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Various Ages and Slopes of Oil Palm in the Bilah Sub-Das, Labuhanbatu Regency on the Physical Properties of the Soil

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ABSTRACT

Oil palm (*Elaeis guineensis* Jacq.) cultivation is a primary economic sector in Indonesia, with North Sumatra being a leading production region. However, the sector's expansion, exemplified in the Bilah Sub-watershed, Labuhanbatu, has raised concerns regarding the deterioration of soil physical properties, posing a risk to long-term agricultural sustainability. While plantation age and topographic slope are identified as key influencing factors, their interactive effects remain inadequately examined. This study, therefore, aimed to analyze the differences in soil physical characteristics across varying oil palm ages and slope gradients. Conducted from May to August 2025 in Negeri Lama Village, the research employed a factorial design with three plantation ages (newly planted, 5, and 12 years) and three slope classes (0-3, 3-8, and 8-15%). Parameters assessed included soil texture, organic matter content, porosity, water content, and permeability. The results demonstrate that increasing plantation age positively correlates with improved soil conditions, marked by higher organic matter, porosity, water content, and permeability, alongside reduced bulk density. Conversely, steeper slopes significantly degrade these same properties. The study underscores the critical interaction between these two factors. Its importance for the oil palm industry lies in providing empirical evidence for developing site-specific soil management strategies. The findings advocate for enhanced conservation practices, particularly on slopes exceeding 8%, to mitigate degradation and ensure the ecological and economic sustainability of this vital commodity system.

Keywords: Bulk Density; Oil Palm; Slope; Soil Physical Properties; Tree Age

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INTRODUCTION

The expansion of oil palm plantations (*Elaeis guineensis* Jacq.) in Indonesia has reached a monumental scale, placing the country as the world's largest producer of Crude Palm Oil (CPO). The latest data from the Indonesian Statistics (2023) indicates that the national oil palm area has reached 14.99 million hectares, with CPO production of 46.88 million tons in 2022. North Sumatra Province, with Labuhanbatu Regency as a primary contributor, serves as the epicenter of this palm oil agribusiness. However, behind its significant contribution to national foreign exchange and employment, this expansion wave has cast a shadow of alarming environmental degradation, particularly in vulnerable ecosystems such as watersheds (Srisunthon and Chawchai 2020).

The Bilah Sub-watershed in Labuhanbatu Regency exemplifies this paradigm, where the dynamics of environmental stress due to oil palm intensification require in-depth study, starting from the ecosystem's foundation: the soil. Land degradation, manifested through the deterioration of soil physical properties, poses an existential threat to agricultural sustainability and environmental health. Soil physical properties such as texture, structure, bulk density, porosity, moisture content, permeability, and infiltration rate are not merely static parameters. They are primary regulators of the soil's hydrological function, controlling water movement and storage, gas exchange, nutrient availability, and providing a medium for root development (Hillel 2003).

Alterations in these key properties, such as increased bulk density (compaction) or decreased infiltration rates, can disrupt the micro-hydrological cycle, increase Consequently, monitoring soil physical properties serves as a crucial initial indicator for assessing the level of environmental stress in a region. Large-scale land conversion to monoculture oil palm plantations has been identified as a primary driver of changes in soil physical

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properties. A meta-analysis by Guillaume et al. (2022) compiling global data, concluded that land conversion, especially from forests, consistently leads to soil compaction (a 10-30% increase in bulk density), up to a 40% decrease in soil aggregate stability, and a significant reduction in infiltration rates. The principal mechanism is extensive mechanical disturbance during land clearing and planting using heavy machinery, which destroys the natural soil structure.

However, the narrative of this change is non-linear and dynamic, strongly influenced by the plantation's developmental stage. During the immature plant phase (TBM; ages 1-3 years), soil disturbance peaks. Intensive tillage, terracing, planting, and fertilization activities, coupled with inadequate canopy cover, render the soil highly susceptible to compaction and erosion (Evans et al. 2021). Over time, in the young to mature productive plant phase (TM; ages 4-15 years), conditions gradually improve. A closing canopy protects the soil from raindrop impact energy, while a deepening root system and abundant litter input begin to enhance soil structure through aggregate formation and increased organic matter. However, in the old productive plant phase (Old TM; >15 years), new stresses emerge. The cumulative traffic of heavy equipment during harvesting and maintenance, along with a potential decline in soil biological activity, can induce secondary compaction and degrade soil porosity. (NCASI 2004).

Therefore, understanding the trajectory of soil physical properties across the palm oil plantation age continuum is not optional but essential for assessing the tipping point of soil health. Another layer of complexity is topographic variation, specifically slope gradient. The Bilah Sub-watershed features a heterogeneous landscape, ranging from alluvial plains near rivers to undulating and hilly regions. Slope gradient fundamentally alters the potential energy of rainwater, making land with steep slopes (>15%) inherently more prone to erosion. Erosion processes not only transport fine soil particles and nutrients (resulting in topsoil loss) but also selectively leave behind coarser sand particles. This can alter soil texture to a coarser composition, reduce water-holding capacity, and worsen soil structure in upstream areas (Sobol et al. 2017).

In oil palm plantations, although conservation practices like cover crops (e.g., Centrosema molle and Pueraria phaseoloides) have been adopted, their effectiveness varies widely. On steep slopes during the TBM phase, where soil covered by such legume crops may not yet be optimal, the erosion risk remains very high. This synergistic interaction between biological factors (plant age determining canopy and litter cover) and physical factors (slope gradient controlling erosion intensity) will create a unique and complex spatial pattern of soil physical properties across the Bilah Sub-watershed landscape (Liu et al. 2025).

Understanding these interactions is critical for designing precise, site-specific conservation strategies rather than applying uniform measures. Labuhanbatu Regency, with the bar Sub-watershed in it, has undergone a dramatic land transformation. A report by the DLKH North Sumatra (2022) indicates 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 impaired hydrological regulation. This disturbance is strongly suspected to be linked to land cover changes and upstream cultivation practices. However, to date, comprehensive and detailed scientific data quantifying the in-situ physical properties of soil, and how they are influenced by the key variables of plantation age and slope, remain scarce. This data gap hinders the formulation of evidence-based management policies and recommendations for achieving sustainable oil palm cultivation in the region.

Based on the outlined urgency and knowledge gaps, this study is designed to conduct an in-depth investigation of the soil physical properties in oil palm plantations within the Bilah Sub watershed. The focus is to elucidate the variability induced by differences in Plantation Age and Slope Gradient, as well as the interaction between these two factors.

The novelty of this research lies in its integrative approach, simultaneously analyzing the influence of temporal factors (plant growth stages: TBM, TM, Old TM) and spatial factors (slope gradient classification) within a single framework in a specific tropical sub-watershed undergoing intensive oil palm expansion. Most prior studies tend to examine these factors in isolation or within different agroecosystem scales and contexts. By deconstructing this complexity through interaction analysis, this study aims to provide a scientific roadmap that can serve as a basis for implementing more adaptive and site-specific plantation management practices. The ultimate goal is to ensure long-term productivity while preserving the ecological function of the Bilah Sub-watershed as a vital life support system.

MATERIALS AND METHODS

The research was conducted at the oil palm plantation of Negeri Lama, District of Bilah Hilir, Labuhanbatu Regency. The soil type is Inceptisol with an altitude of 15 meters above sea level, located at coordinates N: 98^{0}.011'.22.41" E: 02^{0}.016'.24.31" as shown in Figure 1. Soil sample analysis was conducted at the Soil Fertility Laboratory, Faculty of Agriculture, Universitas Sumatera Utara.

Figure 1. Administration map of research site

The materials used in this study were intact soil samples at depths of 0-30 and 30-60 cm and disturbed soil samples taken compositely. The tools used were GPS (Global Position System), abney level, sample ring, mineral soil drill, field knife, hoe, cutter, plywood or board, plastic bags, rubber bands, labels, stationery, camera, office software, Arc-GIS software, Avenza MAP Application, and Munsell Color Soil Chart book. The study was conducted using a survey method, representative areas selected using Purposive Random Sampling method in oil palm plantation with various ages with 3 replications. Soil sampling was carried out on the following land: T1 = Newly planted oil palm plantation, slope 3-8%, T2 = 12-year-old oil palm plantation, slope 3-8%, T3 = Newly planted oil palm plantation, slope 8-15%, T4 = 5-year-old oil palm plantation, slope 8-15%, and T5 = 12-year-old oil palm plantation, slope 8-15%. The stages of the research were: preparation, making a work map ; located at coordinates N: 98^0.017'.23.41" E: 02^0.018'.25.31 ground check of the work map, field data collection, and soil analysis in the laboratory. The analysis parameters in this study were soil texture (hydrometer method), organic matter content (Loss on Ignition method), Bulk Density (gravimetric method), total pore space, soil water content (gravimetric method), and permeability (De Boodt method based on Darcy's Law).

RESULTS AND DISCUSSION

Results

Soil texture class. The analysis results of soil texture class at various ages and slope of oil palm plantations are presented in Table 1. Table 1 shows that the soil at several ages of oil palm plantations has a texture class of silt loam, clay loam, clay, to sandy clay. The texture at several ages of oil palm plantations is influenced by differences in parent material and weather level.

Table 1. Soil texture at various ages of oil palm trees

Age (Year)	Slope (%)	Sample	Soil Texture	
			Depth 0-30 cm	Depth 30-60 cm
5	3 – 8	S20	Silt loam	Silt loam
		S21	Silt loam	Silt loam
		S22	Silt loam	Clay loam
10	3 – 8	S23	Silt loam	Clay
		S22	Loamy	Sandy
		S23	Sandy	Sandy
	8 – 15	S51	Silt loam	Loam
		S52	Silt loam	Silt loam
		S53	Sandy loam	Sandy loam
15	3 – 8	S31	Sandy loam	Silt loam
		S32	Sandy loam	Loam
		S33	Loamy	Sandy
	8 – 15	S61	Sandy loam	Loam
		S62	Silt loam	Loamy
		S63	Silt loam	Silt loam

The analysis show differences in soil texture at plant age with different slope and depth. The difference in soil texture is influenced by the content of existing fractions thus also affect the soil physical properties. The good or bad of soil physical properties are influenced by the texture of the soil itself. According to Harahap, Oesman, et al. (2021), soil texture is not influenced by land use type or differences in plant age because changes in soil texture require a long-time span. Inceptisol is a newly developed soil, usually has a texture that varies from coarse to fine, depending on the level of parent material weathering Harahap, Purba, et al. (2021) while Walida et al. (2020), reported that there are variations in particle size fractions at plant age and depth. In oil palm plantation area, sand fraction is higher compared to forest soil (unprocessed). In the depth of 0-20 cm, soil density level is relatively lower than in the 20-40 cm.

Content of soil organic matter. The analysis results of soil organic matter content at several ages of oil palm tree with slope gradients are presented in Table 2 and Figure 2. Based on the data in Table 2, the influence of oil palm age and slope gradient class on Soil Organic Matter (SOM) content in the Bilah Sub-Watershed, Labuhanbatu Regency, can be analyzed. The discussion focuses on two soil layers (0-30 cm and 30-60 cm) to observe the vertical distribution of Soil Organic Matter (SOM).

Table 2. Soil organic matter at various ages of oil palm trees

Age of Oil Palm (Year)	Organic Matter (%)	Soil Layer (cm)	
		0- 30 cm	30-60 cm
5	(0-3)	1.97 ± 0.12	2.12 ± 0.12
5	(3-5)	2.09 ± 0.12	2.21 ± 0.12
5	(6-8)	2.05 ± 0.12	2.42 ± 0.12
10	(0-3)	2.07 ± 0.12	2.63 ± 0.12
10	(3-5)	2.11 ± 0.12	2.65 ± 0.12
10	(6-8)	2.21 ± 0.12	2.53 ± 0.12
15	(0-3)	2.58 ± 0.12	3.02 ± 0.12
15	(3-5)	2.71 ± 0.12	2.58 ± 0.12
15	(6-8)	2.81 ± 0.12	3.05 ± 0.12

Generally, the data shows a trend of increasing SOM content with the increasing age of the oil palm plantation from 5 to 15 years. In the 0-30 cm layer, the average SOM value increased from the range of 1.97–2.09 (5 years) to 2.58–2.81 (15 years). A more pronounced increase was observed in the 30-60 cm layer, where the SOM value at 15 years (range 2.58–3.05) was much higher than at 5 years (range 2.12–2.42). This phenomenon can be explained by the continuous accumulation of leaf and frond litter along with plant growth, accompanied by the development of a wider and deeper root system in older plants. Dead and decomposing roots become an important source of organic matter input for deeper soil layers. This finding aligns with the research of Deng et.al. (2018), which reported more significant accumulation of soil organic carbon in revegetation systems that have reached a stable phase after 10-15 years.

The influence of slope gradient shows a more complex pattern and interacts with plantation age. At 5 and 10 years of age, no consistent pattern was observed where a specific slope class always yielded the highest SOM. However, at 15 years of age, slopes with a gradient of 6-8% showed the highest SOM values for both soil layers (0-30 cm: 2.81; 30-60 cm: 3.05). This may be related to specific conditions at the research site, such as more intensive soil conservation management (e.g., terracing or cover cropping) on steeper slopes to prevent erosion, thereby better retaining organic matter.

On gentler slopes (0-3%), although potentially experiencing lower erosion, microbial decomposer activity might be higher due to more favorable moisture and aeration conditions, leading to a faster rate of organic matter decomposition. These results indicate that in the study area, land management practices may have a stronger influence than the natural slope factor itself in determining SOM stocks. A comparison between the two soil layers reveals that at 10 and 15 years of age, the SOM content in the 30-60 cm layer is often higher than or equal to that in the 0-30 cm layer. This is an interesting finding because conventionally, the top layer is considered to have the highest organic content. The high SOM in the subsurface layer can be attributed to several factors: (1) leaching of dissolved or suspended organic particles from the top layer, (2) bioturbation (soil fauna activity) that transports organic matter to deeper layers, or (3) previous land use history that left organic residues in that layer. This condition shows that assessing soil quality based solely on the topsoil may overlook important carbon dynamics in the subsoil.

Bulk density. The analysis result of bulk density at several ages of oil palm with slope can be seen in Table 3. Bulk density increases with increasing age of oil palm. Oil palm aged 0 years have the highest bulk density and the lowest soil organic matter content (Figure 3) because land clearing using heavy equipment make soil become more compacted.

Table 3. Bulk Density at various ages of oil palm trees

Age (Year)	Slope (%)	Soil Layer (cm)	
		0-30(g.cm^{-3})	30-60 (g.cm^{-3})
New Planting	**0-3**	1.02	0.97
New Planting	**0-5**	1.04	1.07
5	**3-5**	1.05	1.07
5	**6-8**	1.09	1.10
10	**0-3**	1.11	1.13
10	**3-5**	1.07	1.15
10	**6-8**	1.09	1.15
15	**0-3**	1.06	1.12
15	**3-5**	1.05	1.14
15	**6-8**	1.09	1.14

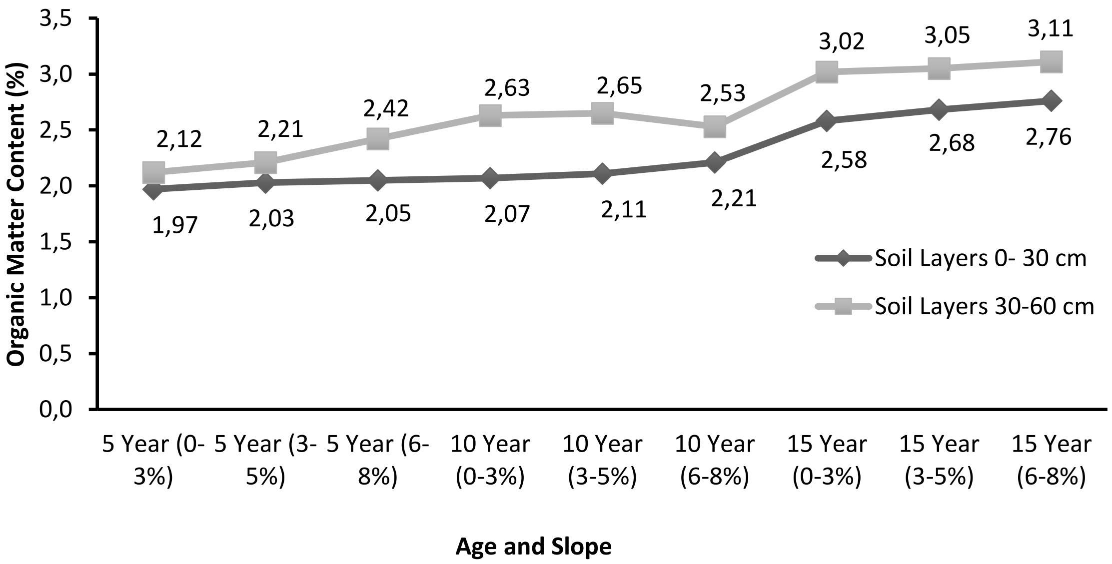

Figure 2. The effect of palm age and land slope to content of soil organic matter (%)

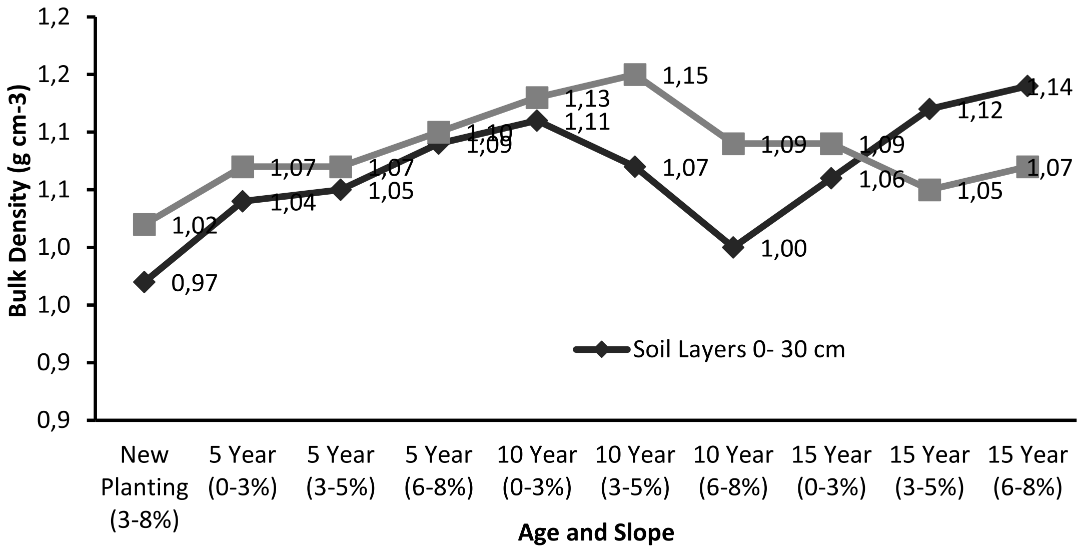

Figure 3. The effect of palm age and land slope to content of Soil Bulk Density (BD) (g cm^{-3})

New Planting (3-8% slope): Shows the lowest bulk density values in both soil layers (1.02 g cm^{-3} at 0-30 cm and 0.97 g cm^{-3} at 30-60 cm), indicating less compacted soil likely due to recent land preparation and minimal root system development. 5-Year-Old Stand: A general increase in bulk density is observed compared to new planting. Values are higher in the 30-60 cm layer across all slopes. The 6-8% slope shows the highest surface bulk density (1.09 g cm^{-3}), suggesting potential compaction or natural soil consolidation processes. 10-Year-Old Stand: The highest bulk densities are recorded in this age group. The 0-3% slope shows the highest surface value (1.11 g cm^{-3}), while the subsurface (30-60 cm) values peak at 1.15 g cm^{-3} for the 3-5% and 6-8% slopes, which may be related to maturing root systems and long-term soil settling. 15-Year-Old Stand: Bulk density values show a slight decrease or stabilization in the surface layer (0-30 cm) compared to the 10-year stand, ranging from 1.05 to 1.09 g cm^{-3}. However, subsurface density remains high (1.12 to 1.14 g cm^{-3}), similar to the 10-year stand, indicating persistent compaction in the subsoil. Overall Trend: Bulk density generally increases with standing age, particularly in the deeper soil layer (30-60 cm). The influence of slope gradient on bulk density is variable across different ages, with no single, consistent trend. Oil palm aged 5 and 12 years have lower bulk density compared to 0 years. This is because root development will break up the soil so that the soil is less dense. The canopy density levels of 5 years and 12 years are increasing thus protecting the soil from rainwater impact.

Total pore space (TPS). The analysis results of the Total Pore Space (TPS) can be seen in Table 4 and Figure 4. The total pore space increases with the increasing age of oil palm. The increase in the total pore space is influenced by the increasing content of organic matter and the decrease in bulk density thus soil will form more pore space and an increase in the total pore space of the soil. Soil at 5 years old of oil palm has almost the same of total pore space value because the bulk density also has almost the same value, while on a slope of 3-8%, 12 years old has a higher average value compared to a slope of 8-15%.

Table 4. Total Pore Space (TPS) at various ages of oil palm trees

Age (Year)	Slope (%)	Soil Layer (cm)			
		0-30 (g.cm^{-3})		30-60 (g.cm^{-3})	
New Planting	**0-3**	45.11	±2.1	42.44	±1.8
New Planting	**0-5**	43.11	±1.9	43.15	±2.0
5	**3-5**	48.13	±2.3	42.43	±1.7
5	**6-8**	48.54	±2.5	42.66	±1.9
10	**0-3**	49.65	±1.8	52.15	±2.2
10	**3-5**	51.65	±2.4	44.21	±1.6
10	**6-8**	50.65	±2.1	45.11	±1.8
15	**0-3**	46.54	±1.7	51.5	±2.3
15	**3-5**	46.54	±2.0	44.32	±1.5
15	**6-8**	52.44	±2.7	44.32	±1.7

Water content. The analysis results of soil water content can be seen in Figure 5. Soil water content increases with the age of oil palm. High organic matter content can reduce soil density so that the number of soil pores will be high, which affects the soil's ability to hold water. The increase in the amount of litter as the plant ages increase affects the amount of available organic matter, which will affect the soil water content. The density of the plant canopy can affect the soil water content because a denser plant canopy can increase the occurrence of soil evaporation or decrease the evaporation of the soil. Oil palm aged 12 years have wider canopies than those aged 5 and 0 years.

Soil permeability. The analysis results of soil permeability at various ages and slope of oil palm can be seen in Figure 6. Soil permeability increases with the age of oil palm, due to higher organic matter content, increasing total pore space, and a decrease in bulk density. Soil permeability value decreases with increasing land slope. The slope of 3-8% at both 5 and 12 years is higher than the slope of 8-15% at the same plant age. This is affected by magnitude of erosion on the soil.

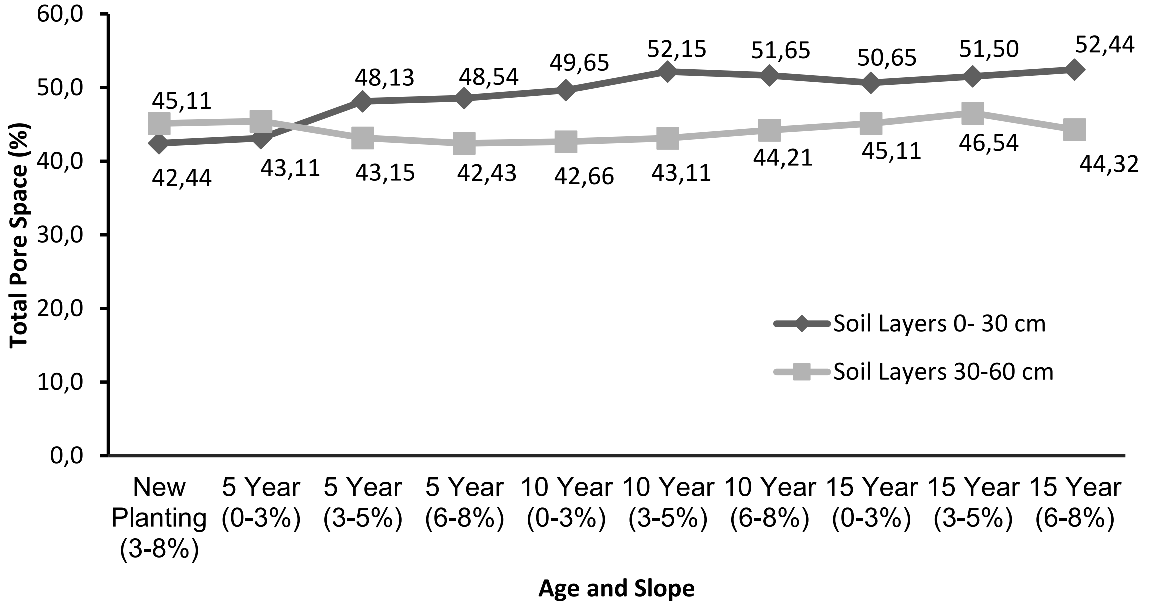

Figure 4. The effect of palm age and land slope to content of total Pore Space (%)

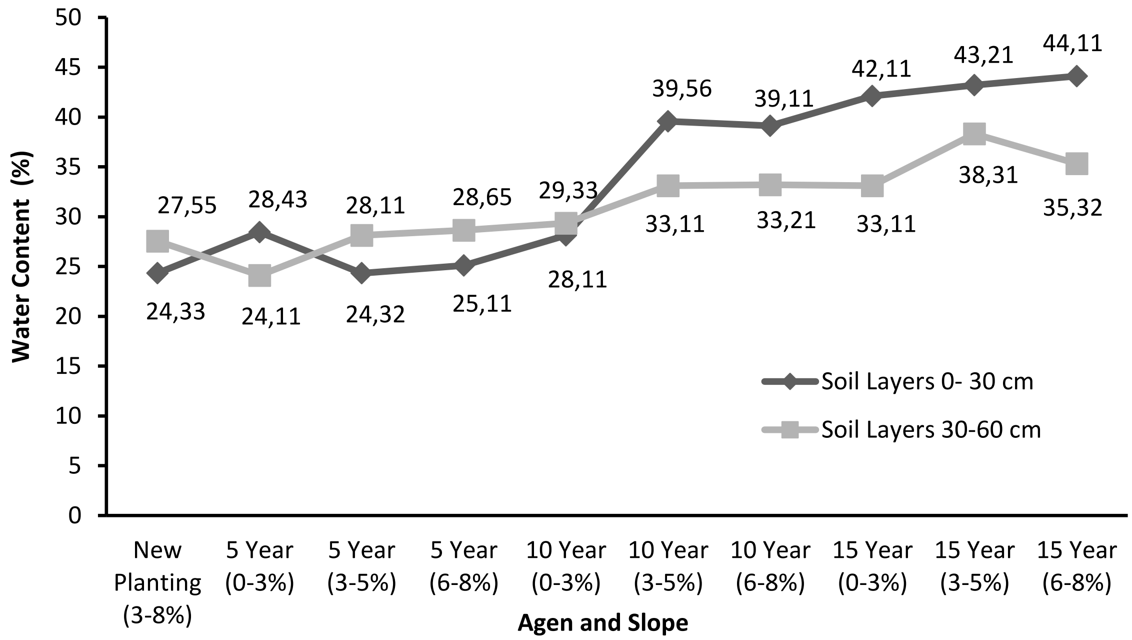

Figure 5. Soil water content (%)

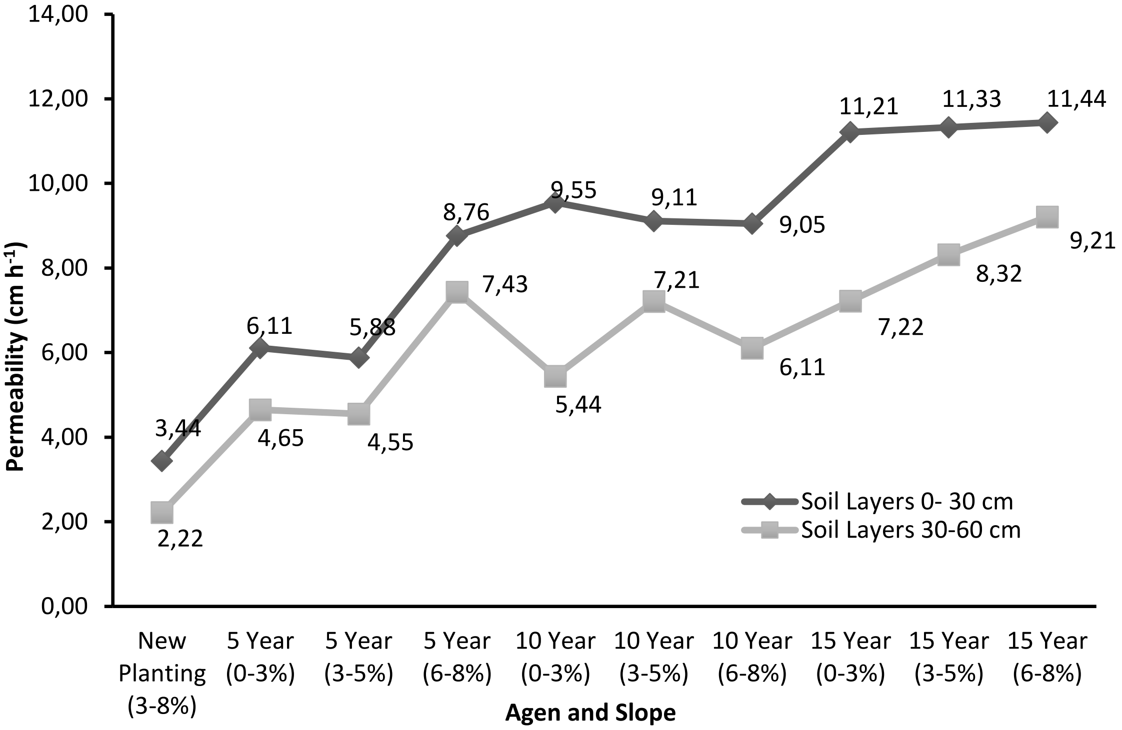

Figure 6. Soil permeability (cm h^{-1})

Discussion

Soil organic matter content (%) of newly planted (3 - 8%), 5 Years (3 - 8%) and 12-year-old oil palms with slopes of 8-15% have an average organic matter content of 5.1% at a depth of 0-30 cm and 2.9% at a depth of 30-60 cm. Increasing the slope causes a decrease in soil organic matter content. This is because the more sloping the land surface, the energy of the surface water flow (runoff) will also increase so that the surface flow will carry litter and result in a decrease in organic matter content. According to Azhar et al. (2024), land cover with slope can affect the soil organic C content. Dense land cover with high slopes has a lower organic C content compared to dense land cover with low slopes. The soil physical and chemical properties in different land uses are related to the management practices. Spatial variations between soils can cause variations in texture (El Bilali et al. 2021)

The soil bulk density value in the 0-20 cm layer is relatively lower compared to the 20-40 cm layer where the organic matter content is very low (Jayeola et al. 2025). On the slope, there is an increase in bulk density along with increasing slope. The high and low of bulk density is affected by several factors such as content of soil organic matter, soil texture, number of soil pores, and plant roots. High soil organic matter content can make the bulk density value decrease. Soil with high organic matter is usually looser than soil with lower organic matter. Organic matter will increase the number of soil pores so that the soil density will decrease. Bulk Density is influenced by structure (in terms of pore space), soil texture (in terms of particle size and density) and organic matter content (Lei et al. 2025).

Soil with high organic matter content tends to have good and stable of soil physical properties. One of stable soil physical properties is low bulk density because it has a more total pore space. The existence of land processing activities and a low canopy density level will cause an increase in bulk density. Raindrops will directly hit the ground so that the soil will become denser (Mazigh et al. 2022). A high canopy density level can protect the soil surface from being destroyed by the impact of rainwater, so that there is no blockage in the soil pores (Okon et al. 2017). This is related to the decreasing bulk density and the increasing of organic material content. According to Pérez-Sato et al. (2023), high organic material can reduce bulk density. Low bulk density is related to increasing of soil porosity due to the presence of organic and inorganic fractions in the soil. According to Santoso et al. (2024), soil that has a low bulk density has a high total pore space, conversely, soil that has a high bulk density has a low total pore space. This is related to the decreasing bulk density and the increasing of organic material content. According to Swails et al. (2024), high organic material can reduce bulk density.

Low bulk density is related to increasing of soil porosity due to the presence of organic and inorganic fractions in the soil. According to Utami et al. (2024), soil that has a low bulk density has a high total pore space, conversely, soil that has a high bulk density has a low total pore space. Older oil palm has more fronds thus able to contribute high litter and organic matter. According to Govers et al. (2020), organic matter content can suppress the rate of evaporation. High organic matter content can increase humus levels in the soil. Humus is hydrophilic, so it can increase water absorption in the soil and can also increase water storage capacity. Soil water content on each slope also shows a decrease in soil water content along with increasing slope. At a slope of 3-8%, the soil physical properties are better compared to 8-15%. According to Guillaume et al. (2022), the decrease in soil water content is related to land slope.

Water content tends to decrease along with increasing slope. The steeper the slope, the greater the runoff, thus affecting the soil organic matter content bulk density, and total pore space. According to Higgitt and Lu (2021), the high content of organic matter in the upper layer causes a good soil aggregation process. Organic matter is able to unite single into micro aggregates, then micro to macro aggregates thus balancing pore space between micro and macro pores. The balance of soil pores is able to pass water per unit time faster than low organic matter content. Other factors that affect soil permeability are soil texture and total pore space. Soil texture that contains a lot of sand can increase soil permeability. According to Evans et al. (2021), soil texture that contains more sand fractions and has a sandy loam structure will have high soil permeability value. The density of soil fraction configuration in a soil volume causes lower permeability value.

CONCLUSIONS AND SUGGESTIONS

The results of oil palm research at different ages and slopes in the sub-watershed Bilah, Labuhan Batu Regency show that the older the oil palm, the higher the organic matter content, total pore space, water content and soil permeability, but the decreased bulk density. The steeper the slope, the increased bulk density, and decreased organic matter content, total pore space, water content and soil permeability.

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