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Identification of Soil Physical Properties and Their Implications for the Management of Productive Oil Palm Plantations in Marbau District, North Sumatra

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Abstract−The degradation of soil physical properties represents a hidden threat to the sustainable productivity of smallholder oil palm plantations. This study aims to identify the condition of soil physical properties and analyze their implications for the management of mature (TM) oil palm plantations in Marbau District. A survey method was applied using a purposive random sampling design across five farmer blocks. Soil samples were taken at depths of 0-20 cm, 20-40 cm, and 40-60 cm for analysis of texture, bulk density, total porosity, available water content, and aggregate stability. Results indicate the soil is dominated by silty clay texture (silt 42.3%, clay 38.1%, sand 19.6%). The average bulk density of 1.42 g cm^{-3} is classified as high (compacted) and increases with depth. The average total porosity of 46.3% falls into the low-medium category. The average available water content of 11.1% by volume is classified as low, while aggregate stability is in the medium category (Index 0.42). Statistical analysis revealed 100% of samples experienced compaction (bulk density >1.3 g cm^{-3}) and 76% of samples had marginal available water content (10-20% vol). The study concludes that soil compaction is a central problem causing degradation of porosity and water storage capacity, creating a sub-optimal root environment for oil palms. The main recommendations are the implementation of integrated organic matter management and regulation of field traffic as essential strategies for improving soil physical properties.

Keywords: Soil Physical Properties; Mature Oil Palm; Bulk Density; Porosity; Soil Texture; Marbau District

1. INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) is a strategic plantation commodity in Indonesia, contributing significantly to the national economy through exports and employment. Data from the Directorate General of Plantations (2023) records the oil palm area in Indonesia at 15.08 million hectares, of which approximately 41% or 6.19 million hectares are managed by independent smallholders. However, the productivity of smallholder plantations often remains below the plant's genetic potential, with an average Crude Palm Oil (CPO) production of only 2-3 tons per hectare per year, far below the 4-5 tons per hectare per year achieved by large plantations (Susanto et al., 2022).

This low productivity is associated with multiple factors, where soil condition is a key limiting factor that is frequently overlooked. As a growing medium, soil provides water, nutrients, and anchorage for roots. Soil physical properties are primary determinants of soil hydrological functions, aeration, and ease of root penetration. Degradation of soil physical properties, such as compaction (increased bulk density), decreased porosity, and aggregate degradation, directly restricts root development and water availability for plants (Adnan et al., 2021). In smallholder oil palm plantations, suboptimal management practices, such as low organic matter inputs, uncontrolled traffic of equipment and people in the frond piles, and improper management of crop residues, are strongly suspected to cause degradation of these soil physical properties (Nurfalah et al., 2020).

Marbau District in North Labuhanbatu Regency is one of the centers for smallholder oil palm development in North Sumatra. The generally flat to undulating topography and history of prior land use as secondary forest or seasonal agricultural land necessitate an evaluation of its soil condition. Lands converted from forests or other agricultural systems to intensive monoculture oil palm plantations often experience drastic changes in soil physical properties. Research by Gupta et al. (2022) in Malaysian oil palm plantations showed that forest conversion to oil palm increased soil bulk density by 15-30% and reduced macroporosity by up to 40% within the first 10 years. Similar conditions potentially occur in Marbau, but specific, scientifically measured field data are not yet available.

Soil physical properties such as texture are inherent and difficult to change, but properties like bulk density, porosity, and aggregate stability are highly responsive to management. The ideal soil bulk density for oil palm growth ranges from 1.0 to 1.3 g cm^{-3}. Values above 1.4 g cm^{-3} can be categorized as compacted conditions that hinder root growth (Hairiah et al., 2020). Soil solids, pores, and water exist in a dynamic relationship. Low total porosity (<50%) often indicates a dominance of micropores that retain water tightly but limit drainage and gas exchange. Conversely, macropores (>30% of soil volume) are crucial for infiltration and aeration (Rahmat et al., 2019). Soil water availability, which is a function of texture and structure, is a critical parameter, especially during the dry season. Oil palm plants require sufficient water availability throughout the year for optimal fresh fruit bunch (FFB) production. Research by Septiana et al. (2021) in Riau showed a strong positive correlation between available soil water content at 0-40 cm depth and bunch weight in smallholder plantations. Soil aggregate stability, reflecting the soil structure's resistance to dispersion by rainwater or erosivity, is also important for maintaining long-term porosity and infiltration. Stable aggregates protect soil organic matter and reduce erosion risk (Sugiyarto et al., 2020).

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Previous studies on soil properties in oil palm plantations have focused more on chemical properties (fertility) or were conducted in large plantations. Comprehensive data on soil physical properties in smallholder plantations, particularly in specific ecosystems like Marbau, are still very limited. Research by Siahaan et al. (2019) in neighboring South Labuhanbatu found that 60% of soil samples in smallholder gardens had a bulk density >1.4 g cm⁻³. This finding reinforces the suspicion that soil compaction is a serious problem but has not been followed by an integrative analysis of other physical parameters. An initial identification of soil physical properties is an essential diagnostic step before designing appropriate plantation management recommendations. Without adequate understanding of the physical condition of the growth medium, fertilization efforts to improve chemical fertility may be ineffective because nutrients cannot be absorbed by roots due to a non-ideal root environment. Therefore, this research is urgently needed as a scientific database for improving the management of smallholder oil palm plantations in Marbau District.

Based on the above, research entitled "Identification of Soil Physical Properties in Mature Oil Palm (TM) in Marbau District" was conducted, specifically for oil palm farmers. This study aims to measure and analyze key soil physical property parameters, diagnose existing problems, and provide a scientific basis for formulating sustainable soil management recommendations to support increased smallholder oil palm productivity. Research Objectives are: To identify and analyze soil physical properties (texture, bulk density, total porosity, available water content, and aggregate stability) at various depths in mature smallholder oil palm plantations in Marbau District; To evaluate the quality of measured soil physical properties by referring to criteria or quality standards for oil palm growth; To provide preliminary recommendations based on findings for improving the management of soil physical properties at the research site.

2. RESEARCH METHODS

The research was conducted from September to December 2025. Soil sampling locations were in mature smallholder oil palm plantation areas (TM > 8 years) in South Marbau Village and North Marbau Village, Marbau District, North Labuhanbatu Regency, North Sumatra Province. Geographically located at coordinates 2°15' - 2°30' N and 99°45' - 100°00' E. Location selection was done purposively based on uniformity of plant age, accessibility, and willingness of cooperating farmers. Materials used were undisturbed and disturbed soil samples from the field, distilled water, sample labels, and chemicals for laboratory analysis. Tools used included: sample rings (volume 100 cm³), soil auger, sample bags, pycnometer, soil hydrometer, Aggregate Stability sieves (size 0.5 mm & 2 mm), oven, analytical balance, dishes, pressure plate apparatus (or equivalent equipment for determining moisture content at field capacity and permanent wilting point), as well as writing tools and GPS.

This research is quantitative descriptive using a survey method. The sampling design used Purposive Random Sampling. Five farmer blocks representing general conditions in the area were selected purposively. From each block, three sample points were taken randomly. At each point, samples were taken from three depths: the surface layer (0-20 cm), the subsurface layer (20-40 cm), and the deeper layer (40-60 cm). The total samples analyzed were 45 samples (5 blocks x 3 points x 3 depths). Preparation: Field observation, determination of sampling points, and coordination with farmers. And Sampling: Undisturbed soil samples were taken using sample rings for bulk density and porosity analysis, Disturbed soil samples were taken with a soil auger for texture, available water content, and aggregate stability analysis, Samples were labeled and brought to the laboratory. Laboratory Analysis: Each parameter was analyzed according to standard methods. Parameters measured in the research are presented in Table 1:

Table 1. Parameters measured in the research

No.	Parameter	Unit	Method of Analysis	Reference (Citation)
1.	Soil Texture (Sand, Silt, Clay)	%	Hydrometer (Bouyoucos method)	(Gee & Or, 2018)
2.	Bulk Density	g cm⁻³	Core Method (using sample rings)	(Blake & Hartge, 2019)
3.	Total Porosity	%	Calculated from bulk density and particle density (assumed density 2.65 g cm⁻³)	(Danielson & Sutherland, 2019)
4.	Available Water Content (AWC)	% vol	Difference in moisture content at field capacity (-33 kPa) and permanent wilting point (-1500 kPa) using Pressure Plate	(Dane & Hopmans, 2017)
5.	Aggregate Stability	Index (0-1)	Wet Sieving Method for obtaining Mean Weight Diameter (MWD) or Stability Index	(Nimmo & Perkins, 2019)

3. RESULTS AND DISCUSSION

The results of soil physical property analysis in Table 1 and Table 2 reveal critical and interrelated conditions, potentially serving as the main limiting factor for smallholder oil palm productivity in Marbau District. The following is an in-depth discussion of each parameter in relation to oil palm physiology and productivity.

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The soil texture composition dominated by silt (42.3%) and clay (38.1%) up to 60 cm depth forms a silty clay class. From an agronomic perspective for oil palm, this texture is paradoxical. On one hand, the high specific surface area of fine particles provides potential for good Cation Exchange Capacity (CEC) and water retention (Brady & Weil, 2017). However, on the other hand, fine-textured soils are highly susceptible to the formation of massive structure (blocky or massive) and low permeability if organic matter content and management are inadequate. For oil palm plants which have a widespread but sensitive fibrous root system to waterlogging, low permeability is a serious threat. Research by Gupta et al. (2022) showed that soils with clay content >35% and high silt fraction in smallholder oil palm plantations experienced a decrease in infiltration rate of up to 60% compared to initial conditions, increasing the risk of micro waterlogging (local ponding) after high-intensity rainfall. This waterlogging causes anaerobic stress on roots, inhibiting the uptake of crucial nutrients like Nitrogen and Potassium for bunch formation, and in the long term triggers root rot (Adnan et al., 2021).

The average bulk density value of 1.42 g cm^{-3}, with 100% of samples falling into the High to Very High category (≥1.3 g cm^{-3}), is the most concerning finding. Hairiah et al. (2020) set the critical threshold for optimal oil palm root growth at 1.33 g cm^{-3}. Values at the research site consistently exceed this threshold, especially in the 20-60 cm layer (1.44-1.45 g cm^{-3}). Soil compaction increases mechanical resistance to root penetration. Oil palm roots require pressure less than 2.5 MPa for optimal growth. In soils with bulk density >1.4 g cm^{-3}, penetration resistance can exceed 3 MPa, causing inhibited root elongation and a shallow root system (Adnan et al., 2021). Consequently: Water and Nutrient Uptake is Disrupted: Roots cannot explore a wider and deeper soil volume to access water and nutrients, making plants highly dependent on the easily dried top layer. Drought Tolerance Decreases: A shallow root system reduces the plant's ability to withstand long dry seasons. Fertilization Efficiency is Low: Applied fertilizers, especially immobile ones like Phosphorus (P), cannot be reached by roots, thus being lost through runoff or fixation. The main causes are suspected to be uncontrolled traffic in the frond piles (during harvest and fertilization) and minimal organic matter inputs to maintain a loose soil structure (Nurfalah et al., 2020).

The average total porosity of 46.3%, falling into the Medium-Low category (Table 1), is a direct consequence of high bulk density. More critical than total porosity is pore distribution. In mineral soils, optimal porosity consists of approximately 25% macropores (aeration and drainage) and 25% micropores (water storage). High bulk density data indicates compression of macropores (>50 μm). Root Respiration: Intensive root metabolic activity requires smooth supply of O_2 and removal of CO_2. A macropore deficit causes soil O_2 concentration (<10%) to fall below the minimum requirement for oil palm roots (12-15%), triggering anaerobic respiration and ethylene toxicity (Rahmat et al., 2019). Water Infiltration: Macropores are the main channels for water entry into the soil. Reduced macropores increase surface runoff, meaning less rainwater is available for plants and erosion risk increases. This condition explains why, despite fine texture, soil water availability is low.

Available water content in the active root layer (0-40 cm) ranges from 10.8 - 12.5% vol, classified as Low to the lower limit of Medium. This means that of the total water held by the soil, only a small fraction (11-13% of soil volume) is available for plant uptake. Septiana et al. (2021) found a strong correlation (R^2=0.78) between AWC in the 0-40 cm layer and oil palm bunch weight in smallholder plantations. They concluded that AWC <15% vol is a major limiting factor for productivity during dry seasons with water deficit >2 months. The low AWC in Marbau, despite fine texture, is caused by: Compact Structure: Compact soil dominated by isolated and unconnected micropores, so stored water has difficulty moving towards roots. Suspected Low Organic Matter Content: Organic matter functions like a sponge, capable of holding water up to 20 times its weight. Minimal organic matter, due to burning or removal of residues, directly reduces soil water storage capacity (Sugiyarto et al., 2020). Consequently, oil palm plants will experience water stress more quickly during rainless periods, leading to reduced cell division in the process of flower and fruit formation, and an increase in parthenocarpic fruits (without kernels).

The average Aggregate Stability Index of 0.42 (Medium category) indicates the soil structure's resistance to dispersion by rainfall energy is only adequate. This value is at the lower threshold and has the potential to drop to the Unstable category (<0.3) if organic management is not improved (Nimmo & Perkins, 2019). For permanent oil palm plantation systems, low aggregate stability has long-term implications: Crust Formation: Dispersed aggregates will clog surface pores, forming a hard crust layer. This further exacerbates infiltration problems and increases runoff. Accelerated Land Degradation: Increased runoff will erode fine soil particles and organic matter, leading to loss of topsoil fertility. Siahaan et al. (2019) reported erosion rates in smallholder oil palm plantations with low aggregate stability could reach 45 tons/ha/year. Nutrient Cycle Disruption: Stable aggregates act as a "fortress" protecting soil organic matter and microbes from excessive decomposition. Easily disintegrated aggregates accelerate organic matter mineralization, releasing nutrients that can be leached before being absorbed by plants. The profile of soil physical properties in smallholder oil palm plantations in Marbau District depicts a degraded and sub-optimal root environment. The combination of severe soil compaction (indicated by high bulk density and low porosity) with minimal water supply capacity (low AWC) creates a double stress for plants: difficulty developing roots and difficulty obtaining water. Aggregate stability at only a medium level indicates the system's vulnerability to erosion and further quality decline. These findings provide a strong scientific explanation for the low average productivity in smallholder plantations. Interventions focusing on reducing compaction (traffic regulation) and massively increasing soil organic matter (residue management, compost) are no longer just an option, but a necessity to break the degradation cycle and achieve sustainability of smallholder oil palm farming.

Table 1. Average Soil Physical Properties at Various Depths in Smallholder Oil Palm Plantations, Marbau District

No.	Parameter Measured	Unit	Depth (cm)	Average Value ± SD	Criteria*	Criteria Source
1.	Texture (USDA)	%	0-20	Silty Clay (Clay 37%, Silt 43%, Sand 20%)	-	(Soil Survey Staff, 2022)
			20-40	Silty Clay (Clay 39%, Silt 42%, Sand 19%)	-	
			40-60	Silty Clay (Clay 38%, Silt 42%, Sand 20%)	-	
2.	Bulk Density	g cm^{-3}	0-20	1.38 ± 0.07	High (Compacted)	(Hairiah et al., 2020)
			20-40	1.44 ± 0.05	Very High (Compacted)	
			40-60	1.45 ± 0.06		

Note: SD = Standard Deviation. Basis for Criteria Determination

Table 2. Average Soil Physical Properties at Various Depths in Smallholder Oil Palm Plantations, Marbau District

Parameter	Unit	Good Criteria	Medium Criteria	Poor Criteria	% of Samples with Poor Criteria
Bulk Density	g cm^{-3}	1.0 - 1.3 (Optimal)	1.3 - 1.5 (High)	>1.5 (Very High) 1.3 - 1.5 (High)	11% (>1.5 g cm^{-3}) 89% (1.3-1.5 g cm^{-3})
Total Porosity	% vol	>50%	40 - 50%	<40%	0% (<40%) 100% (40-50%)
Available Water Content	% vol	>20%	10 - 20%	<10%	24% (<10% vol) 76% (10-20% vol)
Aggregate Stability Index	-	>0.5	0.3 - 0.5	<0.3	0% (<0.3) 100% (0.3-0.5)

The results in Table 1 and Table 2 visually and quantitatively show that the majority of soil samples at the research site have sub-optimal soil physical quality. Bulk Density: All samples (100%) fall into the High to Very High category (≥1.3 g cm^{-3}), with 89% in the High category and 11% in the Very High category. This is a strong indicator of soil compaction. Total Porosity: All samples (100%) are in the Medium-Low to Low category (<50%). This aligns with the high bulk density, indicating inadequate total pore space. Available Water Content**:** Most (76%) are at the lower limit of the Medium category (10-20% vol), and 24% are already in the Low category (<10% vol). This indicates the soil's capacity to provide water for plants is minimal. Aggregate Stability: Although all samples (100%) are in the Medium category (0.3-0.5), the values are near the lower limit. This indicates soil structure that is vulnerable to degradation by the impact energy of rainwater or erosion. This statistical data and criteria strengthen the finding that soil compaction (high bulk density) is the central problem which then impacts low porosity and water availability. This condition requires specific management intervention.

4. CONCLUSION

Soil physical properties in smallholder oil palm plantations in Marbau District are in a degraded condition, characterized by very high soil compaction (average BD 1.42 g cm^{-3}), low total porosity (46.3%), and marginal water supply capacity (11.1% vol). Soil compaction is identified as the key problem driving the degradation of other parameters, creating a root environment with limited aeration and low water availability, potentially being the main limiting factor for productivity. Soil aggregate stability at only a medium level (ISA 0.42) indicates system vulnerability to erosion and the need to significantly increase soil organic matter content. Interventions are needed to reduce compaction and improve soil structure quality, including through: (a) Establishment of fixed traffic lanes (for harvest, fertilization) that do not cross the root zone near the weeded circle; (b) Enhancement and even management of leaf residues (frond stacking) in the frond piles as an organic matter source; (c) Application of mature compost or manure to the weeded circle.

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