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Evaluation of Selected Soil Physical Properties in Oil Palm, Rubber, and Forest Land in Mukomuko Regency

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ABSTRACT

This study investigates the influence of land use on soil physical properties and horizon thickness in Mukomuko Regency, Indonesia, to assess the impacts of agricultural practices on soil quality. Conducted between February and April 2020, the research utilized a nested design across four districts, with laboratory analyses performed at the Soil Science Laboratory, Bengkulu University. Land use types evaluated included oil palm, rubber, and natural forest. Variables measured comprised soil structure, horizon thickness, aggregate stability, bulk density (BD), texture, and organic carbon (C-organic). Statistical analysis (ANOVA, $p < 0.05$) revealed significant effects of land use on BD, C-organic content, and soil texture, whereas aggregate stability was not significantly influenced by vegetation type or depth. Forest soils exhibited the highest C-organic content (5.78%) and lowest BD (0.82 g cm $^{-3}$), contrasting with oil palm soils, which had the lowest C-organic content (4.22%) and highest BD (0.86 g cm $^{-3}$). Texture analysis showed forest soils had higher sand (19.69%) and clay (50.20%) fractions, while rubber land had the highest silt content (57.59%). Soil physical properties generally declined with depth under rubber and oil palm but fluctuated in forest soils. These results suggest that vegetation type significantly affects soil quality, with forest ecosystems maintaining superior soil conditions compared to intensively managed agricultural systems. Adoption of sustainable land management practices is essential to mitigate soil degradation and enhance long-term productivity.

Keywords: horizon thickness, land use, soil degradation, soil health, sustainable land management

INTRODUCTION

Mukomuko Regency, situated within Bengkulu Province, Indonesia, was officially designated as an administrative district in 2003 following its separation from North Bengkulu Regency (Cahyadinata, 2008). Geographically, the region is bordered by the Indian Ocean to the west and Kerinci Seblat National Park (TNKS) to the east, placing it in a strategically important ecological and economic zone. Among the various economic sectors, plantation agriculture—particularly oil palm (*Elaeis guineensis*) cultivation—has emerged as a leading contributor to Indonesia's non-oil export economy. Mukomuko is currently the largest producer of oil palm within Bengkulu Province, with production levels showing a consistent upward trend driven by expanded cultivation areas and favorable fresh fruit bunch (FFB) prices (Aprizal *et al*., 2013).

Soil physical properties play a critical role in supporting plant growth, as they influence root development, water retention, aeration, and nutrient availability (Arifin, 2010). These properties exhibit spatial and temporal variability due to both natural and anthropogenic factors. Endogenous factors such as parent material, topography, climate, hydrology, and biological activity determine the process of soil genesis, while exogenous influences—such as land management practices, deforestation, fertilization, and the use of heavy agricultural machinery—may significantly alter soil characteristics and functionality (Karlen *et al*., 1997). Land use, defined as the human utilization of land resources (Arsyad, 2000), typically involves modifications to soil conditions aimed at optimizing crop productivity. However, intensive and mechanized land management practices, particularly repeated tillage operations, have been associated with adverse impacts such as soil compaction, reduced porosity, and inhibited root growth (Titiek & Utomo, 1995).

Oil palm, a shallow-rooted species, is particularly sensitive to water stress and thus requires specific edaphic conditions including loamy soil with effective drainage, high fertility, and deep soil profiles (Dwiyana *et al*., 2015). Nevertheless, long-term cultivation and nutrient imbalances often lead to soil degradation. Similarly, rubber (*Hevea brasiliensis*), another prominent crop in Mukomuko, demands distinct physical soil conditions such as a minimum soil depth of 100 cm, good drainage, and a balanced textural composition—typically 35% clay and 30% sand—for optimal growth (Anwar & Suwarto, 2016).

While the conversion of forest land to agricultural plantations, particularly oil palm, offers short-term economic benefits, it also introduces substantial environmental concerns. Forest clearance often leads to significant reductions in soil organic matter and deterioration of both physical and chemical soil properties, especially when associated with slash-and-burn practices. These activities accelerate nutrient leaching and result in long-term soil impoverishment (Syahputra *et al*., 2011). Forest ecosystems, as regulated under Indonesian Forestry Law No. 41/1999, play a crucial role in maintaining environmental stability through climate regulation, hydrological balance, and soil protection (Melaponty *et al*., 2019). The accumulation of forest litter contributes to soil conservation by minimizing raindrop impact,enhancing water infiltration, and improving soil structure and fertility (Abdallah *et al*., 2021 ; Arief, 1994).

Unsustainable land use practices are a major driver of land degradation, leading to reduced soil productivity and altered physical soil properties. Different land use systems—such as oil palm plantations, rubber plantations, and natural forests—exert distinct influences on soil management regimes and vegetation cover, thereby affecting soil characteristics. Accordingly, a comprehensive understanding of soil physical properties under varying land use types is essential to inform sustainable land management and conservation practices.

This study aims to evaluate and compare the physical properties and horizon thickness of soils under oil palm, rubber, and forest land uses in Mukomuko Regency. The findings are expected to contribute to a better understanding of soil dynamics about land use and provide a scientific basis for sustainable land resource management in the region.

MATERIALS AND METHODS

Time and location of the research

The research was conducted in Mukomuko Regency from February to April 2020. This study is part of a faculty research project comprising fieldwork and laboratory analysis. The fieldwork involved collecting undisturbed and disturbed soil samples from four different sub-districts: Lubuk Pinang, Mukomuko City, Teras Terunjam, and V Koto, located in Mukomuko Regency, Bengkulu Province. Laboratory analysis included the examination of soil samples collected during the fieldwork and was carried out at the Soil Science Laboratory of Bengkulu University.

Research design

The study employed a nested design, where the depth factor was nested within four types of vegetation. The vegetation types considered were oil palm (V_1), rubber (V_2), and primary and secondary forests (V_3). The soil depth layers were categorized as 0–10 cm (D_1), 10–20 cm (D_2), 20–30 cm (D_3), 30 –40 cm (D_4), and 40–50 cm (D_5). Each experimental unit was replicated four times across four different sub-districts/villages, resulting in 45 experimental units.

Materials and equipment

The materials used in this study included soil samples (both undisturbed and disturbed). The chemical solutions required for laboratory analysis included water, alcohol, distilled water (aquadest), potassium dichromate ($K_2Cr_2O_7$), and sulfuric acid (H_2SO_4).

The equipment used during the fieldwork included writing tools, a hoe, plastic sample rings, and 1-kg sample bags. The laboratory equipment included an oven, wet sieves, an aggregate machine, buckets, an analytical balance, 100 mL volumetric flasks, a spectrophotometer, Kjeldahl bottles, Erlenmeyer flasks, dropper pipettes, a distillation apparatus, and burettes.

Determination of sampling locations

The sampling locations were determined following a site survey conducted in Mukomuko Regency. The selected research sites were chosen based on specific criteria, including oil palm plantations, rubber plantations, and primary and secondary forests. These locations encompass four villages within different sub-districts: Lubuk Pinang, Mukomuko, Teras Terunjam, and Koto Sub-districts.

Soil sampling

This stage involved collecting disturbed and undisturbed soil samples from a depth interval of 10 cm, with each sample weighing approximately 1 kg. The samples were placed in plastic bags and sealed with rubber bands. Sampling activities were conducted at each experimental unit in the field, focusing on ob-servational variables across the four sub-district lo-cations in Mukomuko Regency.

Soil analysis

The disturbed and undisturbed soil samples collected from the oil palm plantations, rubber plantations, and primary and secondary forests were transported to the Soil Laboratory at the Faculty of Agriculture, Bengkulu University, for analysis according to the research variables.

Research variables

The observed variables consist of primary and supporting variables. The primary variables in-clude soil structure, horizon thickness, aggregate stability, bulk density, and soil texture. Meanwhile, the supporting variable is soil organic carbon (C-or-ganic), which is measured at a depth interval of 10 cm. The soil organic carbon content is analyzed using the Walkley and Black method in the Soil Science Laboratory.

Data analysis

The observational data were statistically ana-lyzed using analysis of variance (ANOVA) at a 5% significance level. If significant differences were observed among treatments, further analysis was conducted using Orthogonal Contrast tests to evaluate the effects of vegetation and the Least Significant Difference (LSD) test at a 5% significance level to assess the effects of depth.

RESULTS AND DISCUSSION

General overview of the research location

The research was conducted in Mukomuko Regency, which is geographically situated at 101° 01'15.1" – 101°51'29.6" East Longitude and 02° 16'32.0" – 03°07'46.0" South Latitude. The study covers four villages across different sub-districts, namely Lubuk Pinang Village in Lubuk Pinang Sub -district, which is located on forested and secondary forest land; Pondok Tengah Village in V Koto Sub-district; Selagan Jaya in the City of Mukomuko; and Pondok Kopi Village in Teras Terunjam Sub-district. These four villages and sub-districts represent distinct land units, with the exception of Lubuk Pinang Village, which represents primary and secondary forest land at varying soil depths (0-10 cm, 10-20 cm, 20-30 cm, and 30-40 cm).

The locations on oil palm plantations generally exhibit lower average organic carbon content, silt, and clay content, but higher sand fraction compared to rubber plantations and secondary forests. This difference is attributed to the higher organic matter contribution from the leaf litter of rubber plants, resulting in higher organic carbon content in rubber plantation soils compared to oil palm. High soil organic matter is typically associated with a decrease in sand fraction, while silt and clay fractions increase.

Based on observations in primary and secon-dary forest lands, the organic carbon content is lower compared to rubber and oil palm plantations. This is due to the sloping terrain in the forest areas, where steep slopes increase the kinetic energy (rainfall) of surface runoff, which, in turn, significantly impacts the release and transport of topsoil. The removal of topsoil by surface runoff results in the depletion of organic carbon, as the topsoil, rich in organic material, is carried away to flatter regions. This finding aligns with Monde *et al*. (2008), who reported that open lands are prone to significant erosion, and much of the organic carbon is lost through erosion during surface runoff. In contrast, forested land generally maintains higher organic carbon levels due to the accumulation of organic matter on the forest floor.

The organic carbon content tends to decrease with increasing soil depth, whether in rubber, oil palm, or forested land. This decrease is due to the accumulation of organic matter, primarily from fallen leaves, which is concentrated in the upper layers of soil, leading to a reduction in organic carbon as soil depth increases. Organic matter in forest soils tends to be lower than in rubber and oil palm plantations, due to the observation of forested land on sloping terrain. Soil carbon is directly related to soil organic matter, which fluctuates over time due to factors such as temperature, soil texture, soil management, and organic material inputs (Purbalisa *et al*., 2020). Temperature affects the rate of organic matter decomposition—higher temperatures accelerate the decomposition process. Clay-textured soils tend to retain organic matter better, while soil acidity is influenced by the decomposition of organic material. Soil management practices can reduce organic matter levels due to the loss of organic material through erosion, transport, or burning (Sukmawati & Harsani, 2018). The presence of organic material in deeper soil layers is often the result of soil mana-gement, transport by soil organisms, and organic matter leaching (Ichriani *et al*., 2012). Sipahutar *et al*. (2014) also reported a decline in organic carbon content with increasing soil depth.

Clay content tends to increase with depth, while dust content decreases with soil depth, and sand content does not show significant variation. At a depth of 0-20 cm, the soil texture of rubber plantations is classified as sandy clay, while at 20-30 cm, the soil texture is sandy clay loam, at 30-40 cm it is clay loam, and at 40-50 cm it is clay. For oil palm plantations, the soil texture at 0-10 cm is sandy clay, at 10-20 cm it is clay loam, at 20-40 cm it is clay loam, and at 40-50 cm it is clay. In the primary forest, the soil texture at 0-10 cm is clay loam, while at 20-50 cm it is clay. For secondary forest land, the soil texture across the 0-50 cm depth is clay.

The decrease in organic carbon content is largely due to the continuous supply of organic material to the upper soil layers. The presence of organic material in deeper layers results from soil management, transport by soil organisms, and leaching (Joos & Tender, 2022 ; Ichriani *et al*., 2012). This supports the findings of Lawrence *et al*. (2015) and Sipahutar *et al*. (2014), who reported a general decline in organic carbon content with increasing soil depth.

Based on observations of average soil depth across vegetation types, the organic carbon (C-organic) content in rubber plantations was recorded at 5.48%, slightly higher than in oil palm plantations, which had a value of 5.22%. This difference is attributed to the accumulation of organic matter, including plant litter and fallen leaves, on the soil surface. The higher organic carbon content in rubber plantations is primarily due to the continuous input of organic material.The dominant soil texture class in rubber plantations is silty clay (LtB), while in oil palm plantations, the dominant texture is clay loam (LLt) (Table 1).

In primary forests, the average organic carbon content across depths was 4.69%, lower than that in rubber and oil palm plantations but higher than in secondary forests, which had an average of 2.29%. This disparity in organic carbon content can be attributed to observations made on sloped areas. The steep gradients increase the kinetic energy of surface runoff caused by rainfall, resulting in the erosion of the topsoil layer rich in organic material. Consequently, organic carbon content decreases as the eroded material is transported to flatter areas. The dominant soil texture in both primary and secondary forests is clay (Lt).

Variance analysis

The results of variance analysis indicate that soil aggregates in the size ranges of 1–2 mm and 2–4 mm, as well as total aggregate stability, were not significantly affected by vegetation type or soil depth within the vegetation. However, the organic carbon (C-organic) content was significantly influenced by both vegetation type and soil depth within the vegetation.

Table 1. Organic carbon content and soil texture in rubber, oil palm. primary forest, and secondary forest lands at different soil depths

Vegetion types	Soil deph (cm)	C	Sand	Silt	Clay	Texture class
		(%)				
Rubber	0 – 10	6.65	15	61.33	23.67	LB
Rubber	20 – 30	5.83	12	63.33	24.67	LB
Rubber	20 – 30	5.09	11.33	45.33	43.33	LLtB
Rubber	30 – 40	4.92	10.33	41.67	48	LtB
Rubber	40 – 50	4.92	10.67	39.33	50	Lt
Average		5.48	11.87	50.20	37.93	LtB
Oil palm	0 – 10	6.27	18.33	59.33	22.33	LB
Oil palm	20 – 30	5.44	17.67	51.33	31	LLtB
Oil palm	20 – 30	4.97	16.33	48.33	35.33	LtB
Oil palm	30 – 40	4.87	18.00	46.67	35.33	LtB
Oil palm	40 – 50	4.57	23.67	35.00	41.33	Lt
Average		5.22	18.8	48.13	33.07	LLt
Primary forest	0 – 10	6.47	37.1	27.2	35.7	LLt
Primary forest	20 – 30	5.1	32.6	14	53.4	Lt
Primary forest	20 – 30	3.31	18.1	28.3	53.6	Lt
Primary forest	30 – 40	2.32	8.9	26.3	64.8	Lt
Primary forest	40 – 50	6.25	11.5	29.8	58.7	Lt
Average		4.69	21.64	25.11	53.25	Lt
Secondary forest	0 – 10	3.15	32.16	19.54	48.3	Lt
Secondary forest	20 – 30	2.21	25.14	28.51	46.35	Lt
Secondary forest	20 – 30	2.66	9.48	14.87	75.65	Lt
Secondary forest	30 – 40	1.91	8.08	10.7	81.22	Lt
Secondary forest	40 – 50	1.51	4.05	16.15	79.8	Lt
Average		2.29	15.78	17.95	66.27	Lt

Notes : LB = silty loam. LLtB = silty clay loam. LtB = silty clay. Lt = clay. LLt = clay loam

Bulk density (BD) showed no significant effect based on vegetation type but was significantly influenced by soil depth within the vegetation. The percentage of sand was not significantly affected by vegetation type or soil depth. In contrast, silt percentage was significantly influenced by vegetation type but not by soil depth. Finally, the clay percentage was significantly affected by vegetation type but not by soil depth (Table 2).

Table 2. Summary of variance analysis results

Variable	Vegetation types	Soil depth within vegetation
Aggregate stability 2-4 mm	1.64 ns	0.65 ns
Aggregate stability 1-2 mm	1.53 ns	1.97 ns
Total aggregate stability	2.47 ns	2.29 ns
C-organic	20.59*	2.43*
Bulk Density (BD)	0.23 ns	1.03*
Sand Percentage	1.67 ns	1.13 ns
Silt Percentage	16.52*	1.68 ns
Clay Percentage	16.51*	1.68 ns

Notes : * = Significant effect. ns = No significant effect

Differences in physical properties across land use types

Based on the results of the 5% LSD (Least Significant Difference) test (Table 3), the influence of vegetation types shows that the organic matter content across rubber plantations, oil palm plantations, and forest areas varies significantly. The organic matter content in rubber plantations is 4.48%, in oil palm plantations 4.22%, and in forest areas 5.78%, indicating that forest areas have higher organic matter content compared to rubber and oil palm plantations.

The differences in organic matter content among rubber, oil palm, and forest land use are quite pronounced. According to the criteria, forest areas have very high levels of C-organic content, while rubber and oil palm plantations are classified as having high levels. This is due to the higher organic matter supply from leaf litter in forest areas compared to rubber and oil palm plantations. Additionally, forest canopies are wider than those in rubber and oil palm plantations, resulting in significantly lower erosion rates in forest areas.

Frequent erosion reduces the topsoil layer as it is carried away by surface runoff. According to Ichriani *et al*. (2012), the topsoil layer continuously receives an ongoing supply of organic matter. Organic matter in the subsoil layer, however, is attributed to soil tillage, transport by soil organisms, and leaching of organic matter (Amini & Asoodar, 2015). Zhou *et al*. (2019) and Sipahutar *et al*. (2014) also reported that C-organic levels tend to decrease with increasing soil depth (Table 3).

Table 3. Effect of vegetation types

Vegetation types	C-organic (%)	Bulk density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)
Rubber	4.48 b	0.83	11.87	50.20 a	37.93 b
Oil Palm	4.22 b	0.86	18.8	48.13 a	33.07 b
Forest	5.78 a	0.82	19.69	22.72 b	57.59 a

Note: Values followed by the same letter within the same column are not significantly different according to the LSD test at a 5% significance level.

The bulk density (BD) in forest land is lower compared to rubber and oil palm plantations, likely due to the looser soil structure in forest areas, which results in lower bulk density values (Table 3). Similarly, rubber plantations have higher organic matter content than oil palm plantations, contributing to lower soil bulk density. In contrast, oil palm plantations contribute minimal organic matter due to the nature of oil palm trees, which do not shed their leaves frequently. This results in denser soil and relatively higher bulk density.

Soil texture reflects the relative proportions of sand, silt, and clay fractions within the soil. The analysis of soil texture showed that the highest sand fraction percentage was found in forest land, the highest silt fraction in rubber plantations, and the highest clay fraction in forest land.

Effect of vegetation types by depth

Vertically, the organic matter content at all observation points generally decreases with increasing soil depth (Table 4). This reduction in organic matter content at certain soil depths is attributed to the limited decomposition of organic material from the vegetation above. Organic matter tends to accumulate primarily on the soil surface.

The effect of depth on vegetation type shows a decline in organic matter content in rubber and oil palm plantations. In contrast, no decrease in organic matter content was observed in forest land, likely due to the slope gradient present in forest areas.

Observations from the LSD test at a 5% significance level show that the C-organic content in rubber and oil palm plantations decreases consistently with increasing soil depth. According to Ichiriani *et al*. (2012), the topsoil layer consistently receives a continuous supply of organic material. The presence of organic matter in deeper soil layers is attributed to soil tillage, transport by soil organisms, and the leaching of organic material (Prince, 2017).

Table 4. Effect of vegetation types by depth

Depth (cm)	Vegetation types		
	Rubber	Oil palm	Forest
	C-organic (%)		
D_1 (0–10)	6.65 a	6.27 a	3.73 a
D_2 (10–20)	5.83 ab	5.44 b	2.93 b
D_3 (20–30)	5.09 b	4.97 c	2.34 c
D_4 (30–40)	4.92 b	4.87 c	1.71 d
D_5 (40–50)	4.92 b	4.57 c	3.18 b

Note: Values followed by the same letter within the same column indicate no significant difference according to the LSD test at a 5% significance level.

Sipahutar *et al*. (2014) also reported that C-organic content tends to decrease with increasing soil depth. However, in forest land, C-organic content decreases from depths of 0–10 cm to 30–40 cm but increases at 40–50 cm. Vertically, the increased C-organic content at 40–50 cm is likely due to observations in sloped areas where organic material moves downward with soil. This is consistent with the findings of Monde *et al*. (2008), who stated that open land is highly susceptible to erosion, and during surface runoff, a significant portion of C-organic is carried away. Conversely, forested areas have higher C-organic content due to the accumulation of organic material on the forest floor (Xiong *et al*., 2023).

Soil profile depth

Soil profile observations in the rubber plantation revealed the presence of five distinct horizons: horizon A1 (0–3 cm) characterized by a granular structure, horizon A2 (3–14 cm) with a granular structure, horizon A3 (14–20 cm) also exhibiting a granular structure, horizon B (20–30 cm) with a blocky structure, and horizon B1 (30–50 cm) likewise exhibiting a blocky structure. In the oil palm plantation, three horizons were identified: horizon A1 (0–2 cm) with a granular structure, horizon A2 (2–23 cm) also with a granular structure, and horizon A3 (23–50 cm) displaying a blocky structure. In contrast, the forest soil profile comprised four horizons: horizon O (0–6 cm) with a granular structure, horizon A1 (6–16 cm) with a granular structure, horizon A2 (16–30 cm) exhibiting a blocky structure, and horizon B (30–50 cm) with a blocky structure (Table 5).

The soil color observations revealed five soil colors in the rubber plantation, three in the oil palm plantation, and five in the forest soil (Table 5). The horizons within the soil profile differed in the number of roots and stones present. Plant roots were predominantly found in the upper soil layers, while stones were more commonly observed in the lower horizons. The average percentage of stones in the soil profile on slopes indicates that the lower slope positions (downslope) tend to accumulate eroded material from the upper slopes. Due to gravity, finer particles such as silt and clay are transported more easily than gravel and stones. These stones pose mechanical resistance to root growth as roots cannot penetrate compact layers or stones (Alfiyah *et al*., 2020).

Table 5. Soil profile depth

Vegetation types	Depth (cm)	Horizon	Structure	Soil color
Rubber	0–3	A1	Granular	7.5 YR 4/1 (Dark Gray)
	3–14	A2	Granular	7.5 YR 5/8 (Strong Brown)
	14–20	A3	Granular	7.5 YR 6/6 (Reddish Yellow)
	20–30	B	Blocky	7.5 YR 6/4 (Light Brown)
	30–50	B1	Blocky	7.5 YR 6/6 (Reddish Yellow)
Oil Palm	0–2	A1	Granular	7.5 YR 4/6 (Strong Brown)
	2–23	A2	Granular	5 YR 3/2 (Dark Reddish Brown)
	23–50	A3	Blocky	7.5 YR 5/8 (Strong Brown)
Forest	0–6	O	Granular	5 YR 3/3 (Dark Reddish Brown)
	6–16	A1	Granular	5.6 YR 4/4 (Reddish Brown)
	16–30	A2	Blocky	7.5 YR 4/6 (Strong Brown)
	30–50	B	Blocky	7.5 YR 5/8 (Strong Brown)

Note: Description of soil profile observations conducted in Mukomuko Regency

Soil organic matter is a critical factor influencing the physical properties of soil (Kumar *et al*., 2022). Analysis of C-organic content at three soil depths showed that forest soils had higher C-organic content compared to the other two sites. In contrast, soils in the oil palm plantation exhibited the lowest organic matter content across all three soil depths.

Aggregate stability

Stable aggregate stability creates favorable conditions for plant growth. Aggregates contribute to an optimal physical environment for root development by influencing soil porosity, aeration, and water retention. In soils with unstable aggregates, disturbances can cause the aggregates to disintegrate easily. Fine particles resulting from disintegration can clog soil pores, increasing bulk density, reducing aeration, and slowing permeability. Aggregate stability also significantly determines the soil's susceptibility to erosion.

The variation in aggregate stability across three land uses—rubber, oil palm, and forest—is presented in Table 6. At the rubber plantation, the highest aggregate stability for 1–2 mm particle size was observed at a depth of 20–30 cm, for 2–4 mm particle size at 10–20 cm depth, and for total aggregate stability at 0–10 cm depth. In the oil palm plantation, the highest values for 1–2 mm particle size occurred at 10–20 cm depth, and for both 2–4 mm particle size and total aggregate stability, the highest values were observed at 10–20 cm depth. In the forest soil, the differences in 1–2 mm aggregate size were minimal across all depths, while the highest values for 2–4 mm particle size and total aggregate stability were recorded at 0–10 cm depth. Differences in soil aggregate stability across the three land types (rubber, oil palm, and forest) are influenced by organic matter content, which affects soil bulk density, increases total soil porosity, and enhances soil aggregate stability. Unstable aggregates occur due to the loss of binding materials, leading to disintegration into individual soil particles (Rahmat *et al*., 2020).

Soil aggregates are clusters of soil particles bound together more strongly than to surrounding particles. Aggregate stability can be defined as the soil's ability to resist disruptive forces (Azizi *et al*., 2021). Organic matter acts as a binding agent for soil particles, enhancing the stability of the soil structure. Soils with high organic matter content are more resilient due to their strong binding capacity, which protects them from the disintegrating effects of raindrop impact and prevents erosion caused by surface runoff (Alfaredzi *et al*., 2023; Fadila *et al*., 2022). Additionally, adequate organic matter content promotes a crumbly soil structure, balances macro- and microporosity, and improves soil water and air availability, thereby supporting plant growth (Nikiyuluw *et al*., 2018).

Across all land uses, the 0-10 cm depth consistently shows the highest total aggregate stability, suggesting that surface soil is better aggregated, likely due to organic matter and biological activity. Aggregate stability decreases with increasing depth for all land uses, with forest soils exhibiting better stability retention compared to rubber and oil palm lands. Forest soils have the most stable aggregates overall, particularly in the 1-2 mm size fraction. In contrast, rubber and oil palm lands show greater instability at lower depths, likely due to soil compaction or reduced organic inputs. The 2-4 mm fraction plays a dominant role in surface stability, while the 1-2 mm fraction contributes more at greater depths.

Table 6. Aggregate stability

Vegetation types	Depth (cm)	Aggregate stability		
		1-2 mm	2-4 mm	Total
Rubber	D_1 (0-10)	9 ab	61.93 a	75.35 a
	D_2 (10-20)	18.07 ab	49.77 ab	63.98 ab
	D_3 (20-30)	22.53 a	21.33 bc	42.49 bc
	D_4 (30-40)	20.27 a	7.27 c	31.26 c
	D_5 (40-50)	7.17 b	27.37 abc	44.92 bc
Oil Palm	D_1 (0-10)	11.27 ab	29.43 a	47.09 a
	D_2 (10-20)	19.60 ab	41.83 ab	57.97 ab
	D_3 (20-30)	17.33 ab	10.57 c	33.67 c
	D_4 (30-40)	10.30 c	7.23 abc	30.01 c
	D_5 (40-50)	10.40 c	10.53 abc	32.39 c
Forest	D1 (0-10)	17.67 a	44.87 a	57.08 a
	D2 (10-20)	18.73 a	28.60 ab	41.61 ab
	D3 (20-30)	22.20 a	29.90 ab	43.50 ab
	D4 (30-40)	21.07 a	11.30 c	27.30 c
	D5 (40-50)	22.27 a	13.03 c	28.93 c

Note: Values followed by the same letter within the same column are not significantly different according to the LSD test at a 5% significance level

Forest soils exhibit the highest aggregate stability across all depths, indicating their superior soil structure and resilience. Rubber and oil palm lands demonstrate lower stability, particularly in deeper layers, reflecting the impact of agricultural activities on soil health. The findings underscore the importance of land management practices in preserving soil aggregate stability and overall soil quality.

In rubber plantations, bulk density remains relatively consistent across the soil profile, ranging from 0.77 to 0.86 g cm^{-3} (Table 7). The absence of significant variation between most depth intervals suggests minimal soil compaction and a relatively uniform soil structure. This condition may be attributed to less intensive land management practices or to the morphological characteristics of rubber tree root systems, which potentially reduce mechanical disturbance.

Conversely, in oil palm plantations, bulk density exhibits a clear increasing trend with soil depth, reaching a maximum of 0.90 g cm⁻³ at the 40–50 cm depth (D_5). This pattern indicates considerable soil compaction, likely resulting from the recurrent use of heavy machinery for plantation maintenance and harvesting operations. Moreover, the observed increase in bulk density at greater depths may also be influenced by a decline in organic matter inputs, leading to reduced soil porosity and increased compaction, thereby underscoring the significant impact of plantation management on subsurface soil physical properties.

Table 7. Vegetation types by depth and bulk density

Depth (cm)	Vegetation types		
	Rubber	Oil palm	Forestry
	Bulk density (g cm^{-3})		
D1 (0-10)	0.77 b	0.84 b	1.13 a
D2 (10-20)	0.86 a	0.86 b	0.79 b
D3 (20-30)	0.85 a	0.86 b	0.71 b
D4 (30-40)	0.85 a	0.85 b	0.76 b
D5 (40-50)	0.83 a	0.90 a	0.70 b

Note: Values followed by the same letter within the same column are not significantly different according to the LSD test at a 5% significance level

In natural forest ecosystems, bulk density is consistently lower below the surface layer (D_1), with values ranging from 0.70 to 0.79 g cm^{-3} at deeper depths. These lower values reflect superior soil structure, greater porosity, and enhanced aeration relative to plantation soils. The favorable bulk density profile in forest soils is likely a consequence of minimal anthropogenic disturbance, substantial organic matter accumulation, and the presence of diverse and extensive root systems that promote soil aggregation and stability. This observation highlights the comparatively higher soil quality and ecological functionality under natural forest cover.

Overall, soils under forest vegetation exhibit lower bulk density across most depths compared to those in rubber and oil palm plantations, indicating reduced compaction and better soil physical conditions. The elevated bulk density values in plantation soils, particularly in deeper layers, are likely attributable to intensive agricultural practices and diminished porosity. These findings underscore the necessity for implementing sustainable land management strategies aimed at mitigating soil compaction and maintaining long-term soil health.

CONCLUSION

This study confirms that land use significantly influences soil physical and chemical properties. Aggregate stability (1–2 mm, 2–4 mm, total) was not significantly affected by vegetation type or depth, indicating stable soil structure across systems. Bulk density varied with vegetation type, with higher compaction observed in oil palm plantations, but showed no depth-related changes. SOC content was significantly influenced by both vegetation and depth, with forests exhibiting the highest SOC (5.78%) and oil palm the lowest (4.22%). Sand and clay fractions differed significantly across land uses—forest soils had the highest sand (19.69%) and clay (50.20%) contents—while rubber plantations showed the highest silt content (57.59%). No significant texture variations were observed with depth. Soil quality generally declined with depth in plantation systems, suggesting reduced organic inputs and structural integrity, whereas forest soils displayed more variable patterns due to heterogeneous litter inputs and biological activity. These results highlight the critical role of vegetation in maintaining soil quality. Natural forests improve soil carbon and texture, while intensive uses like oil palm cultivation degrade soil health. Sustainable management practices that reduce disturbance, retain vegetative cover, and enhance organic inputs are essential to preserving soil functionality and ensuring long-term agricultural resilience.

References

Abdallah, A. M., Jat, H. S., Choudhary, M., Abdelaty, E. F., Sharma, P. C. & Jat, M. L. (2021). Conservation agriculture effects on soil water holding capacity and water-saving varied with management practices and agroecological conditions: A Review. *Agronomy*, 11(9), 1681. DOI: https://doi.org/10.3390/agronomy11091681.

Alfaredzi, R., Syakur, S., Khairullah, K. (2023). Evaluasi sifat fisika tanah pada penggunaan lahan monokultur dan polikultur di Kecamatan Labuhan Haji Kabupaten Aceh Selatan. *Jurnal Ilmiah Mahasiswa (JIM) Pertanian*, 8(1), 369–374. DOI: https://doi.org/10.17969/jimfp.v8i1.23043.

Alfiyah, F., Nugroho, Y. & Rudy, G. S. (2020). Pengaruh kelas lereng dan tutupan lahan terhadap solum tanah, kedalaman efektif akar dan pH tanah. *Jurnal Sylva Scienteae*, 3(3), 499–508.

Amini, S. & Asoodar, M.A. (2015). Investigation the effect of conservation tillage on soil organic matter (SOM) and soil organic carbon (SOC) (The Review). *New York Science Journal*, 8 (3), 16-24. DOI: https://doi.org/10.7537/marsnys080315.03.

Anwar, R. N. & Suwarto. (2016). Pengelolaan tanaman taret (*Hevea brasiliensis* Muell. Arg) di Sumatera Utara dengan aspek khusus pembibitan. *Buletin Agrohorti*, 4(1), 94–103.

Aprizal, Asriani, P. S. & Sriyoto. (2013). Analisis daya saing usahatani kelapa sawit di Kabupaten Mukomuko (Studi Kasus Desa Bumi Mulya). *Jurnal AGRISEP*, 12(2), 133–146. DOI: https://doi.org/10.31186/jagrisep.12.2.133-146.

Arief, A. (1994). Hutan Hakikat dan Pengaruh Terhadap Lingkungan. Yayasan Obor Indonesia, Jakarta.

Arifin, M. (2010). Kajian sifat fisik tanah dan berbagai penggunaan lahan dalam hubungannya dengan pendugaan erosi tanah. *Jurnal Pertanian MAPETA*, 12(2), 72–144.

Arsyad, S. (2000). Konservasi Tanah dan Air. UPT Produksi Media Informasi. Lembaga Sumberdaya Informasi. IPB Press., Bogor.

Azizi, S., Hendarto, K. & Buchari, H. (2021). Pengaruh pemberian pupuk hayati dan pupuk pelengkap alkalis terhadap kemantapan agregat tanah dan hasil produksi cabai merah. DOI:https://doi.org/10.25181/jplantasimbiosa.v3i1.2099.

Cahyadinata, I. (2008). Pemetaan produk andalan sektor pertanian di Kabupaten Mukomuko. *Jurnal AGRISEP*, 7(2), 69–81. DOI: https://doi.org/10.31186/jagrisep.7.2.69-81.

Dwiyana, S.R., Sampoerno, S., Ardian, A. (2015). Waktu dan volume pemberian air pada bibit kelapa sawit (*Elaeis gueneensis* Jacq) di main nursery. *Jurnal Online Mahasiswa Fakultas Pertanian Universitas Riau*, 2(1), 1-10.

Fadila, I., Khairullah, K. & Manfarizah, M. (2022). Analisis indeks stabilitas agregat tanah pada beberapa kelas lereng dan penggunaan lahan di Kecamatan Bukit Kabupaten Bener Meriah. *Jurnal Ilmiah Mahasiswa Pertanian*,7(2),705–711.

Ichriani, G. I., Atikah, T. A., S, Z. & Fatmawati, R. (2012). Kompos tandan kosong kelapa sawit untuk perbaikan daya simpan air tanah kapasitas lapang. *Jurnal Penelitian Universitas Palangkaraya*, 19(3), 160–164.

Joos, L. & Tender. C.D. (2022). Soil under stress: The importance of soil life and how it is influenced by (micro)plastic pollution. *Computational and Structural Biotechnology Journal*, 20, 1554-1566. DOI: https://doi.org/ 10.1016/j.csbj.2022.03.041.

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F. & Schuman, G. E. (1997). Soil quality: A concept, definition, and framework for evaluation (A Guest Editorial). *Soil Science Society of America Journal*, 61(1), 4–10. DOI: https://doi.org/10.2136/sssaj1997.03615995006100010001x.

Kumar, Y.R., Kaushal, S., Kaur, G. & Gulati, D. (2022). Effect of soil organic matter on physical properties of soil. *Just Agriculture*. 1(2), 25-30.

Lawrence, C.R., Harden, J.W., Xu, X., Schulz, M.S. & Trumbore, S.E. (2015). Long-term controls on soil organic carbon with depth and time: A case study from the Cowlitz River Chronosequence, WA USA. Geoderma, 247-248, 73-87. DOI: https://doi.org/10.1016/j.geoderma.2015.02.005.

Melaponty, D. P., Fahrizal & Manurung, T. F. (2019). Keanekaragaman jenis vegetasi tegakan hutan pada kawasan hutan Kota Bukit Senja Kecamatan Singkawang Tengah Kota Singkawang. *Jurnal Hutan Lestari*, 7(2), 893–904. DOI: https://doi.org/10.26418/jhl.v7i2. 34558.

Monde, O. A., Sinukaban, N., Murtilaksono, K. & Pandjaitan, N. (2008). Dinamika karbon (C) akibat alih guna lahan hutan menjadi lahan pertanian. *J. Agroland*, 15(1), 22–26.

Nikiyuluw, V., Soplanit, R. & Siregar, A. (2018). Efisiensi pemberian air dan kompos terhadap mineralisasi NPK pada tanah Regosol. *Jurnal Budidaya Pertanian*, 14(2), 105–122. DOI: https://doi.org/10.30598/jbdp.2018.14.2.105.

Prince, P. (2017). Soil organic matter/carbon dynamics in contrasting tillage and land management systems: A case for smallholder farmers with degraded and marginal soils. *Communications in Soil Science and Plant Analysis*. 48. 1-19. DOI: https://doi.org/10.1080/00103624.2017.1406099.

Rahmat, S., Khairullah & Sufardi. (2020). Sifat fisika Entisols Darussalam setelah pemberian pembenah tanah pada pertanaman sawi musim tanam ke empat. *Jurnal Ilmiah Maha-siswa Pertanian*, 5(2), 317–326.

Sipahutar, A., Marbun, P. & Fauzi. (2014).Kajian C-organik, N dan P Humitropepts pada ketinggian tempat yang berbeda di Kecamatan Lintong Nihuta. *Jurnal Online Agroekoteknologi*, 2(4),1332–1338.

Syahputra, E., Sarbino & Dian, S. (2011). Weeds assessment di perkebunan kelapa sawit lahan Gambut. *J. Tek. Perkebunan & PSDL*, 1(1), 37–42. DOI: https://doi.org/10.26418/plt.v1i1.120.

Titiek, & Utomo, W.(1995). Hubungan Tanah, Air dan Tanaman. IKIP Semarang Press., Semarang.

Xiong, J., Wang, G., Richter, A., DeLuca, T.H., Zhang, W., Sun, H., Hu, Z., Sun, X. & Sun, S. (2023). Soil organic carbon accumulation and microbial carbon use efficiency in subalpine coniferous forest as influenced by forest floor vegetative communities. *Geoderma*, 438. DOI:https://doi.org/10.1016/j.geoderma.2023.116648.

Zhou, W., Han, G., Liu, M. & Li, X. (2019). Effects of soil pH and texture on soil carbon and nitrogen in soil profiles under different land uses in Mun River Basin, Northeast Thailand. *PeerJ* 7:e7880. DOI: https://doi.org/10.7717/peerj.7880.