




Effects of combined compost on soil pore distribution and available water capacity in tropical coffee plantations

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ABSTRACT

Physical soil degradation in smallholder coffee plantations threatens water availability and increases drought vulnerability. This study examines the effect of single and combined compost derived from *Saccharum officinarum* leaves, *Coffea canephora* pulp, and *Gliricidia sepium* leaves on soil pore distribution and available water capacity (AWC) in Typic Humudepts, Sumbermanjing Wetan, Malang. The experiment was arranged in a randomized block design (RBD), comprising seven treatment combinations each replicated three times. Compost was applied at 40 cm depth at 10 kg plant⁻¹ year⁻¹, with soil samples collected at 0–49 cm and 49–60 cm one year after application. Compost type significantly affected total porosity and AWC at both depths. Treatment P4 (50% *Coffea canephora* pulp + 25% *Saccharum leaves* + 25% *Gliricidia leaves*) produced the highest porosity (0.77 cm³ cm⁻³) and AWC (0.30 cm³ cm⁻³) in the topsoil, increasing macroporosity by 6%, mesoporosity by 26%, and decreasing microporosity by 24% relative to the control. AWC was primarily governed by total porosity. These findings indicate that blending compost optimizes soil pore distribution and AWC, providing a practical and accessible approach to strengthen drought resilience in smallholder coffee systems.

Keywords: available water capacity, compost amendment, pore size distribution; water retention curve.

INTRODUCTION

Coffee is a high-value plantation commodity that contributes strategically to Indonesia's overall economic performance. On a global scale, Indonesia is the fourth largest coffee producer after Brazil, Vietnam, and Colombia (Rosiana *et al.*, 2017), however its coffee production has not yet reached its optimal level. Coffee cultivation in Indonesia is generally carried out on rainfed land, making it highly vulnerable to climate change. This condition is exacerbated by long-term intensive management and excessive use of chemical fertilizers, which cause soil quality degradation, including a decrease in soil organic matter, increased soil compaction, and reduced water retention capacity, ultimately negatively affecting crop productivity (Gomes *et al.*, 2020). This has

become the main challenge in sustainable smallholder coffee plantation management.

Assessment of soil health in coffee plantations relies substantially on physical parameters measured within the root zone, particularly bulk density, total porosity, pore size distribution, and available water capacity. Soils with high bulk density indicate soil compaction that can impair water retention and root penetration (Rivier *et al.*, 2022). Maintaining or improving soil structural stability is important to preserve soil pore space. Soil pores are the void spaces in the soil that serve as pathways for water and solute transport (Wang and Zhang, 2024). Soil pore distribution directly controls water and air movement within the soil profile, thereby affecting water availability for plants, root aeration, and soil biota activity. Soil with good porosity and a balanced pore distribution

among macropores, mesopores, and micropores will be able to supply sufficient water to plants while maintaining optimal aeration conditions (Sekucia et al., 2020). The amount of water that can be absorbed and utilized by plants is called available water capacity, which lies between field capacity and the permanent wilting point (Ibrahimi and Alghamdi, 2022; He et al., 2022). Soil structural degradation due to improper management will reduce available water capacity (AWC) and increase the risk of drought stress in coffee plants, particularly during dry seasons. Therefore, it is important to manage the soil with compost application to improve available water capacity.

Compost application is one effective strategy for improving soil physical properties and increasing soil water retention capacity. Local organic materials with potential as compost sources include *Saccharum officinarum* leaves, coffee pulp, and *Gliricidia sepium* leaves. Coffee pulp is an abundant post-harvest waste in coffee production centers and has a relatively high organic carbon content, thus having the potential to improve soil structure (Sanchez-Monedero et al., 2019; Bilibio et al., 2023). *Gliricidia* sp. leaves are known as a source of high-quality organic matter with high N content and a low C/N ratio that accelerates the decomposition and nutrient release processes, and effectively increases soil aggregate stability (Liyanage et al., 2022). Meanwhile, *Saccharum officinarum* leaves contain high cellulose and hemicellulose that contribute to the formation of a more persistent humus fraction in the soil and play an important role in maintaining long-term water storage capacity (Farni et al., 2022). The combination of compost from sugarcane leaves, coffee pulp, and *Gliricidia* sp. leaves was chosen to balance the C:N ratio and produce high-quality compost capable of improving soil physical properties.

Compost application has been predominantly implemented at the soil surface, as documented in numerous studies (Phuong et al., 2020; Domínguez et al., 2019; Goldan et al., 2023). ; however, subsoil-targeted application is increasingly recognized as necessary to accelerate organic matter delivery to the active root zone. Studies evaluating compost incorporation at depths of 60–100 cm have demonstrated promising outcomes (Sumartono, 2023; Putri et al., 2022; Hutabarat and Simanjuntak, 2022), and subsoil management in clay-textured soils has been shown to reduce compaction, enhance aggregate stability, and improve permeability, collectively facilitating

deeper root penetration (Breslauer et al., 2020; Wang et al., 2021; Avila et al., 2020). Despite these advances, prior research has largely focused on single-source compost (Diacono and Montemurro, 2015; Blanco-canqui, 2022), while studies on mixed-material compost remain scarce—particularly regarding its effects on soil pore distribution and available water capacity (AWC), both of which are key indicators of soil physical quality (Reichert et al., 2020; Sun et al., 2021). Therefore, this study was conducted to examine the impact of compost application from combined materials on soil pore distribution and available water capacity. The objectives of this study are to analyze the impact of subsoil compost application on: i) physicochemical soil characteristics, ii) soil pore distribution, iii) available water capacity, and iv) the influence of soil properties on AWC.

METHODS

Study site

This study was conducted at a smallholder coffee plantation located in Argotirto Village, Sumbermanjing Wetan District, Malang Regency, East Java, Indonesia within the geographic range of 8°16'57.02"S, 112°41'1.67"E. This research was conducted over of single season of coffee (12 months). The research were carried out from March 2024 to September 2025 Compost was applied in March 2024, and soil samples were collected in March 2025, one year after application. The site was selected on account of its significant role as a regional coffee production center, encompassing a total plantation area of 1.066 ha. Coffee plants are cultivated at an altitude of 598 m asl under mean air temperatures ranging from 22.5 to 26.2 °C and an average relative humidity of 77.92% (BPS, 2023). The site experiences a tropical climate, with mean annual precipitation of 2.227 mm; monthly rainfall averages 228 mm during the wet season and declines to 18 mm during the dry season (Karangploso Climate Station, 2023). The soil at the experimental site is classified as a *Typic Humudepts* according to the USDA Soil Taxonomy (Soil Survey Staff, 2014), based on the soil profile description reported by Saraswati et al. (2022). All soil chemical and physical analyses were performed at the Soil Chemistry and Physics Laboratory, Faculty of Agriculture, Universitas Brawijaya, Malang.

Experimental design

A field experiment was established to evaluate the effect of compost source on soil physical properties and pore size distribution. The study was conducted in a 10-year-old Robusta coffee plantation with a planting spacing of 3 × 3 m. The experiment was established on a minimum total area of 3.648 m² (76 × 48 m, approximately 0.36 ha), comprising 21 experimental plots (7 treatments × 3 replicates), each measuring 10 × 10 m (9 plants per treatment plot) (Figure 1), with a 6 m buffer between blocks and a 3 m outer boundary buffer on all side. Three types of locally available organic materials were used to prepare the composts: *Saccharum officinarum* (sugarcane) leaves, coffee pulp, and *Gliricidia sepium* leaves. All compost treatments were subsurface-applied through four planting holes (12 cm in diameter) around each coffee plant at a standardized rate of 10 kg plant⁻¹ year⁻¹, equivalent to 2.5 kg compost per hole, following the recommendation of the Minister of Agriculture Regulation (2014). The compost was incorporated to a depth of 40 cm at the rainy season. Compost moisture content was

maintained at approximately 20%, and the material was applied once annually during the rainy season. Seven treatment combinations were arranged in a randomized block design (RBD) with three replications, as detailed in Table 1. The chemical characteristics of each compost formulation are presented in Table 2.

Sampling and analysis of soil properties

Soil samples were collected one year after compost incorporation at a lateral distance of 15 cm from each compost application hole. One representative tree was selected per plot, and sampling was repeated three times with the values subsequently averaged. Two sampling depths were established based on soil profile description: topsoil (0–49 cm) and subsoil (49–60 cm). Disturbed soil samples (approximately 500 g) were collected using a soil auger for the determination of soil organic carbon (SOC) by the Walkley and Black wet oxidation method. Undisturbed core samples were extracted using rings (5 cm in diameter and 5 cm in height) for the measurement of bulk density (BD), soil water

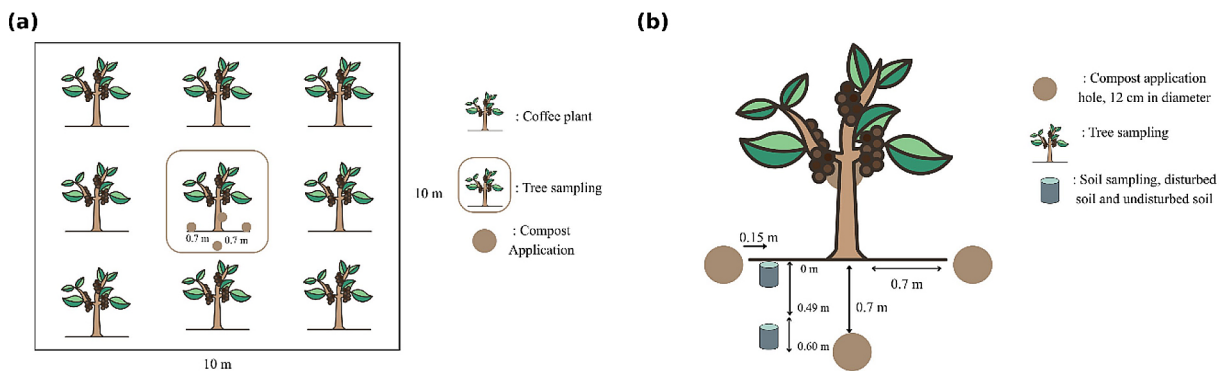


Figure 1. Research layout: (a) experimental unit layout for one treatment, with a spacing of 6 × 6 m between treatments; and (b) soil sampling scheme at depths of 0–49 cm and 49–60 cm

Table 1. Compost combinations applied in the smallholder coffee plantation

No	Treatment code	Treatment description
1	P0	No compost application (control)
2	P1	Compost from <i>Saccharum officinarum</i> leaves (100%)
3	P2	Compost from <i>Coffea canephora</i> pulp (100%)
4	P3	Compost from <i>Gliricidia</i> sp. leaves (100%)
5	P4	Compost from <i>Coffea canephora</i> pulp (50%) + <i>Saccharum officinarum</i> leaves (25%) + <i>Gliricidia</i> sp leaves (25%)
6	P5	Compost from <i>Gliricidia</i> sp leaves (50%) + <i>Coffea canephora</i> pulp (25%) + <i>Saccharum officinarum</i> leaves (25%)
7	P6	Compost from <i>Coffea canephora</i> pulp (50%) + <i>Gliricidia</i> sp leaves (50%)

Table 2. Characteristics of compost types

Treatment code	Compost characteristics							
	Organic C	Total N	C/N	Total P	Total K	CEC	Humic acid	Fulvic acid
	%	%		%	%	me/100g	%	%
P1	33.14	1.77d	18.78a	0.54bc	0.07e	46.69c	0.77a	0.26
P2	33.84	2.96bc	11.43b	0.73b	1.97c	80.94ab	0.33b	0.40
P3	30.65	4.88a	10.25b	0.93a	2.43b	53.45c	0.54ab	0.54
P4	30.30	2.61c	11.66b	0.53c	1.68d	71.30b	0.52b	0.52
P5	31.76	2.98bc	10.64b	0.59bc	1.74cd	72.11b	0.46b	0.46
P6	35.14	3.43b	10.25b	0.55bc	3.49a	90.07a	0.43b	0.43

Note: P1: *Saccharum officinarum* leaves (100%) compost; P2: *Coffea canephora* pulp (100%) compost; P3: *Gliricidia* sp. leaves (100%) compost; P4: *Coffea canephora* pulp (50%) + *Saccharum officinarum* leaves (25%) + *Gliricidia* sp. leaves (25%) compost; P5: *Gliricidia* sp. leaves (50%) + *Coffea canephora* pulp (25%) + *Saccharum officinarum* leaves (25%) compost; P6: *Coffea canephora* pulp (50%) + *Gliricidia* sp. leaves (50%) compost. Different letters within the same column denote statistically significant differences according to the Tukey test at 5% level.

retention, and available water capacity (AWC). Water retention characteristics were determined at three matric potential levels using sandbox and pressure plate apparatus: 0 kPa (pF 0), 10 kPa (pF 2), and 1,500 kPa (pF 4.2). Soil water retention at pF 2 was measured using a sandbox apparatus (suction cell apparatus), whereas retention at pF 4.2 was determined using a pressure plate apparatus, following the method of Klute (1986). For each instrument, water was allowed to drain from the samples until hydraulic equilibrium was reached prior to water content determination. All equilibration procedures were conducted at a room temperature of 25 ± 2 °C. After equilibration at each target matric potential, the samples were oven-dried at 105 °C for 24 h to obtain the gravimetric water content (θ_g), in accordance with the standard procedure for mineral soils (Klute, 1986). The gravimetric water content was subsequently calculated using Equation 1.

$$\theta_v = \theta_g \times \rho_b \tag{1}$$

where: θ_g is gravimetric water content (g g^{-1}), ρ_b is bulk density (g cm^{-3}), and θ_v is volumetric water content ($\text{cm}^3 \text{cm}^{-3}$). The dimensional consistency of this formula is confirmed as: $(\text{g g}^{-1}) \times (\text{g cm}^{-3}) = \text{g cm}^{-3} \approx \text{cm}^3 \text{cm}^{-3}$, given the density of water $\approx 1 \text{ g cm}^{-3}$

Four soil water status indicators were calculated from the data (Table 3): i) saturated water content, or total porosity, calculated at pF 0 or 0 kPa; ii) field capacity, at pF 2 or 10 kPa; iii) permanent wilting point, or micropores, at pF 4.2 or 1500 kPa; and iv) available water capacity, or mesopores, derived as the volumetric difference

between water retained at field capacity and that held at the permanent wilting point:

$$AWC = \theta_{FC} - \theta_{PWP} = \theta_{(pF\ 2)} - \theta_{(pF\ 4.2)} \tag{2}$$

Data analysis

The experiment was conducted following a randomized complete block design (RCBD) with seven treatments and three blocks, yielding a total of $n = 21$ independent experimental units. The independence of observations was ensured through the spatial separation of blocks and the randomized allocation of treatments within each block. All statistical analyses were performed using R version 4.4.2 with the *car* package version 3.1–5 for variance inflation factor and Levene’s test computations. A uniform significance level of $\alpha = 0.05$ was applied to all hypothesis tests. Prior to inferential analysis, the normality of residuals for each response variable was assessed using the Shapiro–Wilk test, while the homogeneity of variance was evaluated using Levene’s test based on the median (Brown–Forsythe modification). Outliers were screened using boxplot inspection and standardized residuals; no observations met the exclusion threshold, and therefore no data points were removed from the analysis.

Differences among treatment means were tested using two-way ANOVA in a general linear model framework, with treatment as a fixed factor and block as a random factor, in accordance with the RCBD model. When ANOVA indicated significant treatment effects ($p < 0.05$), Tukey’s honest significant difference (HSD) test was applied

Table 3. Soil water status indicators and corresponding pF thresholds used in this study.

Soil water status	pF value	Matric suction (kPa)	Soil pore size distribution
Saturated water content	pF 0	0	Total porosity
Field capacity (FC)	pF 2	10	-
Permanent wilting point (PWP)	pF 4.2	1,500	Micropores
Available water capacity (AWC)	pF 2 – pF 4.2	10 – 1,500	Mesopores

Note: FC – field capacity; PWP – permanent wilting point; AWC – available water capacity; pF – logarithm of matric suction expressed in cm H₂O.

for post-hoc mean separation. Pearson product-moment correlation coefficients were computed to evaluate linear associations among all measured soil variables, using listwise deletion of missing values to ensure that all coefficients were calculated from the same set of complete observations. As there were no missing data, the listwise and pairwise approaches yielded identical results.

Variables exhibiting significant correlations with available water capacity (AWC) were considered as candidate predictors for stepwise multiple linear regression. Variables that constitute mathematical components of the dependent variable (i.e., volumetric water content at pF 2 and pF 4.2 as defining components of AWC, since $AWC = \theta_{pF\ 2} - \theta_{pF\ 4.2}$) were excluded *a priori* to avoid tautological relationships. Multicollinearity among the remaining candidate predictors was diagnosed using the Variance Inflation Factor ($VIF = 1/(1 - R^2)$), with $VIF < 10$ set as the inclusion threshold (Hair et al., 2019); none of the candidate predictors exceeded this threshold.

The bidirectional stepwise procedure (combining forward selection and backward elimination) was performed with probability of F-to-enter ≤ 0.05 and probability of F-to-remove ≥ 0.10 . The final regression model was selected based on the highest adjusted R² and the principle of parsimony.

RESULTS AND DISCUSSION

Physicochemical properties of soil

Compost type had no significant effect on SOC and BD values at either soil depth (Tables 4 and 5). The highest SOC occurred in treatment P5 (*Gliricidia* sp. 50% + *Coffea canephora* pulp 25% + *Saccharum officinarum* 25%), as each component contributed distinct carbon compounds-nitrogen-rich proteins, lignocellulosic fractions, and high-cellulose fiber-producing synergistic effects on carbon stabilization (Gil-Martínez et al., 2025). SOC decreased with depth, consistent with the

Table 4. Physicochemical soil characteristics 0–49 cm depth

Treatment	Physicochemical soil characteristics						AWC class*
	SOC %	BD g cm ⁻³	Porosity %	MWD mm	Penetration MPa	AWC cm ³ cm ⁻³	
P0	2.25	1.17	67d	4.31	1.31	0.20c	High
P1	2.14	1.14	74b	4.66	1.21	0.26ab	Very high
P2	2.33	1.13	71c	4.75	1.10	0.24bc	Very high
P3	2.45	1.14	74bc	4.80	1.10	0.27ab	Very high
P4	2.21	1.14	77a	4.09	1.04	0.30a	Very high
P5	2.47	1.15	75ab	4.99	1.04	0.26ab	Very high
P6	2.36	1.12	75ab	4.42	1.12	0.26ab	Very high
P value	-	-	≤ 0.05	-	-	≤ 0.05	

Note: *classification based on LPT, 1980. P0: Control (no compost application) P1: *Saccharum officinarum* leaves (100%) compost; P2: *Coffea canephora* pulp (100%) compost; P3: *Gliricidia* sp. leaves (100%) compost; P4: *Coffea canephora* pulp (50%) + *Saccharum officinarum* leaves (25%) + *Gliricidia* sp. leaves (25%) compost; P5: *Gliricidia* sp. leaves (50%) + *Coffea canephora* pulp (25%) + *Saccharum officinarum* leaves (25%) compost; P6: *Coffea canephora* pulp (50%) + *Gliricidia* sp. leaves (50%) compost. Different letters within the same column denote statistically significant differences according to the Tukey test at 5% level.

Table 5. Physicochemical soil characteristics 49–60 cm depth

Treatment	Physicochemical soil characteristics						AWC class*
	SOC %	BD g cm ⁻³	Porosity %	MWD mm	Penetration MPa	AWC cm ³ cm ⁻³	
P0	1.99	1.16	56b	3.06	1.89	0.13c	Moderate
P1	1.86	1.09	63a	2.85	1.78	0.19ab	High
P2	1.87	1.11	63a	3.50	1.86	0.18b	High
P3	2.00	1.14	65a	2.50	1.59	0.20a	Very high
P4	1.93	1.12	65a	2.54	1.52	0.20a	Very high
P5	1.97	1.11	65a	2.97	1.51	0.19ab	High
P6	1.86	1.14	64a	2.75	1.73	0.19ab	High
P value	-	-	≤0.05	-	-	≤0.05	

Note: *classification based on LPT, 1980. P0: Control (no compost application) P1: *Saccharum officinarum* leaves (100%) compost; P2: *Coffea canephora* pulp (100%) compost; P3: *Gliricidia* sp. leaves (100%) compost; P4: *Coffea canephora* pulp (50%) + *Saccharum officinarum* leaves (25%) + *Gliricidia* sp. leaves (25%) compost; P5: *Gliricidia* sp. leaves (50%) + *Coffea canephora* pulp (25%) + *Saccharum officinarum* leaves (25%) compost; P6: *Coffea canephora* pulp (50%) + *Gliricidia* sp. leaves (50%) compost. Different letters within the same column denote statistically significant differences according to the Tukey test at 5% level.

reduction in litter-derived carbon input, declining microbial substrate availability (Naylor et al., 2022), and the increasing dominance of mineral factors such as clay content and iron oxides in SOC stabilization at deeper layers (Li et al., 2024).

Although BD did not differ significantly among compost treatments, the highest value occurred in P0 (control). Compost application reduced BD relative to the control by promoting aggregate formation through organic matter binding, increased macroporosity, and microbial exudate production (Blanco-canqui, 2022; Lehmann et al., 2020). Similarly, compost type significantly affected porosity at both depths, with the lowest porosity in P0 and the highest in P4 (*Coffea canephora* pulp 50% + *Saccharum* 25% + *Gliricidia* 25%). The lignocellulosic composition of these materials enhances macroporosity through aggregate formation while preventing excessive compaction (Alessandrino et al., 2023).

Compost type had no significant effect on aggregate stability, likely because measurable improvements require 6–11 years of continuous application (Guo et al., 2019), and short-term effects are modulated by soil biological activity, clay content, and moisture conditions (Liu et al., 2023). Penetration resistance also did not differ significantly among treatments, though values were highest in P0, suggesting that organic matter improves soil structure and reduces compaction potential (Lardy et al., 2022). Penetration resistance increased with depth, reflecting overburden pressure, reduced

biological activity, and minimal organic matter input in deeper layers (Ogorek et al., 2025).

Compost type significantly affected AWC at both depths, with P0 recording the lowest and P4 the highest values. The superior AWC in P4 reflects complementary biochemical contributions: lignin from coffee pulp promotes humic substance formation and water-holding capacity (Dadi et al., 2019; Nguyen et al., 2023); cellulose and silica from sugarcane leaves improve structural stability (Farni et al., 2022); and nitrogen-rich *Gliricidia* litter accelerates decomposition and stimulates extracellular polysaccharide production, enhancing aggregate-bound water retention (Castellini et al., 2025; Acar et al., 2025).

Soil pore distribution

Compost type significantly affected macropore distribution at 0–49 cm depth, with P4 (50% *Coffea canephora* pulp + 25% sugarcane leaves + 25% *Gliricidia* sp.) producing the highest macropore percentage (Figure 2). This is attributable to the high lignin content in coffee pulp and sugarcane leaves, which slows decomposition and promotes stable humic compound accumulation, while simultaneously stimulating lignolytic fungi that produce extracellular polysaccharides and hyphal networks to bind microaggregates into macroaggregates (Cotrufo et al., 2019; Lehmann et al., 2017). High C/N organic inputs also stimulate earthworm activity, generating stable

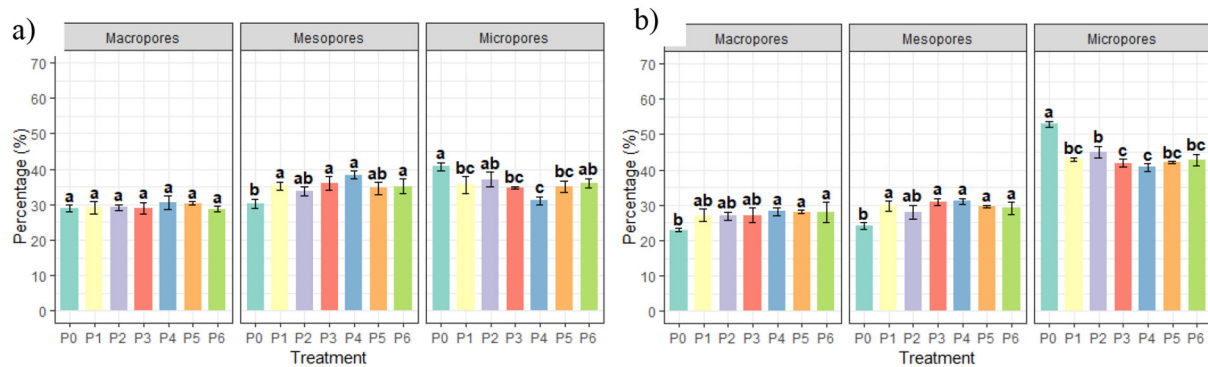


Figure 2. Pore distribution graph at 0–49 cm depth (a) and 49–60 cm depth (b). P0: Control (no compost application) P1: *Saccharum officinarum* leaves (100%) compost; P2: *Coffea canephora* pulp (100%) compost; P3: *Gliricidia* sp. leaves (100%) compost; P4: *Coffea canephora* pulp (50%) + *Saccharum officinarum* leaves (25%) + *Gliricidia* sp. leaves (25%) compost; P5: *Gliricidia* sp. leaves (50%) + *Coffea canephora* pulp (25%) + *Saccharum officinarum* leaves (25%) compost; P6: *Coffea canephora* pulp (50%) + *Gliricidia* sp. leaves (50%) compost. Different letters within the same column denote statistically significant differences according to the Tukey test at 5% level

macroaggregate castings and biopores (Hallam and Hodson, 2020). At 49–60 cm, macropore distribution was more uniform among compost treatments but remained significantly higher than the control, consistent with Schneider et al. (2017), who reported that organic matter effects on soil physical properties are generally confined to the application zone.

Mesopore distribution also differed significantly among treatments at both depths, with P0 recording the lowest and P4 the highest values. Compost enhanced mesopores through increased SOC, improved aggregate stability, and provision of porous carbonaceous residues (Abouelamaiem et al., 2018; Skoczko and Guminski, 2024; Khoirunnisak et al., 2024) Aggregate stability gains following compost application are associated with elevated glomalin-related soil protein and microbial activity (Acar et al., 2025), while humic acids produced during decomposition further bind particles into stable mesopore-maintaining aggregates (Aylaj et al., 2023; Spaccini and Piccolo, 2020).

Micropore percentage showed significant variation among treatments at both depths, with P0 consistently recording the highest values. This indicates that compost addition redistributes pore size by promoting macroaggregate formation, consolidating micropores into larger diameter pores; a process consistent with reports that compost application increases macroporosity by 20–27% relative to control (Rasa et al., 2024). Micropore percentage was higher in the topsoil than in the subsoil, reflecting more intensive SOM dynamics and microaggregate formation in the

upper layer, where approximately 90% of SOC is sequestered within aggregates (Zhao et al., 2024).

Water retention curve

The water retention curves presented in Figure 3 show that compost application increased the soil's ability to retain water at both measured depths (0–49 cm and 49–60 cm) compared to the control (P0). At both soil depths, the control treatment (P0) had the steepest curve slope with values of -10.50 (topsoil) and -15.54 (subsoil), indicating that water is released more quickly (low retention). In contrast, treatment P4 (*Coffea canephora* pulp (50%) + *Saccharum officinarum* leaves (25%) + *Gliricidia* sp. leaves (25%) compost) had the shallowest slope value of -7.90 (topsoil) and -10.76 (subsoil), indicating that the soil can store available water for longer (good retention).

The horizontal dashed lines at pF 2.0 (field capacity, -10 kPa) and pF 4.2 (permanent wilting point, -1.500 kPa) serve as agronomically critical references, with the volumetric water content between these thresholds defining plant-available water (PAW) as the primary determinant of soil productivity. All compost treatments exhibited higher water retention at pF 2 than the control, reflecting compost-driven improvements in soil aggregation and pore space that enhance water-holding capacity (Leelamanie and Manawardana, 2019; Bondi et al., 2022). Combined-material treatments, particularly P6 (coffee pulp 50% + *Gliricidia* 50%) and P4 (*Coffea canephora* pulp 50% + *Saccharum* 25% + *Gliricidia* 25%),

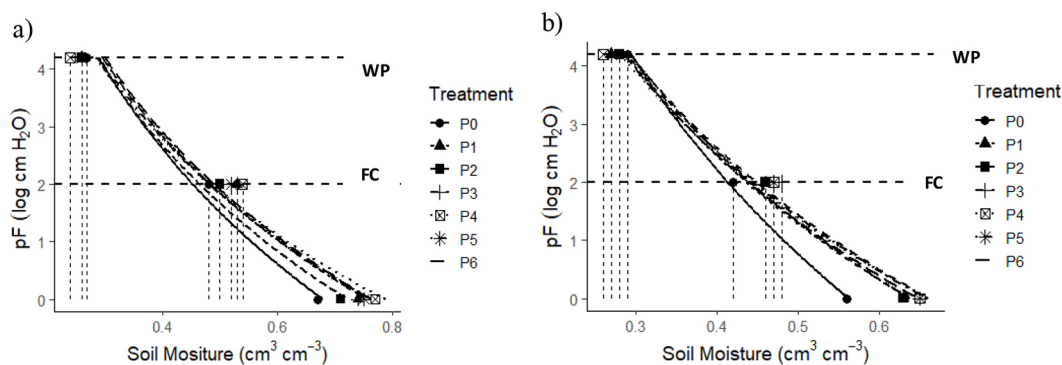


Figure 3. Water retention curve at 0–49 cm depth (a) and 49–60 cm depth (b). P0: Control (no compost application) P1: *Saccharum officinarum* leaves (100%) compost; P2: *Coffea canephora* pulp (100%) compost; P3: *Gliricidia* sp. leaves (100%) compost; P4: *Coffea canephora* pulp (50%) + *Saccharum officinarum* leaves (25%) + *Gliricidia* sp. leaves (25%) compost; P5: *Gliricidia* sp. leaves (50%) + *Coffea canephora* pulp (25%) + *Saccharum officinarum* leaves (25%) compost; P6: *Coffea canephora* pulp (50%) + *Gliricidia* sp. leaves (50%) compost. Different letters within the same column denote statistically significant differences according to the Tukey test at 5% level

outperformed single-material treatments due to complementary biochemical properties: slowly decomposing lignin from coffee pulp and readily mineralizable nitrogen from *Gliricidia synergistically* enhance aggregation and retention (Lazicki et al., 2020; Řezáčová et al., 2021), while silicate (SiO_2) from sugarcane leaves in P4 further improves soil structural stability (Farni et al., 2022).

At pF 4.2, water is retained exclusively in micropores and bound tightly to the soil matrix, rendering it generally unavailable to plants (Kowaljew et al., 2017). Compost-treated soils showed lower pF 4.2 values than the control, as evidenced by the leftward shift of the water retention curve (Figure 2), consistent with studies demonstrating that compost amendments reduce the permanent wilting point by improving aggregate stability (Kranz et al., 2023; Acar et al., 2025). The simultaneous decrease in pF 4.2 and increase in pF 2 water content confirms a net benefit to PAW, primarily driven by the larger gain in field capacity (Guyader, 2024).

Comparison between depths revealed contrasting retention dynamics. The 0–49 cm layer exhibited a wider spread of water content values among treatments, indicating a stronger compost effect, whereas the 49–60 cm layer showed a narrower spread, reflecting the attenuation of organic matter influence with depth. This pattern is consistent with the well-documented concentration of organic matter management effects in the topsoil, where litter and compost inputs promote stable aggregate formation and modify overall pore size distribution, thereby enhancing retention (Khoirunnisak et al., 2023; Ferreira et al., 2022).

The application of P4 combination compost increased AWC (from 0.20 to 0.30 $\text{cm}^3 \text{cm}^{-3}$ in the topsoil) compared to the control (P0) through four synergistically operating mechanistic pathways (Figure 4). First, decomposition of compost organic matter produces humic and fulvic acids that interact with soil mineral surfaces to form stable organo-mineral complexes through Ca^{2+} , Fe^{3+} , and Al^{3+} cation bridges, thereby promoting the formation and stabilization of microaggregates (Erika et al., 2018; Zhu et al., 2024). Second, the functional groups $-\text{OH}$ and $-\text{COOH}$ in humic compounds form hydrogen bonds with water molecules and increase water retention capacity through nanopore networks in the humic matrix up to three times compared to soil without organic amendments (Ampong et al., 2022). Third, the availability of labile carbon from compost organic matter stimulates soil bacterial activity in producing extracellular polysaccharides (EPS) that function as natural biological adhesives that bond primary particles into cohesive aggregates and increase soil mesoporosity (Olagoke et al., 2022; Luo et al., 2024). Fourth, arbuscular mycorrhizal hyphae developing in organic matter-rich soil form physical networks that bridge microaggregates into more stable macroaggregates, reinforced by glomalin protein (GRSP) that is recalcitrant and capable of permanently binding soil particles in the long term (Lehmann et al., 2017; Morris et al., 2019). These four mechanisms together produce measurable improvements in soil pore architecture, namely a 26% increase in mesopores, a 6% increase in macropores, and a 24% decrease in micropores compared to the

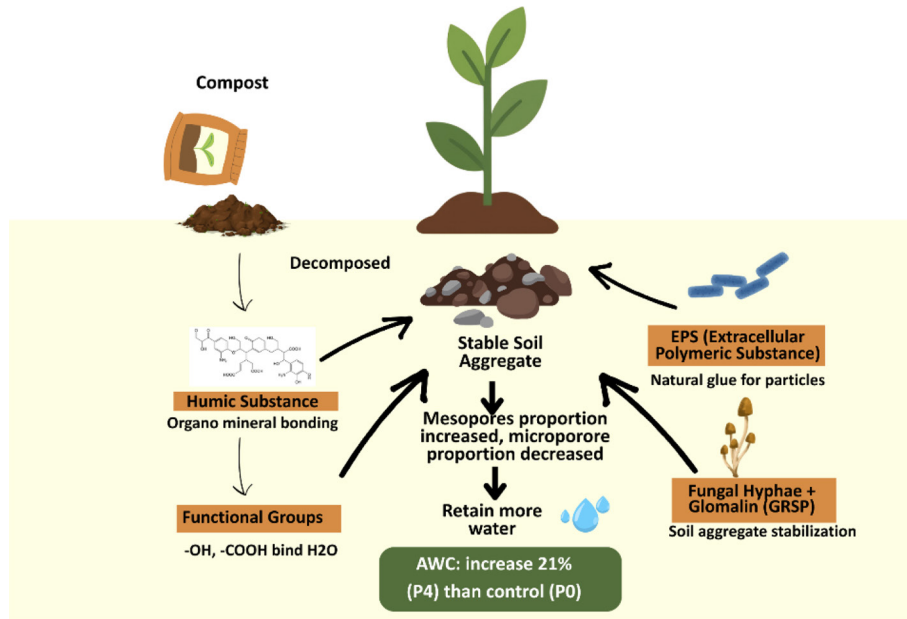


Figure 4. Mechanism of compost application on improving available water capacity.

AWC: Available water capacity; P0: control; P4: coffee pulp (50%) + *Saccharum officinarum* leaves (25%)

control, extending the soil water availability range delimited by field capacity (pF 2.54) at the upper boundary and the permanent wilting point (pF 4.2) at the lower boundary. This is consistent with findings from various studies reporting that organic amendment application significantly increases aggregate stability and soil water-holding capacity through increases in organic carbon content and microbial activity (Rivier et al., 2022; Bondi et al., 2022; Wang et al., 2022).

Pearson correlation coefficients presented in Figure 5 demonstrated that topsoil AWC was positively and significantly associated with water content at pF 0 ($r = 0.85$) and pF 2 ($r = 0.76$), and negatively correlated with pF 4.2 ($r = -0.73$),

confirming that AWC increases with greater water storage at saturation and field capacity but declines as water is held more tightly at wilting point tension. In the subsoil, pF 2 exhibited the strongest positive correlation with AWC ($r = 0.82$), exceeding that of pF 0 ($r = 0.66$), indicating that subsoil water availability is more strongly governed by field capacity than by saturated conditions – consistent with the dominance of mesopores that retain water at field capacity tension more effectively than rapidly draining macropores (Fukumasu et al., 2022; Jabro and Stevens, 2022). Variables significantly correlated with AWC were subsequently subjected to stepwise multiple regression.

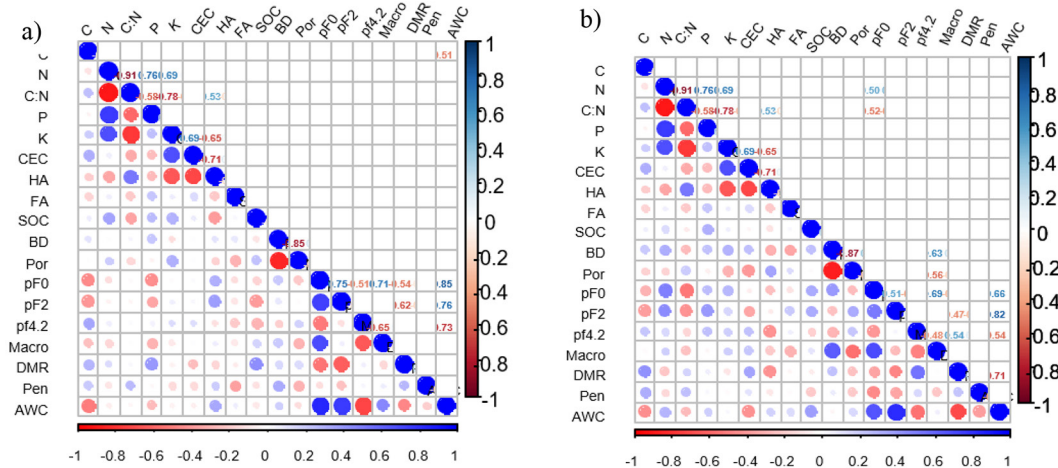


Figure 5. Correlation between variables 0–49 cm depth (left) and 49–60 cm depth (right)

Stepwise regression revealed that topsoil AWC was best explained by pF 0 alone ($Y = -0.385 + 0.873 \cdot \text{pF } 0$; $R^2 = 0.702$), accounting for 70.2% of AWC variation. In the subsoil, both pF 0 and DMR were significant predictors ($Y = -0.076 + 0.475 \cdot \text{pF } 0 - 0.013 \cdot \text{DMR}$; $R^2 = 0.696$), explaining 69.6% of variation. The positive coefficient for pF 0 confirms that greater water storage capacity under saturated conditions positively contributes to AWC, while the negative coefficient for DMR reflects that a higher macropore-to-mesopore ratio reduces plant-available water by diminishing the proportional contribution of mesopores.

The pF 0–AWC relationship is fundamentally mediated by total porosity, which determines water storage from saturation through field capacity. Greater total porosity expands the macropore and mesopore fraction, increasing water retention at low matric potential (pF 0–2.5) (Araújo Santos et al., 2022; Minasny and Mcbratney, 2017). Compost application reinforces this mechanism by enhancing soil aggregation and mesopore formation, thereby widening the plant-available water range between field capacity and the permanent wilting point (Kallenbach et al., 2016).

The lower R^2 in the subsoil regression, and the entry of DMR as an additional predictor, indicate that subsoil pore dynamics are more complex, influenced by factors not captured in the model such as aggregate size distribution, clay mineralogy, and pore tortuosity (Dor et al., 2025; Rabot et al., 2018). The negative DMR–AWC relationship reflects that macropore dominance proportionally reduces the mesopore fraction responsible for storing plant-available water (Fukumasu et al., 2022), a pattern consistent with the diminished organic matter influence in deeper layers (Lal, 2020).

CONCLUSIONS

Compost application significantly affected the physicochemical characteristics, pore distribution, and available water capacity of the soil. The P4 combination compost treatment (50% *Coffea canephora* pulp + 25% *Saccharum officinarum* leaves + 25% *Gliricidia sepium* leaves) consistently produced the best improvement at both soil layers, as demonstrated by the highest total porosity ($0.77 \text{ cm}^3 \text{ cm}^{-3}$) and highest AWC ($0.30 \text{ cm}^3 \text{ cm}^{-3}$) in the topsoil. Treatment P4 also improved overall soil pore architecture, as reflected

by a 26% increase in the mesopore proportion, a 6% increase in macropores, and a 24% decrease in micropores compared to the control. Pearson correlation analysis and stepwise multiple regression showed that AWC in the topsoil layer is predominantly influenced by total porosity (pF 0) with $R^2 = 0.702$, while in the subsoil layer AWC is significantly influenced by pF 0 and DMR with $R^2 = 0.696$, where DMR is negatively correlated with AWC due to the dominance of macropores that reduces the proportion of mesopores storing available water. Thus, combination compost with complementary biochemical compositions has proven effective in improving physicochemical properties, pore distribution, and soil water-holding capacity, thereby having the potential to become a practical soil management strategy for drought mitigation in smallholder coffee plantation systems.

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