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Improving coffee soil health using compost made from sugarcane leaves, coffee pulp, and *Gliricidia* sp.

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ABSTRACT

Agricultural waste management remains a critical environmental concern, necessitating sustainable approaches to transform organic residues into valuable resources. Among these, composting offers an effective solution by converting biomass into nutrient-rich soil amendments and reducing the burden of waste disposal. This study aims to investigate the potential of combined agricultural waste composting for producing high-quality compost and enhancing soil properties in a coffee plantation. Eight composting treatments and three replications were formulated: P1: *Saccharum officinarum* leaves (100%), P2: Coffee pulp (100%), P3: *Gliricidia* sp. leaves (100%), P4: *Saccharum officinarum* leaves (50%) + Coffee pulp (25%) + *Gliricidia* sp. leaves (25%), P5: Coffee pulp (50%) + *Saccharum officinarum* leaves (25%) + *Gliricidia* sp. leaves (25%), P6: *Gliricidia* sp. leaves (50%) + Coffee pulp (25%) + *Saccharum officinarum* leaves (25%), P7: Coffee pulp (50%) + *Saccharum officinarum* leaves (50%), and P8: Coffee pulp (50%) + *Gliricidia* sp. leaves (50%). The findings indicated that the compost mixtures containing *Gliricidia* sp. leaves and coffee pulp yielded a C:N ratio of less than 25, signifying that the compost was mature. The application of compost resulted in an overall increase in soil pH, organic carbon, and total nitrogen, while also ameliorating soil structure through reduced bulk density and enhanced porosity, particularly at a depth of 30–60 cm. These results provide valuable insights for farmers and agricultural policymakers in developing sustainable waste management strategies that effectively address agricultural waste disposal challenges while improving soil fertility and promoting more environmentally friendly coffee production systems.

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1. INTRODUCTION

Agricultural waste represents a significant by-product of global farming activities that, if not properly managed, poses substantial environmental challenges. Annually, approximately 1.3 billion tons of food are wasted globally, which comprises a significant portion of agricultural waste, including crop residues, by-products, and food processing waste (Ishangulyyev et al., 2019). Numerous reviews highlight the mounting challenges of agricultural waste disposal and its environmental ramifications, particularly in developing regions where abundant by-products remain underutilized (Bhuvaneshwari et al., 2019; Koul et al., 2022; Srivastava et al., 2021). Poor waste management results in soil and water contamination through nutrient runoff and toxic compound leaching, threatening food security and ecosystem stability (Mukhopadhyay et al., 2021; Muluneh, 2021; Okereafor et al., 2020).

These challenges are particularly pronounced in major agricultural-producing countries like Indonesia. As the world's fourth-largest coffee producer, generating over 760,000 tons annually, Indonesia faces challenges in managing agricultural waste within smallholder farming systems that dominate 96% of national coffee production (ICO, 2023). The scale of this production generates substantial quantities of organic waste that require effective management strategies. However, these agricultural waste materials provide significant opportunities for sustainable resource recovery when properly managed. The country's agricultural sector produces substantial biomass quantities that, through proper

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composting processes, can be transformed into valuable soil amendments. Compost represents a stable organic product derived from controlled decomposition of organic materials, including agricultural residues and crop by-products. This transformation from waste to resource offers multiple benefits for soil health and agricultural productivity. Application of quality compost enhances soil aggregate stability, reduces bulk density, increases porosity, and improves water infiltration and retention (Domínguez et al., 2019; Wang et al., 2022). Additionally, compost significantly improves soil chemical fertility by supplying essential nutrients, including nitrogen, phosphorus, potassium, and organic matter, while increasing cation exchange capacity (Danapriatna et al., 2023; Vignozzi et al., 2023).

Successful composting requires careful consideration of several critical factors, including the carbon-to-nitrogen (C:N) ratio, moisture content, aeration, and particle size. The initial C:N ratio determines the balance between carbon-rich "brown" materials and nitrogen-containing "green" materials; imbalances may cause slow decomposition or excessive ammonia emissions (Macias-Corral et al., 2019). Proper aeration accelerates decomposition, enhances product quality, and reduces energy consumption, while inadequate oxygen supply limits aerobic microbial metabolism essential for effective composting (Wang et al., 2019).

Sugarcane (*Saccharum officinarum*) leaves contain approximately 28.6% organic carbon, 0.35-0.42% nitrogen, 0.04-0.15% phosphorus, and 0.50-0.42% potassium (Gnanamani & Vijayalakhsmi, 2023), along with substantial structural components (24.26% lignin, 34.14% cellulose) (Farni et al., 2022). However, their high C:N ratio necessitates blending with nitrogen-rich materials for optimal decomposition. Coffee pulp, a direct by-product of coffee processing, contains 26.18% organic carbon, 2.98% nitrogen, 0.18% phosphorus, and 2.26% potassium (Risdawati & Soemarno, 2021), with favourable structural composition (39.2% cellulose, 12.6% hemicellulose, 23.3% lignin) (Nguyen et al., 2023). *Gliricidia* sp. leaves, commonly available in agroforestry systems, contribute high nitrogen content (3.2%), moderate phosphorus (0.72%) and potassium (1.02%) levels, with an optimal C:N ratio of 10.7 (Akoto et al., 2022). This specific combination of sugarcane leaves, coffee pulp, and *Gliricidia* sp. leaves was selected to achieve balanced C:N ratios while utilizing locally abundant materials within integrated coffee production systems.

Previous research on sugarcane leaf composting has focused primarily on single-material applications. Batubara and Listyarini (2017) examined sugarcane leaf litter contributions to soil nitrogen dynamics, while Showler (2023) Investigated direct green manure applications. Studies have demonstrated that incorporating sugarcane trash into soil influences soil physical, chemical, and biological properties, including a reduction in soil electrical conductivity, improvement in water holding capacity, better soil aggregation, and enhanced porosity (Dotaniya et al., 2016; Salman et al., 2023). Additionally, compost derived from sugarcane leaf residues has been shown to improve soil pH; increase available phosphorus, and potassium (Dadi et al., 2019); and enhance crop yields (Gnanamani & Vijayalakhsmi, 2023; Sitthikitpanya et al., 2021) demonstrated that sugarcane leaf amendments have been proven to improve soil health, but a comprehensive analysis of multi-material composting processes and soil property modifications remains limited. Similarly, research on coffee pulp composting has shown promising results, with studies demonstrating that coffee pulp compost can improve soil properties and promote plant growth (Kulandaivelu & Bhat, 2012), yet a systematic evaluation of the effects of combined organic residues on soil characteristics still requires further and more in-depth research.

This study introduces a novel multi-residue composting approach utilizing sugarcane leaves, coffee pulp, and *Gliricidia* sp. leaves—a combination not previously evaluated for soil property enhancement in smallholder coffee systems. Unlike previous single-source compost studies, this research explores the synergistic potential of integrated agricultural waste management tailored for tropical coffee production environments. The researchers hypothesize that balancing the C:N ratio by combining these three materials will produce a superior, higher-quality compost that improves soil properties compared to compost made from individual components. The specific objectives of this study are to investigate the potential of combined agricultural waste composting for producing high-quality compost and enhancing soil properties in a selected coffee plantation.

2. MATERIAL AND METHODS

2.1. Study location and environmental conditions

The research was conducted at the Coffee Farmer's Plantation in Sumbermanjing Wetan, Malang, East Java, Indonesia (8°13'68''S - 8°28'02''S, 112°39'07''E - 112°46'68''E) at an elevation of 598 meters above sea level. The experimental site is characterized by tropical monsoon climatic conditions with an average annual rainfall of 2,235 mm, a mean temperature of 24°C to 32°C, and a relative humidity of 70-90% (BPS, 2023). According to USDA soil taxonomy, the soil is classified as Typic Humudepts with baseline soil properties presented in Table 1. The study was conducted from January to October 2024. All soil analyses were performed at the Soil Physics and Chemistry Laboratory, Faculty of Agriculture, Universitas Brawijaya, Indonesia.

Table 1. Initial soil properties at the experimental site

No	Soil variables	Soil depth (cm)	
		0-30	30-60
1	Bulk density (g cm^{-3})	1.02	1.12
2	Particle density (g cm^{-3})	2.31	2.27
3	Soil texture		
	Sand (%)	19.69	16.75
	Silt (%)	40.86	38.82
	Clay (%)	39.46	44.42
4	Mean Weight Diameter (mm)	4.50	2.80
5	Soil Organic Carbon (%)	1.24	1.04
6	Soil Organic Matter (%)	2.14	1.79
7	pH	5.70	5.62
8	Total N (%)	0.15	0.14

Table 2. Experimental design of composting

No	Kode	Composition (%)	Mixed material (kg)
1	P1	*Saccharum officinarum* leaves (100%)	Goat dung (2)
2	P2	Coffee pulp (100%)	
3	P3	*Gliricidia* sp. leaves (100%)	
4	P4	*Saccharum officinarum* leaves (50%) + Coffee pulp (25%) + *Gliricidia* sp. leaves (25%)	
5	P5	Coffee pulp (50%) + *Saccharum officinarum* leaves (25%) + *Gliricidia* sp. leaves (25%)	
6	P6	*Gliricidia* sp. leaves (50%) + Coffee pulp (25%) + *Saccharum officinarum* leaves (25%)	
7	P7	Coffee pulp (50%) + *Saccharum officinarum* leaves (50%)	
8	P8	Coffee pulp (50%) + *Gliricidia* sp. leaves (50%)	

Table 3. Chemical contents of the base materials

No	Component	*Saccharum officinarum* leaves	Coffee pulp	*Gliricidia* sp. leaves
1	Lignin (%)	29.79	32.92	19.36
2	Polyphenols (%)	5.92	3.41	3.72
3	pH	7.87	6.43	6.79
4	Organic C (%)	37.58	37.39	36.39
5	Total N (%)	1.09	1.84	3.79
6	C:N	34.48	20.32	9.60
7	Total P (%)	0.70	0.79	0.79
8	Total K (%)	0.87	1.19	2.44

2.2. Experimental design

2.2.1. Compost preparation experiment

Raw materials for composting comprised sugarcane (*Saccharum officinarum* L.) leaves, coffee pulp, and *Gliricidia* sp. leaves, sourced from agricultural fields in Argotirto Village, Sumbermanjing Wetan District, Malang Regency. All materials were collected during optimal growth periods, air-dried to 10-12% moisture content, and mechanically chopped into 2-5 cm particle sizes using a mechanical chopper to facilitate decomposition. Eight compost treatments were evaluated using a completely randomized design with three replications, totalling 24 compost units (Table 2). Each compost unit contained 20 kg of organic materials. Raw material characterization was performed to determine the initial chemical properties essential for composting optimization (Table 3).

2.2.2. Composting process and monitoring

Composting was conducted in standardized wooden boxes (60 cm × 60 cm × 60 cm) lined with plastic sheets to prevent soil contact and maintain optimal moisture conditions. Each box was equipped with a removable lid for temperature control and contamination prevention. Raw materials were thoroughly mixed according to specified ratios, with EM4 decomposer (5 mL per kg^{-1}) and molasses (2% w/w) added as microbial activators. Initial moisture content was adjusted to 50-60% using distilled water. Compost temperature was monitored every three days using thermometers inserted 15 cm into the center of the pile. Turning was performed every six days during the active phase (0-5 weeks) and weekly thereafter until maturation. Compost maturity was assessed using multiple indicators: temperature stabilization, C:N ratio (<20), and visual assessment of decomposition completeness. A sample of mature compost was comprehensively analyzed for quality by measuring all parameters, including pH, organic C, total N, total P, and total K.

2.2.3. Field experiment

Field research was conducted to evaluate the impact of compost application on the physical and chemical characteristics of soil. Compost was applied to the soil of 10-year-old robusta coffee plants, with a dosage of 13.5 kg per plant per year, applied to a depth of 40 cm. Fertilization was conducted once per year, with a single dose applied at the beginning of the rainy season. The fertilizer was incorporated into the soil at a depth of 0–40 cm. A control treatment with no compost application was also implemented. Soil sampling was undertaken to analyse the effects of compost application on the physical and chemical characteristics of the soil. The soil sampling occurred three months following the compost application, with samples collected from two depths: topsoil (0-30 cm) and subsoil (30-60 cm).

The physical characteristics analyzed included aggregate stability (Mean Weight Diameter), soil bulk density, and soil porosity. The chemical characteristics examined included soil organic C, total N, and pH. Whole soil samples were collected using a sample ring with a 5 cm diameter for bulk density and porosity analysis. Aggregate soil samples were utilized to analyze the aggregate stability using the mean weight diameter (MWD) technique. The MWD was assessed using the wet sieving method. Disturbed soil samples were used to analyze soil organic C, total N, and pH in H_2O. The soil organic C was analyzed using the Walkley-Black method, the total N was assessed using the Kjeldahl method, and the pH in H_2O was measured using the electrometric method.

2.2.4. Statistical analysis

The data obtained were analyzed using the F-test as part of the Analysis of Variance (ANOVA) at a significance level of 5%. If a significant effect is found, subsequent analyses will be conducted using the Duncan Multiple Range Test (DMRT) at the same 5% level to differentiate between treatments. All statistical data analyses were performed using R software.

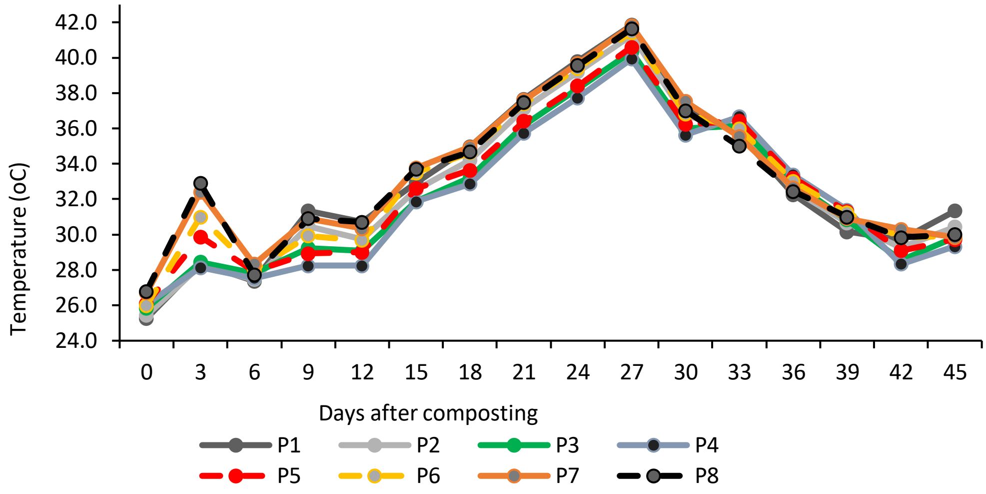

Figure 1. The temperature dynamics during the composting process; P1: *Saccharum officinarum* leaves (100%), P2: coffee pulp (100%), P3: *Gliricidia* sp. leaves (100%); P4: *Saccharum officinarum* leaves (50%) + coffee pulp (25%) + *Gliricidia* sp. leaves (25%), P5: coffee pulp (50%) + *Saccharum officinarum* leaves (25%) + *Gliricidia* sp, leaves (25%), P6: *Gliricidia* sp. leaves (50%) + coffee pulp (25%) + *Saccharum officinarum* leaves (25%), P7: coffee pulp (50%) + *Saccharum officinarum* leaves (50%), and P8: coffee pulp (50%) + *Gliricidia* sp. leaves (50%)

Table 4. Chemical quality of compost

Treatment	pH	Organic C	Total N	C:N	Total P	Total K
		%	%		%	%
P1	7.07 ab	32.66 ab	1.01 c	32.22 a	1.07 a	0.76 c
P2	6.55 b	36.61 a	1.76 ab	20.78 bc	0.64 b	1.01 bc
P3	7.33 a	32.89 ab	2.42 a	13.76 d	0.92 ab	1.77 a
P4	7.34 a	33.67 ab	1.65 bc	20.47 bc	0.71 b	0.9 bc
P5	7.01 ab	35.41 ab	1.81 ab	19.56 bcd	0.75 ab	1.09 bc
P6	7.30 a	29.28 b	1.73 ab	17 cd	0.78 ab	1.23 b
P7	7.20 a	36.33 a	1.45 bc	25.09 b	0.63 b	1.26 b
P8	7.31 a	30.89 ab	1.80 ab	17.21 cd	0.75 ab	1.23 b

Remarks: P1: *Saccharum officinarum* leaves (100%), P2: Coffee pulp (100%), P3: *Gliricidia* sp. leaves (100%), P4: *Saccharum officinarum* leaves (50%) + Coffee pulp (25%) + *Gliricidia* sp. leaves (25%), P5: Coffee pulp (50%) + *Saccharum officinarum* leaves (25%) + *Gliricidia* sp. leaves (25%), P6: *Gliricidia* sp. leaves (50%) + Coffee pulp (25%) + *Saccharum officinarum* leaves (25%), P7: Coffee pulp (50%) + *Saccharum officinarum* leaves (50%), and P8: Coffee pulp (50%) + *Gliricidia* sp. leaves (50%); the numerical values accompanied by different letters within the same column refer to significant differences as determined by the DMRT test at the 5% level.

3. RESULTS AND DISCUSSION

3.1. Temperature variation during the composting process

The composting process that lasted for 45 days showed temperature differences, which are illustrated in Figure 1. Temperature observations were conducted at two distinct stages of composting, specifically during the mesophilic and thermophilic phases. The results indicated that the mesophilic phase of compost occurred within the temperature range of 25°C to 39.8°C from day 1 to day 24. A marked increase in compost temperature was observed 3 days after composting started. The elevation in temperature during the mesophilic phase signifies the activation of microorganisms that initiate the decomposition of readily degradable organic matter (Biyada et al., 2021). Treatments P1 and P4, which were predominantly composed of sugarcane leaves, exhibited lower temperatures. This phenomenon is attributed to the high carbon-to-nitrogen (C/N) ratio found in sugarcane leaves. Compost materials characterized by a high C/N ratio typically undergo a slower decomposition process due to diminished microorganism activity (Azim et al., 2018; Neugebauer et al., 2017). Consequently, the incorporation of *Gliricidia* sp. leaves with sugarcane leaves proves effective in augmenting the temperature of the compost pile. This assertion is supported by the outcomes of treatments P3 and P8, which recorded higher temperatures, indicating more increased microorganism activity.

The thermophilic phase commenced 25 days after composting, exhibiting a pronounced rise in temperature. An increase in temperature during the thermophilic phase is essential for sanitizing the compost pile and mitigating pathogens (Nemet et al., 2021). The elevated temperatures experienced in this phase facilitate the thorough decomposition of organic matter. Subsequently, the compost temperature gradually diminishes, leading to a second mesophilic phase, during which the compost begins to display mature conditions. Nemet et al. (2021) asserted that during the mesophilic II phase, most of the organic matter has undergone decomposition, while any remaining undecomposed material is further processed by mesophilic microorganisms that are progressively reactivating.

3.2. Effects of combining agricultural waste materials on compost quality

The combination of compost materials yields varying chemical qualities of compost (Table 4). It has been determined that combining compost materials significantly influences soil pH. Mature compost generally maintains a stable pH, with the overall treatment reflecting a pH value of approximately 7. The highest pH was recorded in the P4 treatment, while the lowest was in the P2 treatment. The combination of compost materials substantially impacts the organic C value. The findings indicated that the highest organic C value of the compost occurred in the P2 treatment (100% coffee pulp), while the lowest was observed in the P6 treatment (consisting of 50% *Gliricidia* leaves, 25% coffee pulp, and 25% *Saccharum officinarum* leaves).

Statistical analysis revealed that the compost treatment type significantly affected the total N value. Treatment P3 (composed entirely of *Gliricidia* sp. leaves) exhibited the highest total N value due to the relatively high N content in *Gliricidia* sp. compared to other compost materials (Table 3). This resulted in a decrease in the C:N ratio of the compost. The findings of this study revealed that compost mixtures containing *Gliricidia* sp. leaves and coffee pulp (P2, P3, P4, P5, P6, P7, and P8) had a C:N value lower than 25, which can be attributed to the relatively high N value of *Gliricidia* sp. leaves. In contrast, treatment P1 (100% sugarcane leaves) recorded the highest C:N value at 32.22. Additionally, the total P values varied significantly among different compost types (Table 4). Compost produced from sugarcane leaves (P1) had the highest total P content, while composts predominantly composed of coffee pulp (P2, P7) showed lower total P concentrations. The total K values exhibited significant variation across different compost types (Table 4), with the highest total K value recorded in treatment P3 (100% *Gliricidia* sp. leaves).

3.3. Application of compost on the soil physical characteristics

The mean weight diameter did not exhibit a significant difference in the application of various compost treatments at a depth of 0-30 cm; however, a significant difference was observed at a depth of 30-60 cm (Table 5). At the soil depth of 30-60 cm, the highest mean weight diameter occurred in treatment P2 (application of 100% coffee pulp compost), while the lowest was observed in treatment P1 (application of 100% sugarcane leaves compost). Aggregate stability at the 0-30 cm depth was higher than at the 30-60 cm depth, indicating that the soil surface exhibited more stable soil aggregates.

Different compost treatments did not significantly influence the soil bulk density value at a depth of 0-30 cm, while they had a notable effect at a depth of 30-60 cm (Table 5). The highest soil Bulk Density values occurred in treatment P2 (application of 100% coffee pulp compost), while the lowest were observed in treatments P1 (application of 100% sugarcane leaves compost) and P7 (application of 50% sugarcane leaves and 50% coffee pulp compost). Soil porosity did not demonstrate a significant difference in the application of various compost treatments at a depth of 0-30 cm; however, a significant difference was noted at a depth of 30-60 cm. At this depth, the highest soil porosity values occurred in treatment P7 (which involved applying compost containing 50% coffee pulp and 50% sugarcane leaves), while the lowest was observed in treatment P2 (containing 100% coffee pulp compost). Soil porosity values fluctuated at different soil depths; however, the subsoil tended to exhibit lower porosity values.

Table 5. Soil physical characteristics after compost application

Treatment	MWD		BI (bulk density)		Porosity	
	mm		$g\ cm^{-3}$		%	
	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
Control	3.84	2.65 ab	0.99	1.05 ab	53.25	50.28 ab
P1	4.61	1.45 c	1.01	0.93 b	56.24	51.22 ab
P2	4.31	3.56 a	1.08	1.13 a	54.51	41.76 b
P3	4.88	2.02 bc	1.09	0.98 ab	55.83	54.11 ab
P4	4.53	2.52 abc	1.05	0.97 b	52.36	53.77 ab
P5	4.25	2.27 bc	0.99	0.99 ab	58.75	56.28 a
P6	4.64	2.77 ab	1.13	1.02 ab	46.26	54.03 ab
P7	4.11	1.91 bc	1.02	0.94 b	56.71	58.12 a
P8	4.64	2.79 ab	1.12	0.98 ab	50.31	51.89 ab

Remarks: P1: *Saccharum officinarum* leaves (100%), P2: Coffee pulp (100%), P3: *Gliricidia* sp leaves (100%); P4: *Saccharum officinarum* leaves (50%) + Coffee pulp (25%) + *Gliricidia* sp. leaves (25%), P5: Coffee pulp (50%) + *Saccharum officinarum* leaves (25%) + *Gliricidia* sp leaves (25%), P6: *Gliricidia* sp leaves (50%) + Coffee pulp (25%) + *Saccharum officinarum* leaves (25%), P7: Coffee pulp (50%) + *Saccharum officinarum* leaves (50%), and P8: Coffee pulp (50%) + *Gliricidia* sp leaves (50%); the numerical values accompanied by different letters within the same column refer to significant differences as determined by the DMRT test at the 5% level.

Table 6. Soil chemical characteristics after compost application

Treatment	pH		Soil Organic C %		Total N %	
	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
Control	5.92 b	5.79 bc	0.35 d	0.78 c	0.13 e	0.11 cd
P1	6.65 a	6.25 a	1.79 a	0.82 bc	0.19 bc	0.11 d
P2	6.33 ab	6.1 ab	1.34 b	1.53 a	0.18 bc	0.12 bcd
P3	6.52 ab	5.58 c	1.00 bc	1.00 b	0.17 c	0.15 a
P4	6.11 ab	6.27 a	0.89 c	1.03 b	0.16 c	0.11 bcd
P5	6.38 ab	6.53 a	0.86 c	0.84 bc	0.14 de	0.12 bcd
P6	6.27 ab	6.21 a	1.08 bc	0.88 bc	0.21 ab	0.12 bc
P7	6.39 ab	6.42 a	1.70 a	1.02 b	0.18 c	0.12 cd
P8	6.27 ab	6.28 a	1.72 a	1.00 b	0.23 a	0.13 b

Remarks: P1: *Saccharum officinarum* leaves (100%), P2: Coffee pulp (100%), P3: *Gliricidia* sp leaves (100%); P4: *Saccharum officinarum* leaves (50%) + Coffee pulp (25%) + *Gliricidia* sp. leaves (25%), P5: Coffee pulp (50%) + *Saccharum officinarum* leaves (25%) + Gliricidia sp leaves (25%), P6: Gliricidia sp leaves (50%) + Coffee pulp (25%) + *Saccharum officinarum* leaves (25%), P7: Coffee pulp (50%) + *Saccharum officinarum* leaves (50%), and P8: Coffee pulp (50%) + *Gliricidia* sp. leaves (50%); the numerical values accompanied by different letters within the same column refer to significant differences as determined by the DMRT test at the 5% level.

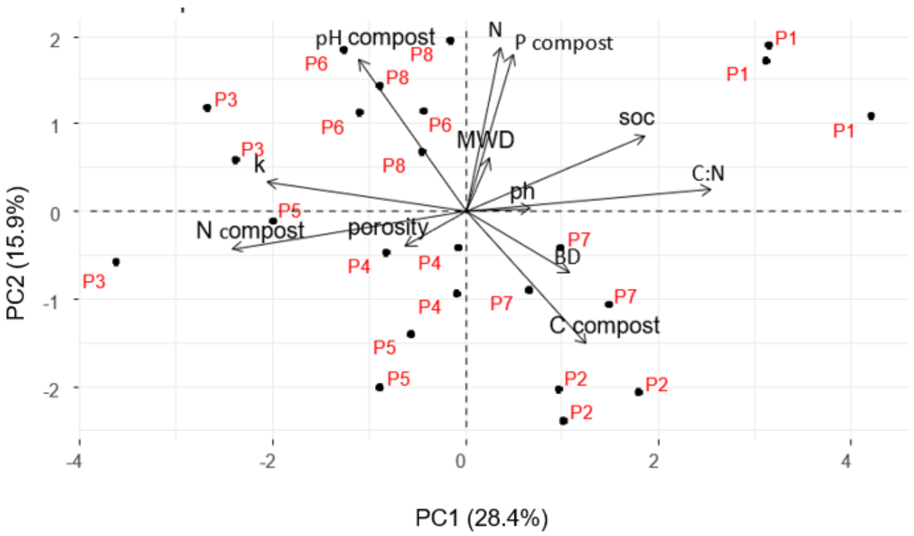

Figure 2. Principal Component Analysis (PCA) and biplot of various treatments, compost quality, and soil characteristics

3.4. Effects of compost application on soil chemical characteristics

Different compost treatments significantly affected soil pH values at both depths (Table 6). At the 0-30 cm depth, the highest soil pH occurred in treatment P1 (applying compost containing 100% sugarcane leaves compost), while the lowest pH was observed in the control treatment (without compost application). This indicated that all compost treatments were able to increase soil pH compared to the control. pH improvement also occurred in the subsoil layer, although it was lower compared to the topsoil. At a soil depth of 30-60 cm, the highest soil pH occurred in treatment P5 (50% coffee pulp + 25% *Saccharum officinarum* leaves + 25% *Gliricidia* sp. leaves), whereas the lowest soil pH was found in treatment P3 (application of 100% *Gliricidia* sp. leaves).

Different compost treatments significantly affected soil organic carbon values at both soil depths. At a depth of 0-30 cm, the highest soil organic carbon occurred in treatment P1 (application of 100% sugarcane leaves compost), while the lowest soil organic carbon was observed in the control treatment (without compost application). At a depth of 30-60 cm, the highest soil organic carbon value occurred in treatment P2 (application of 100% coffee pulp compost), whereas the lowest organic carbon value was found in the control treatment. The increase in soil organic carbon demonstrates the effectiveness of compost in improving soil organic matter status.

Different compost treatments significantly affected total soil nitrogen values at both soil depths. At a depth of 0-30 cm, the highest total soil nitrogen value occurred in treatment P8 (applying compost containing 50% *Gliricidia* sp. leaves + 50% coffee pulp), while the lowest was observed in the control treatment. At a depth of 30-60 cm, the highest total soil nitrogen value occurred in treatment P3 (applying compost containing 100% *Gliricidia* sp. leaves), and the lowest was found in the control treatment. These results indicate that all compost applications were able to increase total soil nitrogen values. Composts containing *Gliricidia* sp. (P3, P6, P8) generally showed high total soil nitrogen values, consistent with the nitrogen-rich characteristics of leguminous plants.

4. DISCUSSION

This study demonstrates that multi-material compost combinations, particularly P4 (50% sugarcane leaves + 25% coffee pulp + 25% *Gliricidia* sp. leaves), P5: coffee pulp (50%) + *Saccharum officinarum* leaves (25%) + Gliricidia sp. leaves (25%), and P6 (25% sugarcane leaves + 50% coffee pulp + 25% *Gliricidia* sp. leaves), represent the most effective treatments for enhancing soil properties in coffee plantation systems. Principal component analysis revealed that these three-material combinations were positioned closest to the coordinate center, demonstrating optimal balance among various soil chemical and physical parameters (Fig. 2). These treatments successfully achieved mature compost quality with C:N ratios approximately 20, while simultaneously improving essential soil properties including aggregate stability (Mean Weight Diameter increased by 10-20% compared to control), reducing bulk density in subsoil (decreased by 6-8% compared to control), enhancing porosity (increased by 7-12% in subsoil), and increasing soil pH (increased by 3-13% compared to control), significantly increasing soil organic carbon content (Soil Organic Carbon increased by 100% compared to control), and increased total N by 30% compared to control.

The superior performance of multi-material combinations stems from the synergistic interactions between diverse organic materials that provide complementary nutritional and structural benefits during decomposition processes. Coffee pulp, rich in lignin content (demonstrated by high organic carbon values in P2 treatment), serves as a carbon source that undergoes slow decomposition, providing sustained energy for microbial populations while contributing to stable organic matter formation (Meng et al., 2021). Lignin's complex structural composition, being predominantly carbonaceous and challenging to decompose, ensures prolonged microbial activity and gradual nutrient release (Ma et al., 2020; Meng et al., 2019). The stable organic matter content in the finalized compost leads to the formation of humic substances, which are vital for soil health (Gao et al., 2019). This slow-release mechanism prevents rapid nutrient loss while maintaining continuous soil organic matter input, essential for long-term soil water retention enhancement.

Complementarily, *Gliricidia* sp. leaves contribute high nitrogen content that facilitates the efficient decomposition of carbon-rich materials. The elevated nitrogen content in treatments P3 and P8, dominated by *Gliricidia* sp., demonstrates this material's capacity to provide essential nutrients for microbial growth and metabolic processes. The negative correlation between C:N ratio and total nitrogen content (Fig. 2 & 3) confirms that increased nitrogen availability accelerates decomposition processes and enhances nutrient availability (Tyasmoro & Saitama, 2024). This nitrogen-rich environment stimulates microbial activity, increasing the production of extracellular polysaccharides and other binding agents that enhance soil aggregate stability and subsequently improve water retention capacity.

Sugarcane leaves provide structural diversity and moderate nutrient content that balances decomposition. The higher phosphorus content in sugarcane leaf treatments (P1) demonstrates this material's contribution to nutrient enhancement, with dry sugarcane leaves containing phosphorus ranging from 0.1% to 0.3% of their dry weight (Kumar et al., 2022). The positive correlation between aggregate stability and compost phosphorus (Fig. 3) content reveals the critical role of phosphorus in soil structure improvement. Phosphorus enhances soil microorganism activity, stimulating the production of extracellular polysaccharides that serve as binding agents for soil particles (Liu et al., 2023; Zhang et al., 2025). Additionally, phosphate ions react with polyvalent cations such as Ca^{2+}, Mg^{2+}, and Al^{3+} to form compounds that function as natural cementing agents, binding soil particles into stable aggregates through cation bridging mechanisms (Li et al., 2020).

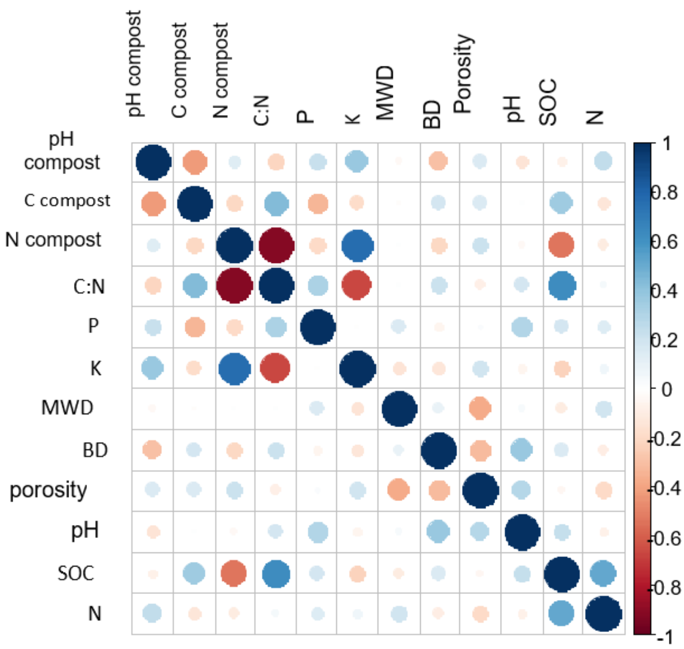

Figure 3. Inter-variable correlations

The quality of the final compost product results from the interactions between microbial activity and initial compost materials. During the heating and thermophilic phases, the pH value is increased due to the capability of microbes to mineralize and decompose organic nitrogen, resulting in the production of ammonium (NH_4^+), which may elevate the compost's pH (Zhang et al., 2018). As composting time extends, the pH value tends to decline, which can be attributed to microbial action that rapidly decomposes proteins, starches, and cellulose into smaller monosaccharide and amino acid molecules, thus producing organic acids and leading to a lower pH (Du et al., 2025). The treatment predominantly composed of coffee pulp (P2) showed lower pH values due to the presence of polyphenols like tannins (Hoseini et al., 2021), that exhibit acidic properties; therefore, releasing tannins contributes to reducing compost pH during decomposition. Tannins are polyphenol compounds characterized by the presence of acidic functional groups. During the process of microbial degradation, these functional groups may be liberated as organic acids, further promoting the decrease of compost pH (Zhang et al., 2020).

The humification process represents another crucial mechanism contributing to enhanced soil water retention. High total potassium content in compost, which showed a significant positive correlation with organic carbon content, facilitates efficient organic carbon decomposition by microorganisms while enhancing organic carbon accumulation (Medina Litardo et al., 2022). When potassium levels are adequate, the humification process intensifies, producing more stable forms of organic carbon that contribute to humic substance formation (Liu et al., 2023). These humic substances possess high water-holding capacity and cation exchange capacity, directly contributing to improved soil water retention and nutrient availability (Gao et al., 2019).

The quality of compost also influences soil property enhancement. Treatments involving combinations of three materials (P4, P5, P6) have better compost quality, which impacts soil characteristics. Consequently, compost application can improve soil aggregates and reduce soil bulk density. This is consistent with the correlation test results (Fig. 3), where increasing N content can reduce soil bulk density. Nitrogen-rich compost leads to improvements in other soil's physical properties, such as enhancing the stability of soil aggregates, increasing soil porosity, reducing soil compaction, and resulting in decreased soil bulk density (Ejigu et al., 2021; Kok et al., 2023). The binding of soil particles through organic matter leads to an improved soil structure (Rahayu et al., 2020), thereby creating more pore space and reducing soil compaction (Jain & Kalamdhad, 2020; Singh et al., 2024). The application of compost tended to enhance soil porosity at both depths. Furthermore, compost can elevate microbial activity, which assists in stabilizing soil structure and increasing overall soil porosity (Liu et al., 2021).

In general, applying compost significantly impacts soil pH, soil organic C, and soil total N content. Specifically, it can enhance soil pH compared to scenarios with no compost application (control). This phenomenon occurs because during the mineralization process of compost, ammonium ions (NH_4^+) are released, which subsequently raises the pH of the soil (Bohacz, 2019). Additionally, applying compost improves the value of soil organic C, particularly in treatments dominated by sugarcane leaves, which exhibit the highest value of soil organic C. This enhancement is attributed to the relatively high carbon content found in sugarcane leaves (Table 2), resulting in a notable release of C into the soil. This is consistent with the correlation test results, which show that compost organic carbon is significantly positively correlated with soil organic carbon values (Fig. 3). The organic carbon content in compost contributes to increased soil organic carbon. Moreover, compost application can augment soil microbial activity due to the nutrients released through compost. An increase in soil microbes can further promote the mineralization of organic matter, thereby increasing soil organic carbon levels (Boutasknit et al., 2021; Sukphun et al., 2023; Susilowati et al., 2024). Furthermore, compost application can elevate total soil N levels; treatments dominated by *Gliricidia* sp. leaves and coffee pulp (P3 and P8) show the highest total N values, which is attributable to the elevated N content in *Gliricidia* sp. leaves (Table 3). Ultimately, compost application raises total soil nitrogen through direct addition of nitrogen and indirect pathways via microbial activity that facilitates nitrogen binding (Domínguez et al., 2019; Lazicki et al., 2020).

However, this study presents several limitations that warrant consideration. The research is conducted under controlled experimental conditions that may not fully represent the complexity of field-scale coffee plantation systems. Additionally, the study duration may be insufficient to assess the long-term sustainability of soil improvements. The research focuses on specific material combinations available in the study region, and the results may vary depending on the organic waste sources or material quality. Furthermore, the study does not evaluate potential negative effects, such as pathogen survival, heavy metal accumulation, or phytotoxicity that may arise from specific material combinations. Future research should address these limitations through long-term field studies and the evaluation of broader environmental impacts to provide comprehensive guidance for sustainable coffee plantation management.

5. CONCLUSION

This study demonstrates the significant potential of combined agricultural waste composting for producing high-quality compost and enhancing soil properties in coffee plantation conditions. Treatments involving combinations of three materials, consisting of sugarcane leaves, coffee pulp, and *Gliricidia* sp. (P4, P5, and P6), produce compost with C:N ratios below 20, indicating advanced maturity and effective nutrient mineralization. Each constituent material contributes distinct agronomic value: coffee pulp enriches the compost with organic carbon due to its lignin content; *Gliricidia* sp. leaves supply bioavailable nitrogen critical for microbial activity and balance decomposition; and sugarcane leaves provide phosphorus, further supporting microbial processes. The synergistic interaction among these materials not only improves compost quality but also enhances soil physicochemical characteristics. Applying compost significantly improves soil physical properties, including reduced bulk density, enhanced porosity, and greater aggregate stability, particularly within the 30–60 cm soil layer. Moreover, soil chemical properties were ameliorated, as evidenced by increased pH, elevated organic carbon content, and improved total nitrogen levels. These enhancements support long-term soil fertility, aligning with sustainable agricultural practices. The findings underscore the importance of strategic formulation in composting by leveraging locally available agricultural residues to optimize nutrient cycling and soil physicochemical characteristics. This integrated waste management approach contributes to the circular bioeconomy by transforming organic waste into valuable agronomic inputs. It offers actionable insights for researchers, land managers, and policymakers seeking to advance sustainable intensification and environmentally sound soil fertility management in perennial cropping systems like coffee plantations.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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