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SOIL CARBON DYNAMICS AND PHYSICAL CHARACTERISTICS IN DIFFERENT SIMALUNGUN COFFEE AGROECOSYSTEMS

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ABSTRACT

*Coffee management systems strongly influence soil carbon dynamics and soil physical quality in tropical coffee agroecosystems. This study was conducted in Simalungun Regency, North Sumatra, Indonesia, to evaluate soil carbon dynamics and selected soil physical characteristics under organic (ORG), semi-organic (SEM), and conventional (CON) coffee management systems. A comparative field study was conducted in three adjacent coffee plantations representing the three management systems. Soil samples were collected at four depths (0–10, 10–20, 20–30, and 30–40 cm) and analyzed for total organic carbon (TOC), carbon sequestration, bulk density, and aggregate stability. Data were analyzed using factorial analysis of variance (ANOVA) followed by Duncan Multiple Range Test (DMRT) at *p* ≤ 0.05. The results showed that ORG consistently exhibited the highest TOC values, especially at depths of 0–10 cm (3.21%), followed by SEM (2.74%) and CON (2.18%). Soil carbon sequestration under ORG was approximately 24% greater than CON, indicating better carbon storage potential under continuous organic matter input. Aggregate stability was also higher under ORG across all aggregate size fractions, while CON exhibited lower aggregate stability and greater bulk density, indicating higher soil compaction. TOC values gradually decreased with increasing soil depth across all management systems, reflecting reduced organic matter input in the subsurface soil. Overall, organic coffee management with continuous organic amendments and minimal soil disturbance increased soil carbon storage and improved soil physical quality, highlighting its potential to support sustainable coffee production and long-term soil health in tropical agroecosystems.*

Keywords: *Carbon; Coffee; Soil Quality; Soil Physical*

INTRODUCTION

Coffee production is one of the strategic plantation sectors that plays an important role in the economy of tropical regions, including Indonesia. In addition to contributing to farmers' income and national revenue, coffee cultivation systems also form agroforestry ecosystems that influence environmental sustainability. However, the increasing intensification of coffee land management over recent decades has triggered various soil degradation problems, including declining soil organic matter, increasing soil compaction, and deteriorating soil physical quality (Widjayanti and Saputra, 2022).

According to Millet *et al.* (2025), coffee plantations not only function as agricultural production systems but also constitute a vital part of agroforestry landscapes, providing various ecosystem services. Coffee systems managed by maintaining shade vegetation and organic matter input play a role in soil conservation, regulating the water cycle, storing carbon, and maintaining soil biodiversity. Conversely, cultivation intensification that reduces vegetation cover and organic matter input can reduce the ecological function of the land and increase the risk of soil resource degradation. Therefore, sustainable coffee land management is an important approach to supporting natural resource conservation and climate change mitigation in highland agricultural landscapes.

Soil is a fundamental component of coffee agroecosystems because it functions both as a plant growth medium and as the largest terrestrial carbon reservoir. Soil organic carbon (SOC) is an important indicator of soil quality and health because it plays a critical role in improving soil structure, increasing water holding capacity, and supporting soil biological activity (Romero-Chávez *et al*., 2026). The loss of SOC due to unsustainable land management practices may accelerate land degradation and reduce long-term coffee productivity (Bradford *et al*., 2016).

Different land management systems are known to exert varying effects on soil carbon dynamics. Organic management systems generally promote greater organic matter accumulation through the application of organic fertilizers, plant residues, and minimal use of synthetic chemical inputs (Liu *et al.,* 2019). In contrast, conventional systems that rely heavily on synthetic fertilizers and pesticides tend to intensify soil disturbance, thereby accelerating organic matter decomposition and soil carbon loss (Dieleman *et al.,*2013). Between these two systems, semi-organic management has emerged as a transitional approach that combines organic and inorganic inputs to maintain a balance between productivity and land sustainability (Indrawati, 2025).

In addition to influencing SOC, differences in coffee management systems also affect soil physical characteristics. Continuous application of organic materials can improve soil aggregation, reduce bulk density, and increase soil porosity (Tao *et al.,* 2024). Conversely, intensive use of mechanical practices and synthetic inputs in conventional systems may lead to soil compaction and reduced aggregate stability. These conditions directly influence water infiltration, soil aeration, root development, and nutrient uptake efficiency in coffee plants (Rodríguez *et al.,* 2022).

Soil organic carbon and soil physical characteristics are closely interconnected in maintaining soil ecosystem functions. High carbon content promotes the formation of stable aggregates through interactions between mineral particles and organic matter (Wasner *et al.,* 2024). Stable aggregates protect carbon from rapid decomposition, thereby supporting long-term carbon storage within the soil. Therefore, evaluation of soil carbon cannot be separated from the assessment of soil physical properties as comprehensive indicators of soil quality (Hamza *et al.* ,2025).

In addition to contributing to climate change mitigation, increasing soil carbon stocks in sustainable coffee systems also plays a role in maintaining environmental quality and ecosystem resilience. Stable soil carbon can improve soil structure, increase water infiltration capacity, and reduce land vulnerability to erosion and degradation. Therefore, evaluating soil carbon stocks and soil physical characteristics in various coffee management systems is crucial for assessing the contribution of coffee agroecosystems to sustainable land management and the provision of environmental services in tropical regions (Rani *et al.,* 2026).

In the context of global climate change, agricultural land has the potential to function both as a source and a sink of atmospheric carbon. Sustainably managed coffee cultivation systems have considerable potential to support climate change mitigation through enhanced soil carbon sequestration (Martinelli *et al.,* 2025). Management practices such as the use of organic mulch, organic matter addition, and maintenance of ground cover vegetation can increase soil carbon stocks while simultaneously improving soil quality. Thus, coffee land management is not only associated with crop productivity but also has broader ecological implications for environmental sustainability (Rahman *et al.,* 2021).

Although numerous studies on soil carbon have been conducted in annual cropping systems and grazing lands, research on soil carbon dynamics in coffee management systems, particularly comparisons among organic, semi-organic, and conventional systems, remains relatively limited (Sebayang & Fari, 2026). This knowledge gap is particularly important in Simalungun Regency, North Sumatra, a major coffee-producing region characterized by volcanic-derived soils and diverse coffee management practices. Most previous studies have focused primarily on crop production aspects without comprehensively linking them to soil physical quality and carbon storage potential. Yet, understanding the relationship between coffee management systems and soil quality is essential for supporting the development of sustainable coffee farming systems in tropical regions (Fari & Sebayang, 2026).

Based on these considerations, this study was conducted to analyse soil carbon dynamics and soil physical characteristics under different coffee land management systems. This research is expected to provide scientific information regarding the influence of coffee management systems on soil quality and soil carbon storage potential. The findings are also expected to serve as a basis for developing more sustainable coffee cultivation practices that are adaptive to future climate change challenges (Ayu *et al*., 2023).

METHOD

This study was conducted from August 2025 to February 2026 in coffee plantation areas located in Simalungun Regency, North Sumatra, Indonesia, at an altitude of approximately 1,100 m above sea level with geographic coordinates of 2°50′51″ N and 98°51′00″ E. The study was carried out in three adjacent coffee plantations representing different management systems, namely organic (5,900 m²), semi-organic (3,600 m²), and conventional (3,100 m²) systems. The study area represents a tropical highland agroecosystem that is highly suitable for Arabica coffee cultivation. The cultivated coffee plants were Arabica coffee of the Sigararutang variety with relatively uniform plant age and land conditions. The organic coffee plantation has implemented organic cultivation practices since 2015 and obtained organic certification from LeSOS (Lembaga Sertifikasi Organik Seloliman) with certificate number 128-LSPO.005-IDN-10-15. A preliminary field survey was conducted to identify the characteristics of the study area, including topographic conditions, soil characteristics, land management systems, and general coffee plantation conditions. The survey results were used as the basis for determining sampling points and selecting appropriate soil sampling methods.

The study was conducted under three different coffee land management systems, namely:

a. ORG (Organic Coffee Management)

The organic coffee management system utilized organic fertilizers while minimizing the use of synthetic chemical inputs. Organic materials applied included cattle manure compost and coffee husk compost. Weed control was carried out manually and biologically using a mixture of sulphur and fermented coffee wastewater as a botanical herbicide. Pest and disease control was conducted using botanical pesticides derived from neem leaves (*Azadirachta indica*), tuba root (*Derris elliptica*), and fermented shrimp paste.

b. SEM (Semi-Organic Coffee Management)

The semi-organic coffee management system combined the use of organic and inorganic inputs. Fertilization was performed using both organic fertilizers and limited amounts of chemical fertilizers, while weed and pest control involved a combination of manual, biological, and limited synthetic pesticide applications.

c. CON (Conventional Coffee Management)

The conventional coffee management system intensively utilized synthetic fertilizers and chemical pesticides. Weed and pest control were routinely conducted using synthetic herbicides and pesticides. The chemical characteristics of the compost materials applied under the ORG system are presented in Table 1.

Table 1. Chemical Characteristics of Compost Used in The ORG Management System

Parameter	Cattle manure compost	Coffee husk compost
pH (H_2O)	7.42	6.85
Organic C (%)	21.36	28.74
Total N (%)	1.82	1.65
C/N ratio	11.74	17.42
Available P (%)	0.84	0.62
Available K (%)	1.26	2.18
Moisture content (%)	32.45	28.17

Source: Primary data analyzed at the Palm Oil Research Center Laboratory (2026).

Soil sampling was conducted purposively within each coffee land management system. Soil samples were collected at four soil depths, namely 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm. Several sampling points were established within each management system, and the collected soils were composited into a single representative sample for each soil depth. Disturbed soil samples were used for soil organic carbon and aggregate stability analyses, while undisturbed soil samples were collected using a ring sampler for bulk density analysis. All collected soil samples were placed in labelled plastic bags and transported to the laboratory for further analysis.

Initial soil physical characteristics were analyzed before further laboratory analyses. The observed parameters included soil moisture content and soil texture, consisting of sand, silt, and clay fractions. Soil texture analysis was conducted using the hydrometer method, while soil moisture content was determined using the gravimetric method. The initial soil physical characteristics under different coffee management systems are presented in Table 2.

Table 2. Initial Physical Characteristics of Soil Under Different Coffee Agroecosystems

Parameter	ORG	SEM	CON
Bulk density (g cm^{-3})	0.92	1.03	1.18
Soil moisture content (%)	34.26	29.84	24.71
Sand (%)	68.42	65.18	61.35
Silt (%)	18.56	20.74	23.62
Clay (%)	13.02	14.08	15.03
Soil texture class	Loamy sand	Sandy loam	Sandy loam

Source: Primary data analyzed at Soil Physics Laboratory, Faculty of Agriculture, Universitas Sumatera Utara (2026).

Description: ORG = organic coffee management, SEM = semi-organic coffee management, CON = conventional coffee management.

Soil organic carbon (SOC) analysis was conducted using the Walkley and Black method. Soil samples were air-dried, gently crushed, and passed through a 2 mm sieve. Approximately 10 g of soil sample was reacted with $K_2Cr_2O_7$ solution and concentrated H_2SO_4 to oxidize soil organic matter. The solution was subsequently titrated using $FeSO_4$ until the endpoint color change was reached. Soil organic carbon content was expressed as a percentage (%).

$$\%C = \frac{(B - S) x\ N\ x\ 0.003\ x\ 1.33\ x\ 100}{W}$$

Description:

%C = soil organic carbon content (%)

B = volume of blank titration (mL)
S = volume of sample titration (mL)
N = normality of $FeSO_4$ solution
W = weight of soil sample (g)

Total soil organic carbon (TOC) was calculated based on soil organic carbon content (%C), bulk density, and soil depth using the following equation:

$$TOC\ (Mg\ ha^{-1}) = \left(\frac{\%C}{100}\right) \times BD \times D \times 10{,}000$$

Description:
TOC = total soil organic carbon (Mg ha^{-1})
%C = soil organic carbon content (%)
BD = soil bulk density (Mg m^{-3})
D = soil depth (m)

TOC calculations were performed for each soil depth, namely 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm. Bulk density was analyzed using the ring sampler method. Undisturbed soil samples were collected at each soil depth using a cylindrical ring sampler and then oven-dried at 105 °C for 48 h until constant weight was achieved. After drying, the soil samples were weighed to determine oven-dry soil mass. Bulk density was calculated based on the ratio between oven-dry soil mass and ring sampler volume and expressed in g cm^{-3}. Bulk density was calculated using the following equation:

$$BD = \frac{M}{V}$$

Description:
BD = soil bulk density (g cm^{-3})
M = oven-dry soil mass (g)
V = ring sampler volume (cm^3)

Soil aggregate stability was analyzed using the wet sieving method following the procedure of Kemper and Rosenaun (1986). Approximately 4 g of air-dried soil sample (<2 mm) was placed into a set of sieves with mesh sizes of 63 µm, 250 µm, and 500 µm. The samples were then immersed in distilled water until all aggregates were completely saturated. The wet sieving process was conducted for 10 minutes using a wet sieving apparatus to separate aggregates according to particle size. After sieving, the soil suspension retained on each sieve was transferred into pre-weighed metal containers and oven-dried at 110 °C for 24 h. The weight of stable aggregates retained on each sieve size was used to determine aggregate distribution and mean weight diameter (MWD) as an indicator of soil aggregate stability. The MWD was calculated using the following equation:

$$MWD = \sum(x_i \times w_i)$$

Description:
MWD = mean weight diameter (mm)
X_i = mean diameter of each aggregate size fraction (mm)
W_i = proportion of the total sample weight retained in each aggregate fraction

The data obtained were analyzed using analysis of variance (ANOVA) with a factorial design to evaluate the effects of coffee management systems and soil depth on the observed parameters. Before analysis, the assumptions of normality and homogeneity of variance were tested. Normality of residuals was evaluated using the Shapiro–Wilk test, while homogeneity of variances was assessed using Levene's test. The sources of variation included treatment management, soil depth, and the interaction between treatment and depth (treatment × depth). Differences among treatments were considered statistically significant at $p \leq 0.05$. When significant effects were detected, Duncan's Multiple Range Test (DMRT) was performed for mean separation at the 95% confidence level. All statistical analyses were conducted using IBM SPSS Statistics version 27 (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

TOC Dynamics Across Soil Depths

The analysis of variance (ANOVA) demonstrated that coffee management systems significantly affected total organic carbon (TOC) dynamics across soil depths ($p < 0.001$; Table 3). Soil depth also exerted a highly significant influence on TOC distribution, indicating that carbon concentration varied substantially throughout the soil profile. In addition, a significant interaction between treatment management and soil depth ($p = 0.014$) suggested that the response of TOC to coffee management systems differed depending on soil depth.

Table 3. Analysis of Variance of TOC Dynamics under Different Coffee Agroecosystems and Soil Depths.

Source of Variation	DF	F	p
Treatment management	2	8.740	<0.001
Depth	3	24.528	<0.001
Treatment × Depth	6	3.126	0.014

Source: Authors' analysis based on primary data using ANOVA (2026).

Across all soil depths, total organic carbon (TOC) was significantly influenced by treatment management and soil depth (Table 3). Analysis of variance showed that treatment management significantly affected TOC content ($F = 8.740$; $p < 0.001$), while soil depth exerted an even stronger influence ($F = 24.528$; $p < 0.001$). In addition, the interaction between treatment management and soil depth was also significant ($F = 3.126$; $p = 0.014$), indicating that the effects of management systems on TOC varied across soil depths. In general, TOC content decreased with increasing soil depth across all management systems. Surface soils (0–10 cm) consistently exhibited greater TOC accumulation compared with deeper layers. This pattern is commonly observed in tropical agroecosystems due to continuous litter deposition, root turnover, rhizosphere activity, and greater microbial biomass near the soil surface (Kamau *et al.,* 2017). Organic residues deposited at the soil surface contribute directly to carbon accumulation and promote the formation of stable macroaggregates that physically protect organic matter from rapid decomposition (Zong *et al.,* 2025).

Among the evaluated systems, ORG consistently maintained higher TOC values than SEM and CON, particularly within the upper soil layer. The greater carbon accumulation under ORG was likely associated with continuous applications of cattle manure compost and coffee husk compost, which increased organic matter inputs into the soil system. Organic amendments not only supply carbon substrates for microbial activity but also enhance aggregate formation and improve soil structural stability (Oyebiyi *et al.,* 2026). Improved aggregation may reduce oxygen diffusion and microbial accessibility to protected organic matter, thereby slowing carbon mineralization and enhancing long-term carbon stabilization (Tang, 2025).

The SEM system exhibited intermediate TOC values, reflecting the combined influence of organic and inorganic management practices. Although organic materials were still incorporated into the system, partial dependence on synthetic inputs may reduce the efficiency of carbon stabilization compared with fully organic management. Meanwhile, CON generally showed lower TOC values across soil depths. Intensive use of synthetic fertilizers and lower organic residue return may accelerate soil organic matter decomposition and reduce soil carbon sequestration potential over time. Similar declines in soil carbon under intensive conventional management have been reported in several tropical agricultural systems, where continuous soil disturbance and limited organic inputs negatively affect carbon persistence (Zheng *et al.,* 2024).

The significant interaction between treatment management and soil depth indicated that differences among management systems were more pronounced in the upper soil layers than in deeper horizons. Surface soils under ORG likely benefited from greater organic residue accumulation and reduced disturbance intensity, while deeper layers exhibited smaller differences due to limited downward movement of fresh organic materials. This finding suggests that management practices primarily influence biologically active topsoil layers where most carbon cycling processes occur (Kaipakasseri *et al.,* 2026).

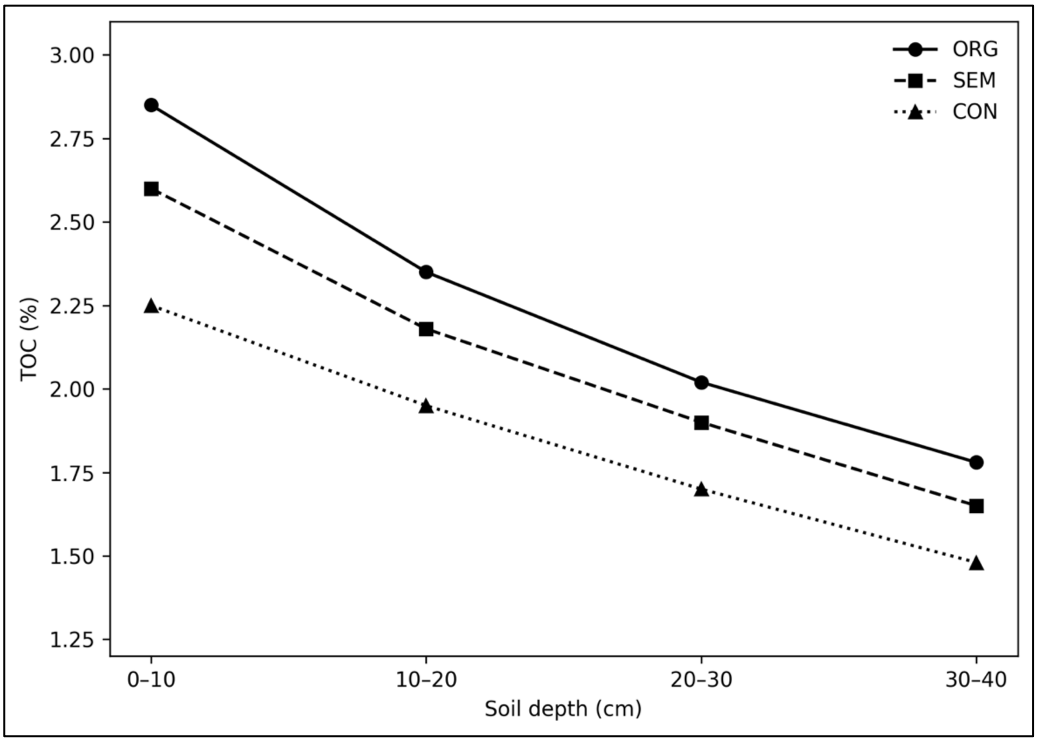

Figure 1. Effects of Different Coffee Agroecosystems on Total Organic Carbon (TOC) Dynamics Across Soil Depth Profiles

Total organic carbon (TOC) decreased progressively with increasing soil depth across all coffee management systems (Figure 2). Surface soils (0–10 cm) consistently exhibited higher TOC values than subsurface layers, indicating that organic carbon accumulation was concentrated in the upper soil horizon. This pattern is commonly observed in tropical agroecosystems due to continuous litter deposition, fine root turnover, rhizosphere activity, and greater microbial biomass near the soil surface (Gougoulias and Shaw, 2014). Among the evaluated management systems, ORG consistently showed the highest TOC values across all soil depths, followed by SEM and CON. At the 0–10 cm depth, ORG exhibited substantially greater TOC accumulation compared with SEM and CON, suggesting that continuous organic matter inputs from cattle manure compost and coffee husk compost enhanced soil carbon storage. Organic amendments are known to supply labile and stable carbon fractions that contribute to aggregate formation and long-term carbon stabilization within the soil matrix (Campos-Cascaredo *et al.,* 2021). In contrast, the lower TOC observed in SEM may be associated with the combined use of organic and inorganic fertilizers, which provides lower organic carbon inputs than fully organic management. Meanwhile, the lowest TOC values in CON were likely related to the predominance of inorganic fertilization and limited organic residue return to the soil, resulting in reduced carbon accumulation. These findings indicate that the quantity and continuity of organic matter inputs play an important role in maintaining soil carbon stocks under different coffee management systems. Similar responses have been reported in volcanic soils, where long-term fertilization practices influence carbon dynamics through changes in microbial activity and nutrient availability (Lyu *et al*., 2025).

The gradual decline in TOC with increasing depth likely reflected reduced incorporation of fresh organic residues and lower biological activity in deeper soil layers. Surface soils generally receive direct carbon inputs from plant litter, decomposing roots, and organic amendments, whereas deeper layers rely primarily on dissolved organic carbon movement and root-derived carbon inputs (Kumar *et al*., 2023). Consequently, differences among management systems became less pronounced at deeper depths due to limited downward transport of organic materials. The higher TOC values observed under ORG may also be associated with improved soil physical protection mechanisms. Soil organic carbon plays a crucial role in promoting aggregate stability and enhancing soil structural development. Organic matter acts as a binding agent that promotes the adhesion of soil particles into stable aggregates through microbial by-products, fungal hyphae, and root exudates. The formation of stable aggregates improves pore connectivity, water retention, and resistance to soil compaction and erosion. In addition, stable soil aggregates physically protect organic matter from microbial decomposition by limiting oxygen diffusion and microbial accessibility, thereby contributing to long-term carbon stabilization within the soil matrix (Das *et al*., 2025). In contrast, lower TOC values observed under CON may indicate accelerated organic matter mineralization resulting from intensive synthetic input use and reduced organic residue return to the soil surface (Khan *et al*., 2025).

The SEM system exhibited intermediate TOC values, reflecting the combined effects of organic and inorganic management practices. Although partial organic inputs may improve soil carbon retention, the continued use of synthetic fertilizers may reduce the efficiency of carbon stabilization compared with fully organic systems. Similar findings have been reported in tropical agricultural soils where integrated nutrient management improves soil quality but remains less effective than continuous organic management in maintaining long-term soil carbon storage (Maffia *et al.,* 2026). These studies demonstrate that a coffee management system based on organic inputs has the potential to enhance soil's function as a carbon sink in tropical highland agroecosystems. Increasing soil organic carbon not only supports coffee crop productivity but also strengthens the role of coffee plantations in providing environmental services through long-term carbon storage and reduced greenhouse gas emissions.

Bulk Density Across Soil Depths

Bulk density (BD) varied considerably among coffee management systems and soil depths (Figure 2). In general, BD increased progressively with increasing soil depth across all treatments. Surface soils (0–10 cm) exhibited lower BD values compared with subsurface layers, indicating that upper soil horizons possessed better soil structure and greater pore space. Conversely, deeper soil layers showed greater soil compaction and reduced porosity. This trend may be attributed to the gradual decline in organic matter content and biological activity with increasing soil depth, resulting in weaker aggregate formation and reduced structural stability.

In contrast, CON exhibited the highest BD values throughout the soil profile. Higher BD under conventional management may be associated with lower organic matter inputs and prolonged dependence on synthetic agricultural inputs, which may reduce aggregate stability and accelerate soil structural degradation. Intensive management practices may also increase soil compaction through repeated field activities and reduced biological activity, leading to lower macroporosity and restricted root penetration. Reduced pore space limits water infiltration and air exchange within the soil, thereby constraining root growth and microbial activity. Over time, these conditions may impair soil physical quality and reduce the capacity of the soil to retain carbon and support sustainable coffee production (Slepetiene *et al.,* 2025).

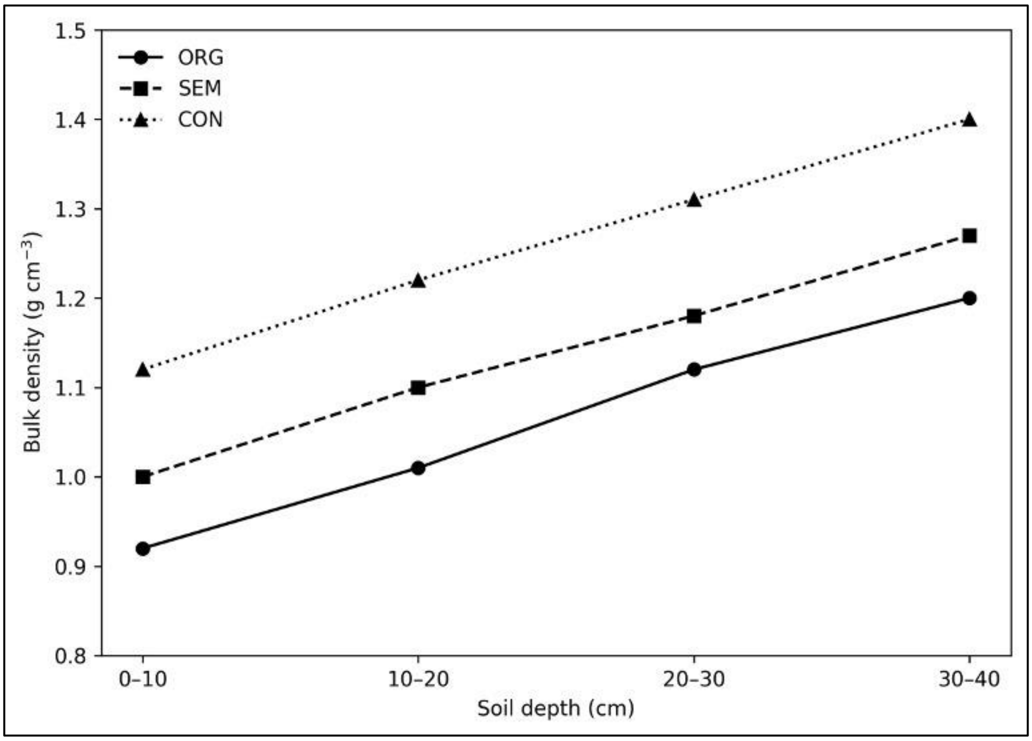

Figure 2. Effects of Different Coffee Agroecosystems on Soil Bulk Density Across Soil Depth Profiles

The gradual increase in BD with soil depth reflected the natural decline in soil organic matter and biological activity in subsurface horizons. Surface soils generally receive continuous additions of plant residues and root exudates that enhance aggregate formation and reduce soil density. In deeper layers, limited organic matter incorporation and reduced root abundance contribute to greater soil compactness. Similar vertical patterns of BD distribution have been widely reported in tropical agricultural soils and are closely associated with declining soil organic carbon concentrations with depth (Ma *et al.,* 2026). Improved soil structure, indicated by lower bulk density values in organic systems, also leads to increased water infiltration and groundwater storage capacity. This is crucial for maintaining the hydrological function of coffee agroecosystems, particularly in highland areas prone to erosion and nutrient loss due to surface runoff.

Carbon Sequestration Across Soil Depths

Carbon sequestration varied considerably among coffee management systems and soil depths (Figure 3). In general, carbon sequestration decreased progressively with increasing soil depth across all treatments. Surface soils (0–10 cm) exhibited the highest carbon sequestration values, whereas deeper soil layers showed substantially lower carbon accumulation. This pattern indicated that biologically active upper soil horizons played a dominant role in carbon storage within tropical coffee agroecosystems. Higher carbon sequestration in surface soils was likely associated with continuous inputs of organic residues, root exudates, and decomposing litter, which provide a major source of carbon for soil organic matter formation. In addition, greater microbial activity and aggregate formation in the upper soil layers may enhance carbon stabilization and retention. As soil depth increased, reduced organic matter inputs and lower biological activity limited carbon accumulation, resulting in lower carbon sequestration values.

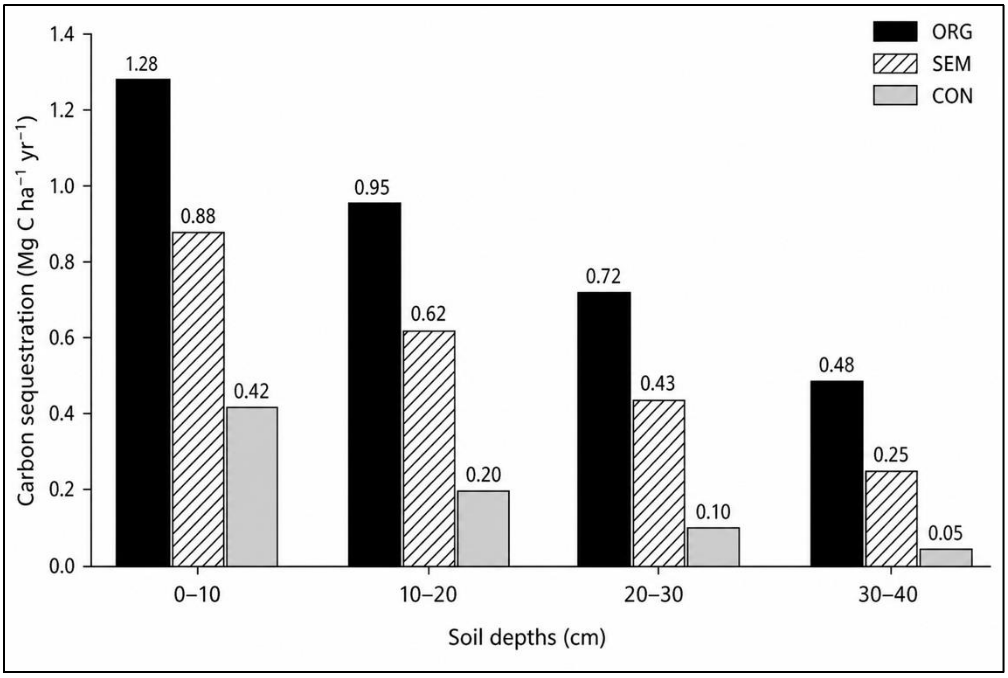

Figure 3. Carbon Sequestration Across Soil Depths under Different Agroecosystems

The decline in carbon sequestration with increasing soil depth was closely associated with reduced organic residue incorporation and lower microbial activity in subsurface soils. Surface layers continuously receive organic inputs derived from litter deposition, root turnover, compost application, and rhizosphere processes, which contribute significantly to soil carbon accumulation (Piccoli *et al.,* 2019). In deeper layers, limited organic matter inputs and lower root density reduce the potential for long-term carbon stabilization. In the present study, carbon sequestration values under ORG decreased from 1.28 Mg C ha^{-1} yr^{-1} at 0–10 cm depth to 0.48 Mg C ha^{-1} yr^{-1} at 30–40 cm depth. Similar declining trends were also observed under SEM and CON, indicating that carbon storage was predominantly concentrated within the biologically active surface horizon (Li *et al*., 2026a).

Among the evaluated systems, ORG consistently exhibited the greatest carbon sequestration across all soil depths. The higher sequestration potential under ORG was likely associated with continuous applications of cattle manure compost and coffee husk compost, which supplied substantial organic carbon inputs into the soil system. Organic amendments increase both labile and stable carbon fractions and promote aggregate formation that physically protects soil organic carbon from rapid microbial decomposition (Li *et al*., 2026b). At the 0–10 cm layer, ORG exhibited carbon sequestration values approximately 45.5% higher than SEM and more than three times greater than CON. This finding demonstrated the strong contribution of continuous organic matter inputs toward enhancing soil carbon storage in tropical coffee agroecosystems.

The SEM system showed intermediate carbon sequestration values, reflecting the combined influence of organic and inorganic management practices. Although partial organic inputs contributed to soil carbon accumulation, the sequestration potential remained lower than ORG due to continued dependence on synthetic agricultural inputs. Meanwhile, CON exhibited the lowest carbon sequestration values across all soil depths. At the 30–40 cm layer, carbon sequestration under CON was only 0.05 Mg C ha^{-1} yr^{-1}, indicating substantially lower carbon retention capacity compared with ORG and SEM. Lower carbon sequestration under CON may indicate accelerated mineralization of soil organic matter caused by limited organic residue return and intensive conventional management practices (Sebayang *et al.,* 2024).

From an environmental management perspective, the high carbon sequestration in organic coffee systems demonstrates that coffee agroecosystems have the potential to provide important environmental services in tropical agricultural landscapes. Higher soil carbon stocks contribute to climate change mitigation by increasing carbon storage capacity while strengthening ecosystem resilience to environmental stressors. Therefore, the implementation of organic-based coffee management systems can be considered a sustainable land management strategy that integrates agricultural production objectives with natural resource conservation (Pramulya *et al.,* 2026).

Agregate Stability

Soil aggregate stability varied substantially among coffee management systems and aggregate size fractions (Figure 4). In general, aggregate stability decreased with increasing aggregate size fraction, where the 63 µm fraction consistently exhibited the highest stability values, followed by 250 µm and 500 µm fractions. Differences among management systems were also clearly observed, particularly within the smaller aggregate fractions.

Organic coffee management (ORG) consistently exhibited greater aggregate stability compared with SEM and CON across all aggregate size fractions. The higher stability observed under ORG indicated that continuous organic matter inputs from cattle manure compost and coffee husk compost enhanced soil aggregation and strengthened aggregate resistance against slaking and dispersion. Organic matter acts as a cementing agent that binds mineral particles together and promotes the formation of stable soil aggregates (Jat *et al*., 2022). In the 63 µm fraction, aggregate stability under ORG reached 62%, compared with 55% under SEM and 42% under CON. Similar trends were also observed in the 250 µm and 500 µm fractions, where ORG consistently maintained the highest stability values across all treatments.

The highest aggregate stability values observed within the 63 µm fractions suggested that microaggregates possessed greater structural resistance than larger aggregate fractions. Aggregate stability declined progressively with increasing aggregate size fraction. Under ORG, stability decreased from 62% at 63 µm to 38% at 250 µm and 28% at 500 µm. Similar declining patterns were also evident under SEM and CON. Microaggregates are generally more stable because they physically protect organic matter within mineral-associated structures, thereby reducing microbial decomposition and aggregate breakdown (Inayah and Arbiwati, 2025). In contrast, macroaggregates are more susceptible to disruption caused by soil disturbance, wetting–drying cycles, and reduced organic binding agents (Wu *et al.,* 2021).

The lower aggregate stability observed under CON may indicate weaker soil structural development resulting from limited organic residue return and prolonged dependence on synthetic agricultural inputs. Reduced organic matter inputs may decrease microbial activity and weaken aggregate-binding mechanisms, leading to greater susceptibility to soil disintegration (Yin *et al.,* 2026). In the present study, CON exhibited the lowest aggregate stability values across all aggregate fractions, ranging from 42% at 63 µm to only 12% at 500 µm. Intensive conventional management practices may also accelerate aggregate turnover and reduce the persistence of stable soil structural units (Abdelrhman *et al.,* 2025).

The SEM system exhibited intermediate aggregate stability values across all aggregate fractions. Partial incorporation of organic amendments likely contributed to aggregate formation and stabilization; however, the effectiveness remained lower than fully organic management systems. At the 250 µm fraction, aggregate stability under SEM reached 30%, whereas ORG exhibited 38% and CON only 22%. Similar trends have been reported in tropical agricultural soils where integrated nutrient management improves aggregate stability but remains less effective than continuous organic matter application (Hidayat *et al.,* 2025).

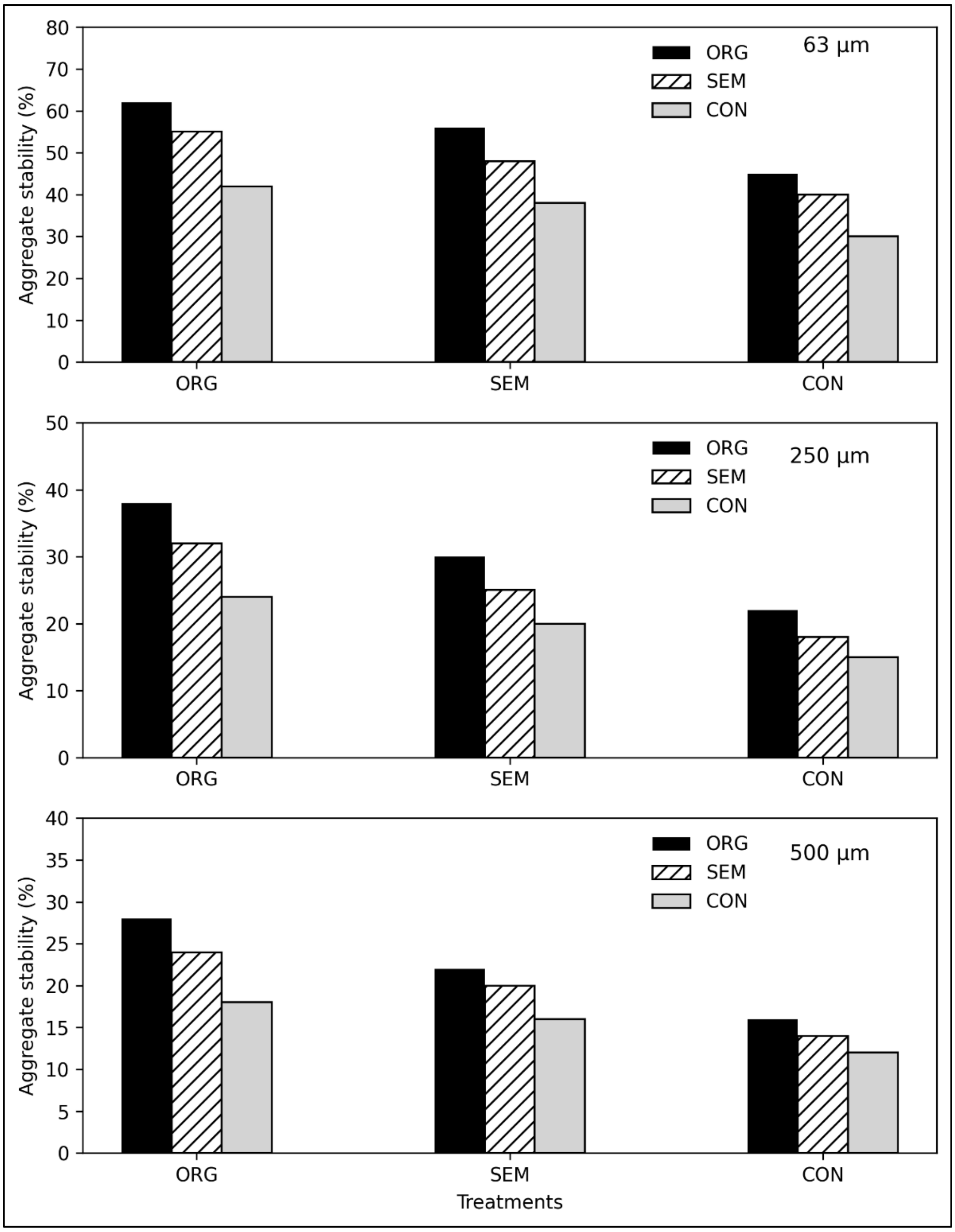

Figure 4. Aggregate Stability Across Different Aggregate Size Fractions Under Different Coffee Agroecosystems

The close relationship between aggregate stability and soil organic carbon observed in this study indicated that soils with higher TOC concentrations generally exhibited stronger aggregate stability. Soil organic carbon contributes directly to aggregate formation by enhancing microbial activity, fungal hyphae development, and organo-mineral interactions that physically stabilize soil particles (Xing *et al.,* 2025). Improved aggregate stability may subsequently enhance soil porosity, water infiltration, root penetration, and resistance to erosion, all of which are essential for maintaining long-term soil productivity and ecosystem sustainability (de Goede *et al.,* 2025). This relationship was clearly reflected in the present study, where ORG consistently showed higher TOC values accompanied by greater aggregate stability across all aggregate size fractions. Higher aggregate stability in organic coffee systems indicates that organic matter-based management can increase soil resilience to physical degradation processes, including erosion and soil structure damage. In the long term, this supports the sustainability of soil ecosystem function and the conservation of land resources in highland coffee agroecosystems (Dessureault-Rompré, 2022).

CONCLUSION AND RECOMMENDATION

Organic coffee management (ORG) significantly improved soil quality compared with semi-organic (SEM) and conventional management (CON) systems by increasing total organic carbon (TOC), carbon sequestration, and aggregate stability while reducing bulk density across soil depths. TOC and carbon sequestration were consistently higher in surface soils (0–10 cm) and gradually decreased with increasing soil depth, indicating greater carbon accumulation in biologically active topsoil layers. ORG also exhibited the greatest aggregate stability across all aggregate size fractions, particularly at 63 μm, suggesting stronger soil structural resistance and enhanced physical protection of soil organic carbon. In contrast, CON showed lower TOC, lower aggregate stability, and higher bulk density, indicating reduced soil structural quality and carbon retention potential. Overall, continuous organic matter inputs through organic coffee management contributed substantially to improving soil physical characteristics and long-term carbon stabilization in tropical highland coffee agroecosystems. Therefore, wider adoption of organic coffee management practices is recommended to enhance soil health, strengthen carbon sequestration, and support sustainable land management. These benefits contribute to climate change mitigation and support the achievement of Sustainable Development Goal 13 (Climate Action).

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