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THE INTERACTIVE EFFECT OF OIL PALM AGE AND SLOPE SLOPE ON SOIL PHYSICAL PROPERTIES IN BILAH SUB-WATERSHEDS

PENGARUH INTERAKTIF UMUR KELAPA SAWIT DAN KEMIRINGAN LERENG TERHADAP SIFAT FISIK TANAH DI SUB-DAS BILAH

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ABSTRACT

Oil palm (Elaeis guineensis Jacq.) expansion in tropical watersheds has raised concerns regarding soil physical degradation and its implications for hydrological functioning. This study investigated the effects of plantation age and slope gradient, as well as their interaction, on soil physical properties in the Bilah sub-watershed, North Sumatra, Indonesia. The study was conducted at Negeri Lama Village, District of Bilah Hilir, Labuhanbatu Regency from May to August 2025. A field survey was conducted across oil palm stands of different ages (0, 5, and 12 years) and slope classes (3–8% and 8–15%) using a factorial design with three replications. Soil samples were collected at depths of 0–30 cm and 30–60 cm to analyze bulk density, soil organic matter, total pore space, water content, and permeability. The results showed that increasing plantation age significantly improved soil physical quality, as indicated by higher soil organic matter, total pore space, water content, and permeability, alongside reduced bulk density. In contrast, steeper slopes were associated with soil degradation, reflected in increased bulk density and reduced porosity, moisture retention, and permeability. The interaction between plantation age and slope gradient revealed spatial variability in soil physical recovery, particularly under moderate slopes where improvements were more pronounced. These findings highlight the importance of considering both biotic (plant age) and topographic (slope) factors in managing soil quality within oil palm-dominated landscapes. The study provides a scientific basis for site-specific soil conservation strategies to enhance long-term productivity while maintaining watershed ecological functions.

KATA KUNCI:

Bulk denisty, kelapa sawit, lereng, sifat fisik tanah, umur pohon

ABSTRAK

Ekspansi kelapa sawit (*Elaeis guineensis* Jacq.) di daerah aliran sungai tropis telah menimbulkan kekhawatiran mengenai degradasi fisik tanah dan implikasinya terhadap fungsi hidrologi. Studi ini menyelidiki pengaruh umur perkebunan dan gradien kemiringan, serta interaksi keduanya, terhadap sifat fisik tanah di sub-daerah aliran sungai Bilah, Sumatera Utara, Indonesia. Penelitian dilakukan di Desa Negeri Lama, Kecamatan Bilah Hilir, Kabupaten Labuhanbatu dari Mei Sampai Agustus 2025. Survei lapangan dilakukan di seluruh tegakan kelapa sawit dengan umur yang berbeda (0, 5, dan 12 tahun) dan kelas kemiringan (3–8% dan 8–15%) menggunakan desain faktorial dengan tiga ulangan. Sampel tanah dikumpulkan pada kedalaman 0–30 cm dan 30–60 cm untuk menganalisis kerapatan curah, bahan organik tanah, ruang pori total, kadar air, dan permeabilitas. Hasil menunjukkan bahwa peningkatan umur perkebunan secara signifikan meningkatkan kualitas fisik tanah, yang ditunjukkan oleh bahan organik tanah, ruang pori total, kadar air, dan permeabilitas yang lebih tinggi, serta penurunan kerapatan curah. Sebaliknya, kemiringan yang lebih curam dikaitkan dengan degradasi tanah, yang tercermin dalam peningkatan kerapatan curah dan penurunan porositas, retensi kelembaban, dan permeabilitas. Interaksi antara umur perkebunan dan gradien kemiringan mengungkapkan variabilitas spasial dalam pemulihan fisik tanah, terutama pada kemiringan sedang di mana perbaikan lebih terlihat jelas. Temuan ini menyoroti pentingnya mempertimbangkan faktor biotik (umur tanaman) dan topografi (kemiringan) dalam mengelola kualitas tanah di lanskap yang didominasi kelapa sawit. Studi ini memberikan dasar ilmiah untuk strategi konservasi tanah spesifik lokasi guna meningkatkan produktivitas jangka panjang sambil mempertahankan fungsi ekologis daerah aliran sungai.

1. INTRODUCTION

The rapid expansion of oil palm plantations (*Elaeis guineensis* Jacq.) in Indonesia has positioned the country as the world's leading producer of crude palm oil (CPO) (Santoso *et al.,*2023; Directorate General of Plantations, 2024). While this expansion contributes significantly to national economic growth (Wijaya & Siregar, 2022), it also raises serious environmental concerns, particularly regarding land degradation and watershed sustainability (Murdiyarso *et al.,*2023; Tarigan *et al.,*2025). Soil physical properties, including bulk density, porosity, water content, and permeability, play a fundamental role in regulating soil hydrological functions, such as infiltration, storage, and runoff (Nugroho *et al.,*2021; Hillel, 1980, cited in Fitriani *et al.,*2022). C hanges in these properties can disrupt soil structure, reduce water-holding capacity, and increase erosion risk (Prasetyo & Nugroho, 2024), ultimately affecting agricultural productivity and ecosystem stability (Lestari *et al.,* 2025).

The widespread conversion of land to oil palm plantations is widely recognized as a major driver of soil physical property degradation (Susanti *et al.,*2021; van Straaten *et al.,* 2022). Mechanical disturbances during land clearing often lead to soil compaction, reduced porosity, and decreased infiltration rates (Fitriani *et al.,* 2022). However, these impacts are not static and can change over time with the age of the plantation (Hidayat *et al.,*2025). Younger plantations generally exhibit higher levels of soil disturbance, whereas older plantations may show partial recovery due to increased organic matter input, root development, and canopy closure (Rahayu & Sitorus, 2024; Panggabean *et al.,* 2024). Topography, particularly slope gradient, further complicates these dynamics (Sulistiyono *et al.,*2023). Steeper slopes are more susceptible to erosion, which selectively removes fine particles and organic matter, thereby damaging soil structure and reducing water retention capacity (Widianingsih *et al.,* 2025; Zhang *et al.,* 2023). Therefore, the interaction between plantation age and slope gradient can result in complex spatial patterns in soil physical properties (Lestari *et al.,* 2025).

A report from the Environmental Agency of North Sumatra Province (2022) indicated a decline in the quality of the Bilah Sub-watershed, characterized by high sediment loads in the Bilah River and unstable water discharge fluctuations, suggesting disruption of hydrological regulation. This disruption is strongly suspected to be related to land cover changes and cultivation practices in the upstream areas. However, to date, comprehensive and detailed scientific data on the actual condition of soil physical properties, as well as the influence of plantation age and slope gradient, remain very limited. This data gap hinders the formulation of evidence-based policies and management recommendations for achieving the sustainability of oil palm plantations in the region. Based on this urgency and knowledge gap, this research is designed to conduct an in-depth investigation into the soil physical properties of oil palm plantations in the Bilah Sub-watershed.

Despite its importance, the combined influence of plantation age and slope gradient on soil physical properties in tropical oil palm systems is still not adequately understood, particularly at the sub-watershed scale (Tarigan *et al.,* 2025; Panggabean *et al.,* 2024). This study aims to fill this gap by evaluating the individual and interactive effects of these two factors on key soil physical property parameters in the Bilah Sub-watershed, North Sumatra.

2. MATERIALS AND METHODS

2.1 Research Location and Time

The research was conducted from May to August 2025. This study was carried out in an oil palm plantation (*Elaeis guineensis* Jacq.) located in Negeri Lama Village, Bilah Hilir District, Labuhan Batu Regency, North Sumatra, Indonesia (N: 098.011'.22.41" E: 02.016'.24.31"), as shown in Figure 1.

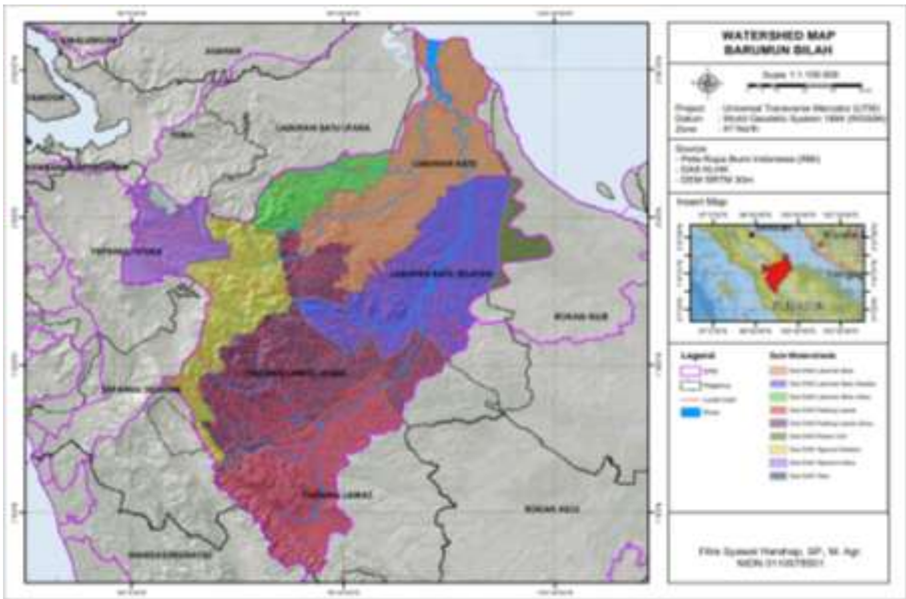

Figure 1. Administrative Map of the Research Location

The research location is situated within the Bilah sub-watershed, a tropical lowland area characterized by intensive oil palm cultivation. This region experiences a humid tropical climate with relatively high annual rainfall and temperature, supporting year-round agricultural activities. The soil at the research site is classified as Inceptisol, which has relatively young pedogenic properties, characterized by moderate development and diverse textures. The research location is situated at an elevation of approximately 15 m above sea level. The topography of the area is heterogeneous, ranging from gentle to moderately steep slopes, making it suitable for evaluating the influence of slope gradient on soil properties.

2.2 Tools and Materials

This research used two types of soil samples: undisturbed soil samples and disturbed soil samples. Samples were collected compositely from two depth layers, namely 0-30 cm and 30-60 cm. Data collection and analysis were supported by various tools. Field equipment included a GPS for positioning, an Abney level for measuring slope, a sample ring, a soil auger, and standard equipment such as knives, hoes, and cutting tools. The samples were then packaged using plywood, plastic bags, and labeled with tags and rubber bands. For documentation and analysis purposes, a camera, Munsell Color Chart book, and software such as office applications, Arc-GIS, and Avenza MAPS were used.

2.3 Research Methods

This research adopted a survey method with sampling locations determined through Purposive Random Sampling in oil palm plantations with varying plant ages. Each treatment unit was replicated three times. Sampling points included several land conditions: new plantations (0 years old) on gentle slopes (3-8%), 12-year-old plantations on gentle slopes (3-8%), new plantations on steep slopes (8-15%), 5-year-old plantations on steep slopes (8-15%), and 12-year-old plantations on steep slopes (8-15%). Broadly, the research stages consisted of preparation, creation and field verification (ground check) of the work map, followed by data collection in the field, and concluded with soil sample analysis in the laboratory. Soil physical parameters tested included texture (hydrometer method), organic matter content (Loss on Ignition), soil density (Bulk Density gravimetrically), total pore space, water content (gravimetrically), and soil permeability measured using the De Boodt method based on Darcy's Law.

3. RESULTS AND DISCUSSION

3.1 Soil Texture Class

The soil texture classes in the oil palm plantation, as presented in Table 1, varied from silty clay to sandy loam. The age and slope of the land influenced this variation, with parent material and weathering level being the primary causes. The analysis results revealed differences in soil texture based on plant age, slope, and land depth. These differences are influenced by the composition of soil constituent fractions, which in turn impact the soil's physical properties. The quality of soil's physical properties is largely determined by its texture. However, it should be noted that soil texture is generally considered a relatively stable property. A study (Wahyuni et al., 2023) stated that soil texture is not easily affected by land use type or differences in plant age because changes in texture require a very long period. For example, Inceptisol soils, which are considered young soils, often show texture variations from coarse to fine, depending on the weathering degree of their parent material (Sitorus & Prasetyo, 2022). Another finding (Hidayat et al., 2021) reported variations in particle size fractions based on plant age and depth in oil palm plantations, where the sand fraction was found to be higher compared to uncultivated forest soils. Furthermore, at a depth of 0-20 cm, soil bulk density tends to be lower compared to the layer at a depth of 20-40 cm.

3.2 Soil Organic Matter Content

The soil organic matter content at various ages and slopes of oil palm plantations is presented in Figure 2. Based on the figure, the lowest organic matter content was found on land aged 0 years, which was 3.56% at a depth of 0-30 cm and 2.2% at a depth of 30-60 cm. For 5-year-old plants, the content increased to 4.96% (0-30 cm depth) and 3.38% (30-60 cm depth) for gentle slopes (3-8%). Meanwhile, on steeper slopes (8-15%) for the same age, the values recorded were 4.26% (0-30 cm) and 2.73% (30-60 cm). The highest average organic matter content was observed in 12-year-old plants with slopes of 3-8%, reaching 5.43% at a depth of 0-30 cm and 3.26% at a depth of 30-60 cm.

Table 1. Soil texture at various oil palm tree ages.

Ages	Slope (%)	Sample	Soil Texture	
			Depth 0-30 cm	Depth 30-60 cm
0	3-8	S20	Sandy Loam	Sandy Loam
		S21	Sandy Loam	Sandy Loam
		S22	Sandy Loam	Clay
5	3 – 8	S23	Sandy Loam	Clay
		S22	Sandy Clay	Sandy Loam
		S23	Sandy Loam	Sandy Loam
	8 – 15	S51	Sandy Loam	Clay
		S52	Sandy Loam	Sandy Loam
		S53	Sandy Loam	Sandy Loam
15	3-8	S31	Sandy Loam	Sandy Loam
		S32	Sandy Loam	Clay
		S33	Sandy Loam	Sandy Loam
	8-15	S61	Sandy Loam	Clay
		S62	Sandy Loam	Sandy Loam
		S63	Sandy Loam	Sandy Loam

Source: Data Analysis Laboratory 2025.

3.2 Bulk Density

The results of bulk density analysis at several oil palm ages with slope inclination can be seen in Figure 3. Bulk density results increase with the age of the oil palm. Oil palms aged 0 years have the highest bulk density and the lowest soil organic matter content (Figure 3) because land clearing using heavy equipment makes the soil more compacted. Oil palm trees aged 5 and 12 years have a lower bulk density compared to young plants. This is due to root development that breaks up the soil, thus reducing soil density. The canopy density at ages 5 and 12 years increases, protecting the soil from the impact of rainwater.

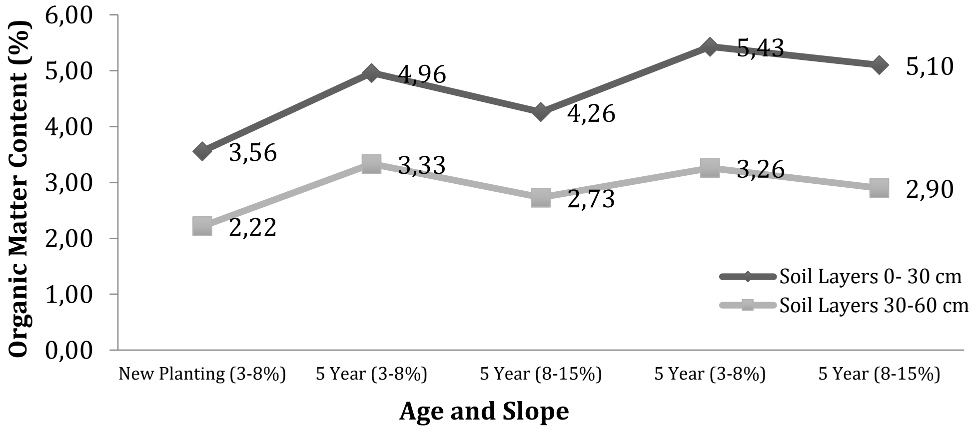

Figure 2. Soil Organic Matter (%).

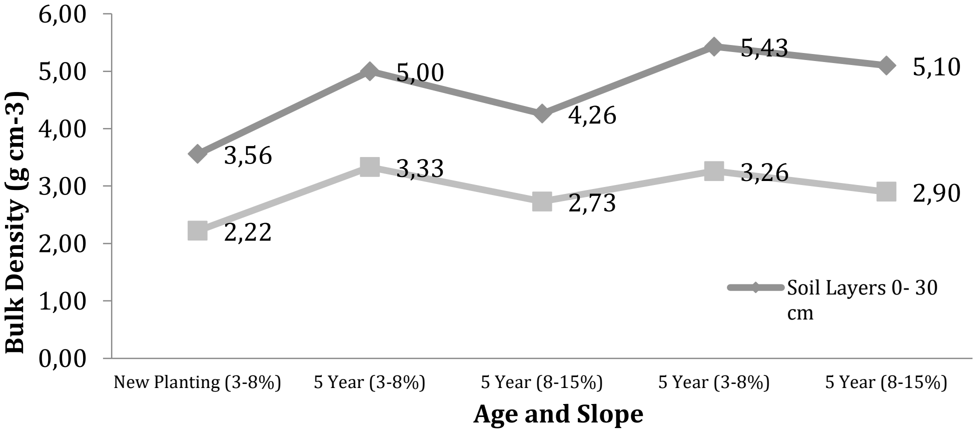

Figure 3. Soil Bulk Density (BD) (g cm^{-3})

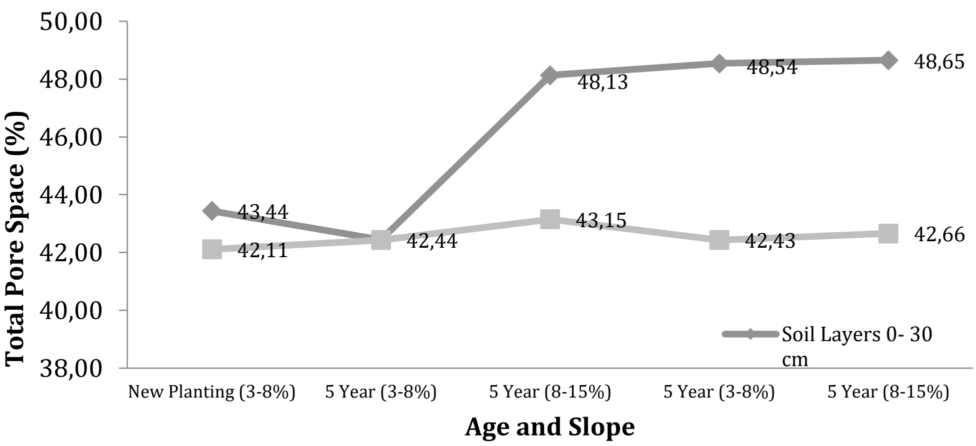

Figure 4. Total Pore Space (%)

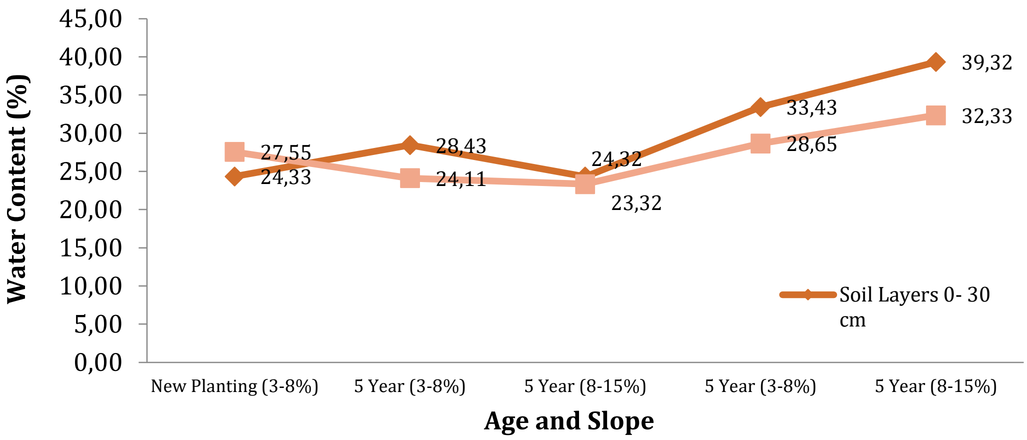

Figure 5. Soil Moisture Content (%)

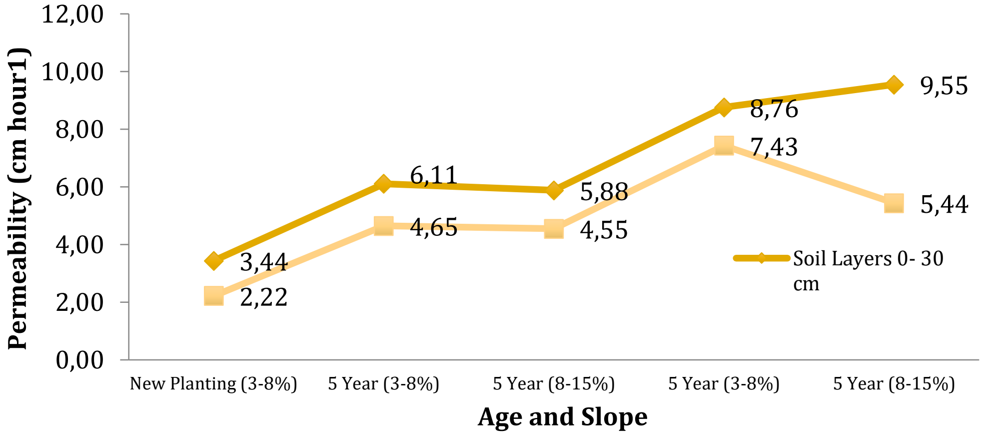

Figure 6. Soil Permeability (cm hour^{-1})

3.3 Total Pore Space (TPS)

Based on Figure 4, it can be observed that Total Pore Space (TPS) increases with the age of the oil palm trees. This phenomenon is triggered by the increasing organic matter content and the decrease in soil density, which together promote pore formation and increase the soil's Total Pore Space (TPS). In 5-year-old plants, the TPS tends to be stable because the soil density is also relatively similar. Meanwhile, on slopes of 3–8%, 12-year-old plants show a higher average TPS compared to slopes of 8–15%.

3.4 Soil Moisture Content

The analysis of soil moisture content (Figure 5) shows an increase with the age of oil palm plants. This increase is primarily driven by higher organic matter content, which reduces soil density and creates a more porous structure, thereby enhancing water retention capacity. The accumulation of leaf litter over time further contributes to organic matter reserves, which subsequently influences soil moisture. Additionally, canopy density plays a significant role in regulating soil moisture content. A denser canopy, as observed in 12-year-old plants, reduces evaporation from the soil surface compared to younger plantations (5 or 0 years old).

3.5 Soil Permeability

Based on Figure 6, soil permeability in oil palm plantations shows different patterns when viewed from the perspective of plant age and land slope. Soil permeability values tend to increase in older plants. This is due to a higher organic matter content, which reduces soil density and increases total pore space. Conversely, soil permeability decreases with increasing slope gradient. At the same plant age (5 and 12 years), permeability values on gentle slopes (3-8%) are higher than on steeper slopes (8-15%). This difference is primarily due to the significant erosion that occurs on steeper slopes.

4. CONCLUSIONS

This research indicates that plantation age and slope gradient play a significant role in determining soil physical properties in oil palm plantations. Increasing plantation age contributes to improved soil quality, evidenced by increased organic matter content, porosity, water retention, and permeability, as well as decreased bulk density. Conversely, steeper slopes are associated with soil degradation, characterized by increased compaction and decreased soil quality parameters. The interaction between plantation age and slope gradient underscores the importance of considering both biological and topographical factors in soil management. These findings emphasize the need for site-specific soil conservation strategies, particularly in sloped areas, to ensure the sustainability of oil palm production while preserving the ecological functions of watersheds.

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