic variable (rainfall, number of rainy days, mean daily maximum and minimum temperature, maximum and minimum relative humidity), values were aggregated at a weekly scale to preserve intra-month variability. These weekly datasets were then paired with corresponding plant growth and soil nutrient data to examine relationships more accurately. Factor analysis was conducted using (i) weekly total rainfall, (ii) weekly mean temperature, and (iii) weekly mean relative humidity as environmental variables, alongside soil chemical properties (pH, total N, total organic C, available P_2O_5, exchangeable K_2O) and plant performance indicators (leaf area, primary branch diameter, chlorophyll content). This approach ensured that extreme short-term conditions were captured in the analysis, rather than being obscured by long-term averages. By documenting both aggregated and event-based climate patterns, and by structuring the factor analysis around weekly datasets instead of seasonal means, the present study provides a more realistic interpretation of how environmental variability influenced nutrient dynamics and vegetative growth in *C. liberica* during the experimental period.

2.2. Ameliorants and Fertilizers

Two ameliorants were tested: Starbo-AFE compost: an organic amendment derived from oil palm empty fruit bunches inoculated with Trichoderma-based Starbo-AFE biostarter, produced by Universitas

Jambi (Figure 2). This compost contains approximately 1.6% N, 0.8% P_2O_5, 1.2% K_2O, 25% organic carbon, and pH 6.8. Volcanic ash: sourced from Kerinci volcanic deposits, sieved to <2 mm, containing ~52% SiO_2, 2.1% K_2O, 3.4% CaO, and 2.5% MgO, with pH 7.4. Basal chemical fertilizers were applied uniformly across treatments: urea (46% N), KCl (60% K_2O), and TSP (46% P_2O_5), at rates consistent with local recommendations (100 g urea, 50 g KCl, and 50 g TSP per plant per year).

Figure 2. Ameliorant and fertilizer

2.3. Experimental Design

A two-factor factorial experiment was arranged in a Randomized Complete Block Design (RCBD) with three replicates. Factor A: Starbo-AFE compost (A_0 = 0 g; A_1 = 250 g; A_2 = 500 g per plant) Factor B: volcanic ash (B_0 = 0 g; B_1 = 250 g; B_2 = 500 g per plant). This produced nine treatment combinations: A_0B_0, A_0B_1, A_0B_2, A_1B_0, A_1B_1, A_1B_2, A_2B_0, A_2B_1, and A_2B_2. Each plot measured 9 m^2, containing six coffee plants, with 1 m buffer spacing between plots. Two plants per plot were randomly selected for measurement, giving a total of 54 sample plants.

Prior to planting, drainage trenches approximately 40 cm deep and 30 cm wide were constructed around each experimental plot to facilitate excess water removal during peak rainfall events. This approach is commonly employed in peat-based horticultural systems to mitigate the risk of waterlogging, which can cause hypoxic stress and nutrient loss through leaching. The construction of these trenches was intended to standardize drainage conditions across all treatments, thereby minimizing variability caused by standing water and ensuring that observed differences in plant and soil parameters could be attributed primarily to the applied soil amendments. The drainage intervention was not a treatment variable but rather a controlled environmental management measure implemented uniformly for all plots.

2.4. Application of Treatments

Before treatment, the experimental site was cleared of weeds and surface litter. A drainage trench (~40 cm deep) was constructed around each plot to manage water levels typical of peat soils. Ameliorants were applied in two equal splits: the first at experiment initiation (April) and the second two months later (June). Materials were incorporated into the top 15 cm of soil within a 1 m radius from the plant base. Application of treatment can be seen in Figure 3.

Figure 3. Application of ameliorants and fertilizers

2.5. Data Collection

The following parameters were measured during the study. Leaf area (cm^2) was recorded monthly using the formula (1):

$$Leaf\ area = length \times width \times 0.75 \quad (1)$$

Leaf length and width (cm) were measured from the midpoint of fully expanded leaves on the third pair from the apex. The primary branch diameter (mm) was measured monthly using a digital caliper, taken at a distance of 5 cm from the stem junction. The number of leaves was counted monthly on selected branches. Chlorophyll content ($mg\ L^{-1}$) was determined three months after treatment using spectrophotometry, following extraction in 80% acetone. Soil properties were also assessed by collecting composite soil samples from a depth of 0–20 cm both before and after the experiment. These samples were analyzed for pH, total nitrogen (Kjeldahl method), organic carbon (Walkley–Black method), available phosphorus (HCl 25%), and exchangeable potassium (flame photometry).

Figure 4. Data collection on branch diameter

2.6. Statistical Analysis

Data were subjected to two-way ANOVA using SAS 9.4 (SAS Institute, Cary, NC, USA). Treatment means were separated using Duncan's New Multiple Range Test (DNMRT) at $\alpha = 0.05$. Orthogonal polynomial contrasts were applied to determine optimal rates of each ameliorant. Where relevant, Pearson correlation analysis was conducted between soil properties and plant growth parameters.

3. Result and Discussion

3.1. Environmental Conditions

The environmental conditions during the experimental period (August–November 2023) reflect the seasonal variability typical of Jambi Province's tropical humid climate (Figure 1). Monthly rainfall ranged from 121.83 mm in August to a peak of 336.42 mm in September, with subsequent values of 257.73 mm in October and 326.40 mm in November. Corresponding mean temperatures were relatively stable, ranging between 23°C and 25°C. This pattern suggests a transition from the drier period in August to wetter months in September and November. A previous study of various Coffea species found C. liberica var. dewevrei to have a mean annual temperature of 24.4 °C (Davis et al., 2023).

From an agronomic perspective, the recorded temperature range is well within the optimal threshold for Coffea liberica, which generally thrives between 22°C and 27°C. Such stable thermal conditions support consistent vegetative growth and physiological processes, including photosynthesis, stomatal regulation, and nutrient assimilation. Temperatures above 30°C or below 15°C can adversely affect coffee growth, leading to stress-induced reductions in leaf expansion and reproductive initiation. The relatively narrow temperature fluctuations observed in this study provided a favorable thermal environment for evaluating the effects of soil amendments without the confounding influence of temperature stress. Previous findings have shown that compost-treated soils exhibit lower sensitivity to rapid temperature changes, thereby enhancing their suitability for experiments aimed at isolating other environmental or management variables (Kok et al., 2023). Moreover, maintaining stable temperature conditions can help clearly distinguish treatment effects. For instance, a study on maize under high-temperature stress demonstrated that regulating temperature in combination with optimized nitrogen regimes preserved key physiological traits and minimized yield losses, underscoring the importance of controlling temperature variability in field experiments (Yan et al., 2017).

Research on peat soils confirms that nutrient leaching increases under high groundwater (or high-moisture) conditions, reducing soil macronutrient levels, while maintaining groundwater ~40–50 cm below surface improves nutrient availability (e.g., N, P) by mitigating leaching (Bakri et al., 2025). Rainfall patterns, however, play a more complex role in peatland coffee systems. While C. liberica is more tolerant of excessive moisture compared to C. arabica, prolonged high rainfall such as in September and November can exacerbate nutrient leaching, particularly of nitrate and potassium, from peat soils. The notably lower rainfall in August (121.83 mm) coincided with the beginning of treatment application, potentially reducing initial leaching losses and allowing better retention of nutrients supplied through Starbo-AFE compost and volcanic ash. Conversely, the elevated rainfall in subsequent months could have reduced the persistence of readily soluble nutrients, especially in treatments without sufficient organic matter to improve nutrient holding capacity. This underscores the relevance of organic amendments in buffering against leaching losses in high-rainfall tropical systems.

Rainfall intensity strongly influences nutrient retention and leaching in tropical peat soils. In our study, rainfall varied considerably during the experimental period, ranging from 135.9 mm in August (relatively dry) to 505.6 mm in October (wettest month). Such fluctuations are critical because nutrients in peat soils particularly N and K are highly mobile and prone to leaching under high rainfall. Previous work in Indonesian peatlands demonstrated that nitrogen leaching losses increased fourfold when seasonal rainfall doubled from 462 mm to 847 mm (2.28 vs. 8.95 kg N ha^{-1}) (Suparto et al., 2015). Similarly, other previous study reported that rainfall and fluctuating water tables altered the ionic composition of peat soil solutions, with marked losses of K^+ and nitrate (Marwanto et al., 2018).

Potassium is particularly sensitive to rainfall-induced leaching. Laboratory leaching experiments in Malaysian peat confirmed that K is the most mobile nutrient, followed by N, Mg, and P; however, addition of organic matter or zeolite significantly reduced K losses (Krishnan et al., 2021). These findings are consistent with our observation that volcanic ash, rich in slow-release minerals, may contribute to longer-term buffering against leaching, while Starbo-AFE compost provides immediate nutrient supply and enhances cation exchange capacity. The rainfall events during October and November (>300 mm month^{-1}) coincided with observed variability in soil N and K concentrations among treatments, suggesting that heavy rainfall likely accelerated leaching in unamended plots. Conversely, higher nutrient retention in compost-amended plots is in line with findings from (Bakri et al., 2025), who showed that integrated organic amendments improved nutrient availability under wet season conditions

The drainage characteristics of peat soils interact strongly with rainfall inputs. Without adequate water management, heavy rainfall can lead to prolonged waterlogging, reducing oxygen availability to roots and inhibiting nutrient uptake (Kaur et al., 2020; Osman, 2018; Rupngam and Messiga, 2024). The installation of drainage trenches (~40 cm deep) around each plot effectively minimized the occurrence of prolonged waterlogging during periods of high rainfall, particularly in October and November when precipitation exceeded 300 mm per month. This standardized measure ensured that soil moisture remained within a range favorable for Coffea liberica root function, reducing confounding effects from excess water on plant performance. Although drainage was not directly tested as a factor in this study, its uniform application across treatments allowed for clearer attribution of observed nutrient retention patterns to the applied amendments rather than to variable water saturation levels.

From a physiological standpoint, rainfall amounts above 200 mm/month, as observed in September, October, and November, ensure sufficient water for transpiration-driven nutrient transport, leaf turgor maintenance, and biomass accumulation. However, the challenge in peatland environments is not water deficit but rather the maintenance of nutrient availability and root-zone aeration. This aligns with the core hypothesis of the present study that combining nutrient-rich organic amendments with mineral inputs may address both chemical and physical limitations of peat soils under high rainfall conditions.

Thus, the environmental conditions during the experiment were generally favorable for C. liberica growth, characterized by stable optimal temperatures and an adequate water supply throughout the study period. The marked increase in rainfall after August underscores the importance of soil amendments that enhance nutrient retention, particularly in leaching-prone peat soils. Previous studies have demonstrated the significant influence of precipitation on nutrient retention and loss in amended soils. For instance, biochar-amended soils exposed to 100 mm of simulated rainfall retained 18% more ammonium and 22% more potassium compared to unamended controls, highlighting the interaction between soil amendments and rainfall in improving nutrient retention (Ojeda et al., 2010), Similarly, field plots that received 80 mm of cumulative rainfall over two weeks following compost application lost 30% less total nitrogen and 25% less dissolved reactive phosphorus than unamended soils (Stöckle et al., 2003). This climatic context is essential when interpreting subsequent growth responses, as it indicates that differences in plant performance are more likely attributable to the ameliorant treatments rather than climatic stress factors. Peat drainage plays a critical role in aeration and nutrient dynamics; drained peat exhibits higher bulk density and reduced organic carbon content, accelerating soil decomposition and influencing nutrient availability (Anshari et al., 2021)

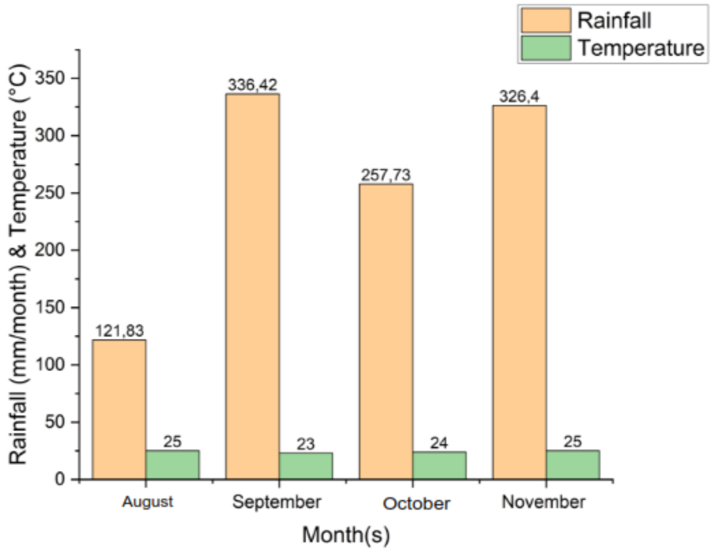

Figure 5. Environmental conditions

The baseline and treatment-level soil characteristics presented in Table 1 highlight the inherent limitations of tropical peat soils for Coffea liberica cultivation and the potential of organic and mineral amendments to improve these properties. Across all treatments, the pH (H_2O) ranged from 4.25 to 4.95, indicating strongly acidic conditions. The corresponding pH values in KCl (3.56–3.68) were consistently lower, reflecting the presence of exchangeable acidity, primarily from hydrogen and aluminum ions (Shamshuddin et al., 2004). Such acidity is detrimental to coffee root development, as it increases the solubility of toxic aluminum species and reduces the availability of essential nutrients such as phosphorus, calcium, and magnesium.

The acidity levels observed are typical of deep organic soils, where slow decomposition under waterlogged conditions leads to the accumulation of organic acids. The higher pH values in the A0 (control) plots compared to some amended plots (e.g., A1-81: pH 4.33) could be related to microbial acidification processes stimulated by the decomposition of added organic matter. While a slight decrease in pH may occur after compost addition due to organic acid release, the longer-term effect is often an eventual rise in pH as mineralization proceeds and base cations are released (Parecido et al., 2021). In this context, volcanic ash, with its significant CaO and MgO content, could gradually contribute to pH buffering over multiple seasons, although such an effect may not be immediately observable in a short-term trial (Kasongo et al., 2011).

Total nitrogen (N) levels varied from 0.15% to 0.51%, with the highest concentrations found in A2-80 (0.51%) and A2-81 (0.41%). Treatments receiving higher rates of Starbo-AFE compost generally showed elevated total N values, reflecting the compost's role as an organic nitrogen source. The low baseline N in peat soils, despite high organic matter content, is linked to nitrogen immobilization in undecomposed organic residues and leaching losses under high rainfall conditions. By introducing a biologically active compost, microbial activity is stimulated, leading to enhanced mineralization and greater availability of plant-accessible nitrogen (Perea Rojas et al., 2019).

Total organic carbon (TOC) ranged from 7.55% in A0-81 to 14.35% in A2-80, indicating a substantial contribution of organic matter from the amendments. Higher TOC values in compost-amended plots are expected due to the direct addition of organic residues, which improve soil structure, increase water-holding capacity, and enhance cation exchange capacity (CEC) in peat soils (Atzori et al., 2021; Aylaj and Adani, 2024; Sayara et al., 2020). Interestingly, some volcanic ash–amended treatments also retained relatively high TOC levels, suggesting that mineral particles from ash may have helped stabilize organic matter through organo-mineral associations (Parecido et al., 2021).

Available phosphorus (P_2O_5) values ranged from 96.16 mg/100 g in A2-81 to 131.88 mg/100 g in A1-81. This variability indicates that both compost and volcanic ash can influence phosphorus dynamics, but in different ways. Organic compost supplies P directly and can chelate aluminum and iron, reducing P fixation. Volcanic ash, rich in silica and base cations, can increase pH in the microenvironment, thereby improving P solubility. However, in highly acidic peat soils, P can still be immobilized by organic matter–metal complexes, explaining why P_2O_5 did not show a consistent trend across treatments (Shamshuddin et al., 2004). Exchangeable potassium (K_2O) was generally higher in amended plots, ranging from 257.72 mg/100 g in A2-81 to 347.76 mg/100 g in A2-82. Potassium is crucial for coffee physiology, playing roles in stomatal regulation, carbohydrate transport, and bean quality (Carvajal, 2015; Ramírez-Builes and Küsters, 2021; Vinecky et al., 2017). Starbo-AFE compost contributed K both from the raw material (oil palm empty fruit bunches are relatively rich in K) and from the mineralization process. Volcanic ash further contributed to K availability through the weathering of feldspars and micas, though this is a slow process.

Overall, the data show that Starbo-AFE compost primarily influences nitrogen and organic carbon content parameters linked to short-term plant growth while volcanic ash potentially supports potassium supply and long-term pH stabilization. The absence of dramatic shifts in pH and P_2O_5 suggests that a longer observation period may be necessary to capture the full ameliorative effect of volcanic ash in peat soils. From an agronomic perspective, these changes in soil chemical properties align with the hypothesized roles of the amendments: compost providing immediate nutrient availability and microbial stimulation, and volcanic ash acting as a slow-release mineral amendment with cumulative benefits. These soil improvements, in turn, underpin the plant growth responses observed in leaf area, branch diameter, and chlorophyll content, which are discussed in subsequent sections.

Table 2. Soil characteristics

Sample Identity	pH H_2O	pH KCl	Total-N (%)	Total Organic Carbon (%)	P_2O_5 in 25% HCl (mg/100g)	K_2O in 25% HCl (mg/100g)
A0-80	4.95	3.68	0.36	7.57	99.12	262.53
A0-81	4.79	3.63	0.39	7.55	111.56	280.06
A0-82	4.54	3.62	0.42	8.72	116.18	304.85
A1-80	4.42	3.56	0.47	11.04	120.18	337.00
A1-81	4.33	3.59	0.45	11.21	131.88	297.13
A1-82	4.25	3.56	0.48	14.12	109.90	291.18
A2-80	4.26	3.60	0.51	14.35	125.57	306.17
A2-81	4.27	3.61	0.41	8.57	96.16	257.72
A2-82	4.36	3.60	0.15	8.16	111.21	347.76

Test Methods:

a. *pH H_2O / pH KCl → WI-SAG-RST-IL-0403 (Electrometry)*
b. *Total-N → WI-SAG-RST-IL-0403 (Kjeldahl-titrimetry)*
c. *Total Organic Carbon → WI-SAG-RST-IL-0403 (Walkley & Black)*
d. *P_2O_5 → WI-SAG-RST-IL-0403 (Spectrophotometry)*
e. *K_2O → WI-SAG-RST-IL-0403 (Flame photometry)*

3.2. Plant Characteristics

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Table 3. Plants characteristics

Treatment	Replication			Total	Average
	1	2	3		
A0B0	54.30	61.35	112.01	227.66	75.89
A0B1	81.89	75.01	110.33	267.23	89.08
A0B2	97.57	98.36	106.56	302.49	100.83
A1B0	86.24	56.37	110.05	252.66	84.22
A1B1	95.00	134.07	82.17	311.24	103.75
A1B2	73.18	80.07	119.58	272.82	90.94
A2B0	129.42	120.49	161.25	411.16	137.05
A2B1	124.97	74.13	102.44	301.53	100.51
A2B2	150.39	114.88	113.35	378.63	126.21
Total	892.95	814.71	1017.75	2725.41	100.94

3.3. Chlorophyll Content

Chlorophyll content serves as an important physiological indicator of photosynthetic capacity, nutrient status, and overall plant vigor. In Coffea liberica, leaf chlorophyll concentration is closely linked to nitrogen (N) and magnesium (Mg) availability, as nitrogen forms part of the porphyrin ring structure of chlorophyll molecules and magnesium is the central atom within that ring (Taiz et al., 2015). Therefore, any amendment that enhances N and Mg availability can directly improve chlorophyll content and, by extension, photosynthetic efficiency. The results in Figure 2 show a clear upward trend in chlorophyll content from control treatments (A0B0) to combined high-rate amendment treatments (A2B2). The lowest chlorophyll concentration was recorded in the untreated control (A0B0: 4.23 mg/L), while the highest values were observed in the combination of 500 g Starbo-AFE compost with 500 g volcanic ash (A2B2: 9.28 mg/L), followed closely by A2B1 (9.23 mg/L) and A2B0 (9.00 mg/L).

These results confirm that Starbo-AFE compost had a pronounced positive effect on chlorophyll synthesis, with increases of more than 100% in the highest compost rate compared to the control. The likely explanation is the readily available nitrogen in the compost, coupled with improvements in soil structure and microbial activity, which enhance nutrient uptake efficiency. Since more than 30 years ago, previous studies showed the coffee plants with adequate nitrogen supply develop broader, darker green leaves with higher chlorophyll concentrations, resulting in increased photosynthetic assimilation rates (De Souza et al., 2023; Fahl et al., 1994; Nunes et al., 1993). Volcanic ash also appears to contribute to chlorophyll enhancement, particularly when combined with high compost rates. Treatments A2B1 and A2B2, which received both amendments, yielded the highest chlorophyll values overall. This suggests a synergistic effect between the two materials: while compost supplies immediate nitrogen for chlorophyll biosynthesis, volcanic ash provides magnesium and other micronutrients that support the structural and functional stability of chlorophyll molecules. This is consistent with findings in our previous study, who reported that volcanic ash application to peat soils increased leaf chlorophyll content in rice due to improved Mg and Ca availability (Armando et al., 2020).

Interestingly, volcanic ash applied without compost (A0B1 and A0B2) did improve chlorophyll levels compared to the control, but the increase was modest (4.61–5.80 mg/L). This supports the idea that volcanic ash alone may not supply sufficient immediately available nitrogen to drive rapid increases in chlorophyll content within a single season. Its contribution is more effective when paired with a nitrogen-rich amendment like compost. From a physiological perspective, higher chlorophyll content directly enhances the plant's ability to capture light energy and convert it into chemical energy through photosynthesis. This increased photosynthetic capacity is expected to translate into greater carbohydrate production, supporting vegetative growth (leaf area, branch diameter) and eventually reproductive development. In coffee, the photosynthetic output during the vegetative phase strongly influences the timing and extent of flowering and fruit set in subsequent seasons.

The large differences between treatments also highlight the role of soil amendment strategies in mitigating nutrient limitations inherent to peat soils. Peat soils are characterized by high acidity and low base cation availability, both of which can constrain chlorophyll formation. Starbo-AFE compost addresses these limitations by supplying both macronutrients (N, P, K) and organic matter that enhances cation exchange capacity, while volcanic ash contributes essential secondary nutrients like Mg and Ca, as well as silica, which can strengthen leaf tissue and improve stress tolerance. Agronomic implications of these results are substantial. For smallholder coffee farmers in peatland areas, increasing chlorophyll content through integrated nutrient management can lead to healthier, more productive plants. Higher chlorophyll levels indicate improved nutrient status and photosynthetic capacity, which are precursors to higher yield potential. Given the cost considerations for farmers, the data suggest that applying 500 g of Starbo-AFE compost alone already delivers significant gains, while adding volcanic ash may provide additional benefits for long-term soil fertility and sustained chlorophyll production. Finally, these findings also have ecological significance. By improving chlorophyll content and photosynthetic efficiency, plants may increase biomass production and carbon sequestration in peatland systems, contributing to climate change mitigation efforts. This aligns with sustainable intensification strategies that aim to increase yields while enhancing ecosystem services.

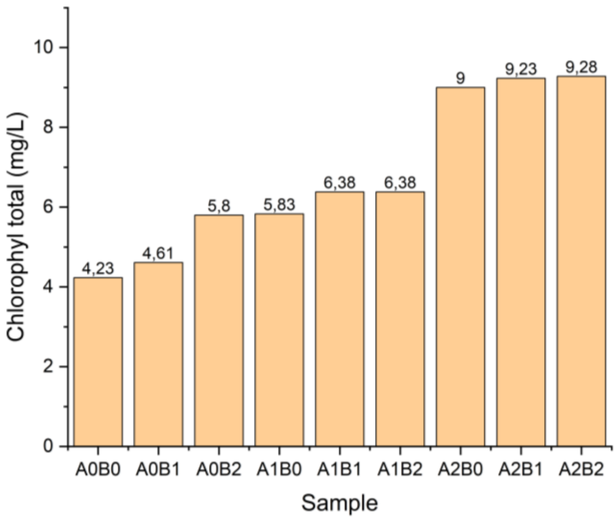

Figure 6. Chlorophyll total analysis

3.4. Mechanistic Interpretation and Agronomic Implications

The differential plant responses observed in this study can be explained by the distinct but complementary modes of action of Starbo-AFE compost and volcanic ash in tropical peatland soils. From a soil chemistry perspective, Starbo-AFE compost serves as an immediate nutrient source, particularly rich in nitrogen (1.6%), phosphorus (0.8% P_2O_5), and potassium (1.2% K_2O). Upon incorporation into peat soils, the compost undergoes rapid mineralization facilitated by the Trichoderma-based biostarter, which accelerates the breakdown of complex organic molecules into plant-available forms. This process releases nitrate and ammonium for nitrogen assimilation, orthophosphate for phosphorus uptake, and potassium ions that are essential for osmotic regulation and enzyme activation. The additional organic matter also increases the soil's CEC, enhancing the retention of base cations in a substrate otherwise prone to leaching under high rainfall conditions.

Volcanic ash, in contrast, is primarily a slow-release mineral amendment. With a composition of ~52% silica, 3.4% CaO, 2.5% MgO, and 2.1% K_2O, it contributes to soil fertility by gradually supplying secondary nutrients (Ca, Mg) and trace elements. These minerals serve key physiological functions: calcium is critical for cell wall structure and signaling, while magnesium is central to chlorophyll molecules and photosynthetic activity. The high silica content can also contribute to strengthening plant tissues, improving resistance to pests and abiotic stress. Importantly, the basic oxides in volcanic ash can buffer soil acidity, thereby improving nutrient availability, especially phosphorus, in acidic peat environments. However, the weathering process of silicate minerals is slow, so the short-term effect is often less pronounced compared to organic amendments.

From a plant physiological perspective, the synergy between Starbo-AFE compost and volcanic ash lies in their combined influence on nutrient supply and uptake efficiency. Compost ensures an immediate and sustained nitrogen supply, which directly promotes leaf area expansion and chlorophyll synthesisboth critical for maximizing photosynthetic capacity. The role of volcanic ash is to provide the magnesium needed for chlorophyll formation and calcium to enhance root membrane integrity, thereby improving nutrient absorption efficiency. Treatments that combined the highest compost and volcanic ash rates (A_2B_2) recorded the highest chlorophyll levels, suggesting that magnesium supplementation from volcanic ash amplified the benefits of nitrogen supplied by compost.

These nutrient-driven improvements in photosynthetic capacity are likely to underpin the observed increases in vegetative growth traits, including leaf area and primary branch diameter. Larger leaves with higher chlorophyll concentrations capture more solar radiation and convert it into carbohydrates, which are subsequently allocated to both structural growth and storage reserves. Thicker primary branches indicate enhanced cambial activity and vascular development, improving the plant's ability to transport water and nutrients. In perennial crops like coffee, these vegetative improvements during the juvenile stage are strongly linked to earlier and more abundant flowering in subsequent seasons.

Agronomically, the findings suggest that applying 500 g of Starbo-AFE compost per plant is an effective short-term strategy for boosting vegetative vigor in C. liberica grown on peat soils. While volcanic ash alone has limited immediate impact, its integration with compost offers additional benefits, particularly for chlorophyll content, which could translate into improved yield potential over time. For farmers, this means that nutrient management plans should consider both immediate and long-term soil fertility goals: compost for rapid growth improvement, volcanic ash for sustained soil health enhancement. From a sustainability perspective, this integrated approach aligns with climate-smart agriculture practices. Utilizing compost derived from oil palm empty fruit bunches recycles agricultural residues, reducing waste and enhancing nutrient cycling. Volcanic ash, a naturally abundant resource in Indonesia, offers a low-cost and environmentally friendly mineral supplement that can gradually rehabilitate degraded peat soils. By improving nutrient use efficiency and plant growth, these amendments may also increase carbon sequestration in coffee biomass, contributing to peatland restoration and climate change mitigation.

3.5. Statistical Result

Analysis of variance (ANOVA) followed by Duncan's New Multiple Range Test (DNMRT) revealed distinct effects of Starbo-AFE compost and volcanic ash applications on the vegetative parameters of Coffea liberica cultivated on peatland. The factorial design allowed evaluation of both main and interaction effects, providing a detailed understanding of amendment performance. The ANOVA indicated a significant main effect of Starbo-AFE compost ($F = 5.91 > F_{0.05} = 3.63$) on leaf area, while volcanic ash and the compost × ash interaction were not significant. The coefficient of variation (CV) was 21.67%, which is acceptable for field-based plant physiology experiments. The highest mean leaf area (137.05 cm²) was observed in treatment A2B0 (500 g compost, no volcanic ash), which was significantly higher than both the control (A0: 88.60 cm²) and A1 (250 g compost: 92.97 cm²). These results suggest that the nutrient-rich organic matter from compostparticularly its nitrogen contentenhanced chlorophyll biosynthesis and cell expansion, leading to greater canopy development (Novita et al., 2018). Volcanic ash did not show a significant short-term effect, possibly due to its slow nutrient release profile in acidic peat soils.

For primary branch diameter, compost application again produced a significant main effect ($F = 4.29 > F_{0.05} = 3.63$), while volcanic ash and interaction terms were not significant. The CV was 11.86%, indicating low variability and high reliability of the data. The largest branch diameter (6.56 mm) was recorded in A2 (500 g compost), significantly exceeding A0 (5.58 mm) and marginally exceeding A1 (6.25 mm). This increase in stem girth likely reflects enhanced nutrient uptake, particularly nitrogen and potassium, improving cambial activity and vascular development (Armando et al., 2020). Volcanic ash alone did not produce a measurable effect within the experiment period.

In contrast to the vegetative parameters, the number of fruiting primary branches showed no significant differences across treatments, with F-values for compost (0.20), volcanic ash (0.69), and their interaction (0.14) all below the critical F-value. The CV was 74.66%, indicating high variability likely due to environmental and physiological factors unrelated to the treatments. As C. liberica is a late-maturing crop, reproductive traits such as fruiting branch development are influenced more by plant age, carbohydrate reserves, and seasonal cues than by short-term soil nutrient amendments (Sobari et al., 2012).

The statistical outcomes confirm that Starbo-AFE compost significantly enhances vegetative growth, specifically leaf area and branch diameter, in young C. liberica plants on peatland. The lack of significant effects from volcanic ash and from the interaction term suggests that, within the six-month experimental period, volcanic ash's contributions primarily in supplying base cations and improving pH were not yet fully expressed. Its benefits may become more apparent in multi-season or multi-year studies.

From a methodological standpoint, the factorial ANOVA effectively separated treatment effects despite moderate environmental variability. The DNMRT mean separation clearly identified 500 g compost per plant as the most effective rate for improving vegetative parameters. For practical recommendations, this dose offers a balance between significant growth gains and resource efficiency. Future research should focus on extended evaluation periods to capture volcanic ash's long-term soil conditioning effects and potential contributions to reproductive performance and yield.

3.6. Recommendation for the Future Research

The findings of this study provide clear evidence that Starbo-AFE compost significantly improves vegetative growth of Coffea liberica in tropical peat soils, while volcanic ash contributes synergistically to chlorophyll enhancement. However, the results also reveal several research gaps and limitations that warrant further investigation to optimize nutrient management strategies for sustainable peatland coffee production. First, the present experiment was conducted over a six-month period, capturing only short-term responses in a juvenile coffee crop. As C. liberica is a late-maturing perennial species, long-term trials spanning multiple growing seasons are necessary to evaluate the cumulative effects of volcanic ash on soil pH buffering, base cation enrichment, and overall yield performance. This will help determine whether the mineral amendment's slower nutrient release pattern translates into measurable improvements in reproductive parameters, bean quality, and economic returns.

Second, the interaction between Starbo-AFE compost and volcanic ash warrants further mechanistic study, particularly regarding nutrient dynamics in peat soils. Future research should incorporate soil nutrient fractionation, microbial community profiling, and nutrient use efficiency analysis to better understand how these amendments influence nutrient cycling, root–soil interactions, and plant physiological processes. Such studies could clarify why volcanic ash's benefits are more evident when combined with organic amendments rather than applied alone. Third, given the high rainfall and leaching potential in tropical peatlands, nutrient loss monitoring should be integrated into future work. Measuring nutrient leaching rates through lysimeter studies or runoff analysis will allow optimization of amendment application timing and frequency, reducing input losses and environmental risks.

Fourth, while this study focused on peatland conditions in Jambi, the geographical and edaphic variability of peat soils across Indonesia suggests that similar experiments should be replicated in other peatland coffee-producing regions. Comparative studies will help validate whether the observed growth responses are location-specific or broadly applicable, thereby strengthening recommendations for national coffee development programs. Fifth, integrating economic and life cycle assessments (LCA) into future research would be valuable for guiding farmer adoption. Evaluating the cost–benefit ratio, return on investment, and carbon footprint of compost and volcanic ash application will ensure that proposed nutrient management practices are both profitable and environmentally sustainable for smallholders. Lastly, the potential for synergistic combinations with other soil improvement strategies such as biochar, legume cover cropping, or mycorrhizal inoculation should be explored. These integrated approaches may further enhance nutrient retention, microbial activity, and plant resilience, complementing the benefits of Starbo-AFE compost and volcanic ash.

4. Conclusion

This study provides the first factorial field evaluation of Starbo-AFE compost and volcanic ash on Coffea liberica growth in tropical peat soils. The results clearly show that Starbo-AFE compost significantly enhances vegetative growth, with 500 g plant^{-1} delivering the largest gains in leaf area and branch diameter. These improvements are attributed to the compost's immediate nutrient availability, particularly nitrogen, and its ability to improve soil organic carbon and cation exchange capacity. Although volcanic ash did not significantly influence growth parameters in the short term, its inclusion alongside compost increased chlorophyll content, suggesting a synergistic role in supplying magnesium and other base cations critical for photosynthesis. Soil data further indicate volcanic ash's potential as a long-term soil conditioner, contributing to potassium availability and pH stabilization in acidic peat environments. The absence of treatment effects on the number of fruiting primary branches reflects the juvenile stage of the coffee plants and the need for longer observation to capture reproductive responses. Practical recommendations from this study include applying 500 g Starbo-AFE compost per plant as a baseline fertility strategy for Coffea liberica in peatland systems, with volcanic ash incorporated for long-term soil health. These practices not only enhance productivity but also promote sustainable nutrient management, recycle agricultural residues, and leverage locally available mineral resources. Future research should focus on multi-year trials to assess volcanic ash's cumulative effects on soil chemistry and coffee yield, as well as economic analyses to determine cost–benefit ratios for smallholder adoption.

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Ethical Statements

No need ethical declaration.

CRediT Author Statement

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