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Physical and Chemical Characteristics and Classification of Soil in Plantation Land, Bareng Wonosalam, Jombang Regency

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Abstract

Soil is a fundamental factor influencing agricultural productivity, as it determines nutrient availability, water retention, and the long-term sustainability of farming systems. The Bareng Wonosalam District of Jombang Regency is a significant agricultural area with varied topography and intensive land use; however, comprehensive soil characterization in this region remains limited. This study aimed to analyze the physical and chemical characteristics of soils in plantation lands and classify them taxonomically to inform sustainable management. A representative plantation site in Pulosari Dua was selected using land-use and slope overlays. Five soil horizons (Ap, AB, Bt1, Bt2, BC) were described. Samples were analyzed for moisture content, texture, bulk density, pH (H_2O, KCl), electrical conductivity, organic carbon, total nitrogen, available phosphorus (Olsen, Bray), exchangeable cations (K, Na, Ca, Mg), cation exchange capacity (CEC), and base saturation (BS). Results showed moisture content of 6.2–20.8%, bulk density of 1.23–1.52 g/cm³, pH of 5.35–5.99, and organic carbon of 0.77–3.61%. Exchangeable K and Na were low (<0.60 cmol·kg⁻¹), while Ca ranged from 3.69–7.06 cmol·kg⁻¹. Textures were silty clay and clay, with BS of 53.5–117.1% and CEC of 9.15–12.93 cmol·kg⁻¹. The soils were classified as *Typic Hapludalfs*. Recommended practices include dolomite liming, potassium fertilization, structural amendments, and terracing. These actions are expected to enhance soil fertility, water retention, and plantation productivity by enabling targeted soil amendments, balanced nutrient application, and erosion control measures that directly address the identified limitations.

1. Introduction

Soil is a fundamental factor influencing agricultural productivity, as it determines nutrient availability, water retention, and the long-term sustainability of farming systems. In plantation agriculture, where perennial crops rely on stable soil conditions for many years, understanding the physical and chemical properties of soil is crucial for maintaining yields and preventing soil degradation. Bareng Wonosalam District, situated at the foot of Mount Anjasmoro at 500–600 m above sea level and spanning 121.63 km² (Kurniawati et al., 2024), is a major plantation area that produces durian, cloves, salak, coffee, and bananas—commodities central to local livelihoods and the regional economy. The district's cultural identity is also tied to agriculture, with the Kenduren festival celebrating the durian harvest, while spice crops such as vanilla contribute additional economic value (Hidayah et al., 2021).

Previous studies have shown that slope gradient, land use, and tillage practices significantly influence soil fertility: low slopes tend to retain cations and organic carbon, whereas steep slopes are more prone to nutrient leaching (Aji et al., 2024). Recommended soil improvement measures for the area include liming, manure application, potassium fertilization, and terracing (Andi et al., 2023; Pramaditya, 2023). However, comprehensive soil characterization in Bareng Wonosalam remains limited, restricting the ability to design targeted, site-specific management strategies. Evaluating soil quality is therefore essential to identify constraints such as nutrient deficiencies, acidity, poor structure, or low water-holding capacity.

This study aims to (1) quantify key physical and chemical soil properties in plantation lands of Bareng Wonosalam District, (2) classify the soils according to established taxonomic systems (Soil Staff Survey, 2022), and (3) recommend targeted management practices based on identified limitations. These actions are expected to enhance soil fertility, water retention, and plantation productivity by enabling precise soil amendments, balanced nutrient application, and erosion control measures that directly address the identified constraints.

2. Material and Methods

2.1. Research Time and Location

The research was carried out in Pulosari Dua, Bareng Village, Bareng Subdistrict, Wonosalam District, Jombang Regency, East Java. The study was conducted at a single representative site, selected based on land-use and slope criteria that are consistent with the dominant conditions in the district. This site was chosen to minimize variability due to lithology and climate, it lies between 112°20′00″ and 112°21′10″ East longitude, bordered by Wonokerto Village to the north, Wonosalam to the east, Jenisgelaran to the south, and Bareng to the west laboratory to all physical and chemical analyses followed standard procedures (Soil Staff Survey, 2022) and took place at the Land Resources Laboratory II, Faculty of Agriculture, Universitas Pembangunan Nasional "Veteran" Jawa Timur, in November 2024.

2.2. Research Design

The method employed in this study was a quantitative descriptive survey, which combined both field-based and laboratory-based approaches to obtain a comprehensive understanding of soil characteristics. The research involved direct field observations to document visible physical features, landforms, and management conditions influencing soil formation and properties. These observations were complemented by the systematic collection of soil samples from selected sites, which were subsequently analyzed in the laboratory to determine various physical and chemical parameters, including texture, pH, organic carbon content, and nutrient status. This integrated approach enabled the accurate quantification and interpretation of soil variability across the study area, providing a solid empirical basis for further evaluation and discussion of land suitability and soil management strategies.

2.3. Research Procedures

The study comprised four sequential stages. In the preparation stage, the study employed a quantitative descriptive survey focused on a single representative plantation site. The selection of the observation and soil sampling location was carried out using a purposive sampling approach to ensure that the site represented the dominant land-use type and topographic conditions of the study area. Spatial analysis was conducted by overlaying land-use maps with slope class maps derived from a Digital Elevation Model (DEM). This process identified areas combining plantation land cover with representative slope gradients. Based on this analysis, a single representative site in Pulosari Dua, Bareng Wonosalam District, was selected, and all field and laboratory equipment were assembled. During the field stage, each point was photographed; slope angles were measured with a digital clinometer; vegetation cover and compass orientations were recorded; and soil pits were excavated to 200 cm using an auger, hoe, and pickaxe. At each genetic horizon (Ap, AB, Bt1, Bt2, BC), disturbed (scoop) and undisturbed (ring) samples were collected, labeled, and transported to the laboratory. Finally, raw data were tabulated and processed in Microsoft Excel for statistical analysis and reporting.

2.4. Soil Physical Analysis

Air-dried and sieved (<2 mm) subsamples were analyzed using standard methods. Texture was determined via the pipette method. Gravimetric moisture content was measured to evaluate the soil water status in the five plantation plots, and the corresponding water factor (F.w.) for each sample horizon. Soil samples were oven-dried at 105 °C to constant weight and weighed before and after drying to calculate moisture percentage. Bulk density was calculated from the mass and volume of undisturbed ring cores, while particle density was measured using a pycnometer. Total porosity was derived from these two measurements. Permeability tests employed constant-head permeameters to record water flow rates through repacked cores. All physical tests were conducted in triplicate for each horizon to ensure precision and account for soil heterogeneity.

2.5. Soil Chemical Analysis

Chemical properties were measured on finely ground subsamples. Soil pH was recorded in a 1:2.5 soil-to-water suspension and in 1 M KCl using a calibrated pH meter. Electrical conductivity and redox potential were determined using an EC meter and a Platinum electrode, respectively. Organic carbon was quantified by the Walkley–Black oxidation method and spectrophotometry. The total nitrogen content was determined via Kjeldahl digestion and distillation. Available phosphorus was extracted using the Olsen method for neutral to alkaline samples and the Bray I method for acidic samples, followed by colorimetric analysis. Exchangeable K^+ and Na^+ were leached with 1 M ammonium acetate and measured by flame photometry; Ca^{2+} and Mg^{2+} were titrated with

EDTA. Cation exchange capacity was calculated as the sum of exchangeable bases and exchangeable acidity. Each chemical test was performed in duplicate to validate accuracy.

2.6. Observations

Morphological descriptions at each sampling point revealed five genetic horizons. The Ap horizon (0–27 cm) exhibited a silty-clay texture, wavy microrelief, a coarse weak-crumb structure, a firm-sticky consistency, moderate porosity, and sparse medium-sized roots. The AB horizon (27–50 cm) shared a similar texture but displayed fewer pores and finer roots. Horizons Bt1 (50–91 cm) and Bt2 (91–94 cm) showed angular moderate crumbs, increased clay content, and minor gravel (1 % at Bt2), indicative of clay illuviation. The BC horizon (94–106 cm) contained 10 % coarse gravel within a compact silty-clay matrix. Physiographically, the area is situated on Pleistocene Anjasmoro volcanic deposits, characterized by a mountainous relief with complex slopes (20–200 m elevation difference, 19°–38° gradient), a southeast aspect, terraced landforms, and average slope lengths of approximately 10.8 m.

2.7. Data Analysis

All laboratory measurements were converted to standard units and processed using Microsoft Excel. Descriptive statistics, including means and ranges, were calculated to characterize the spatial variability of soil physical and chemical properties across horizons. This organized dataset enabled comparative analysis among sampling points and supported soil classification according to the USDA Soil Taxonomy, as well as the interpretation of fertility status.

3. Results and Discussion

3.1. Soil Moisture Content

The results of the water factor (F.W. Ratio), which reveal marked variability in moisture retention and hydraulic properties among the sampling locations, are summarized in Table 1. The laboratory results in Table 1 reveal a clear moisture gradient across the five sampling points, with sample K4H5 showing the highest moisture content (20.8%) and F.w. factor (1.263), and K4H1 showing the lowest (6.2%, F.w. = 1.066). This variation highlights how low soil moisture intensifies matric suction, thereby accelerating water infiltration into the soil profile (Chitta et al., 2021). Conversely, high humidity in K4H5 suggests slower infiltration rates but greater water availability near the surface. Such contrasts often reflect differences in antecedent rainfall, soil texture, and organic matter content, which mediate the soil's water-holding capacity and hydraulic conductivity.

Table 1. Soil Moisture Content Test Results

Sample Code	% Moisture	F. W. Ratio
K4H1	6.20	1.06
K4H2	13.48	1.16
K4H3	18.60	1.23
K4H4	7.99	1.09
K4H5	20.80	1.26

Notes: Laboratory test results for Land Resources at UPN Veteran East Java; *K4 = Site code for the Pulosari Dua plantation location in Bareng Wonosalam District; *H = Horizon (H1 refers to the Ap, H2 to the AB, H3 to the Bt1 H4 to the Bt2, H5 to the BC)

Table 2. Correlation Analysis Between % Moisture and % Soil Texture Fraction

	% Moisture	% Sand	% Silt	%Clay
% Moisture	1			
% Sand	-0.51	1		
% Silt	-0.13	0.85	1	
%Clay	0.17	-0.87	-0.99	1

Soil texture and structure emerged as key controls on moisture distribution. Locations dominated by silty clay and clay textures (Table 8) exhibited higher water retention due to smaller pore sizes and greater surface area for capillary adsorption (Hadi Pratiwi et al., 2022). In contrast, coarser-textured zones, such as K4H1, facilitated rapid drainage, yielding lower moisture levels. Land-use practices further modulate these dynamics: plantations of clove and nutmeg, with their deeper rooting systems, can enhance subsurface percolation and reduce surface moisture (Irawan et al., 2022).

The correlation analysis between soil texture fractions and gravimetric moisture content supports these observations (Table 2), revealing a moderate negative relationship with sand content (r = –0.511). This indicates that horizons with higher sand percentages tend to retain less water due to the dominance of macropores and rapid gravitational drainage. Silt content exhibited a very weak negative correlation with moisture (r = –0.126), indicating a negligible influence on water retention within the studied profile. In contrast, the clay content showed a weak positive correlation with moisture (r = 0.173), consistent with the theoretical role of clay in enhancing water-holding capacity through increased micropore volume and surface area. However, the relatively low correlation coefficient for clay may reflect the narrow range of clay variation among horizons or the confounding effects of other soil properties such as organic matter content. All samples (K4H1–K4H5) were collected from a single representative site, with each code denoting a distinct soil horizon within the same profile. Therefore, variability in measured parameters reflects vertical differences between horizons rather than spatial variation across sites. These findings align with established principles of soil physics, where coarse-textured soils generally exhibit lower field capacity and moisture retention compared to finer-textured soils.

From an agronomic perspective, understanding this spatial variability is vital for irrigation scheduling and soil management. In low-moisture areas (e.g., K4H1), supplemental irrigation or organic mulches can mitigate plant water stress. In high—moisture zones (e.g., K4H5), drainage management and avoiding waterlogging become priorities. Tailoring water management to these micro-variations will optimize crop performance and sustainable land use in Wonosalam's plantations (Ali et al., 2022).

3.2. Soil pH, EC, and Redox

The measured values for each horizon across the five sampling points are presented in Table 3. Table 2 presents the soil's acidity, salinity, and redox status across the five sampling horizons. Soil pH ranged from slightly acidic (pH H_2O 5.35, pH KCl 4.15 in K4H4) to moderately acidic (pH H_2O 5.99, pH KCl 4.28 in K4H3). The lower pH in K4H4 likely results from the enhanced leaching of basic cations and higher Al^{3+} activity under local topographic and vegetative conditions (Prabowo & Subantoro, 2018). Electrical conductivity (EC) varied widely, ranging from 6.8 µS/cm (K4H5) to 93.5 µS/cm (K4H1), indicating that K4H1 retains more soluble salts, possibly due to lower drainage or proximity to salt-bearing parent material. In contrast, K4H5's low EC reflects effective leaching and minimal salinity buildup (Sihombing et al., 2022). The redox potential (Eh) increased with depth and moisture, ranging from 128 mV in K4H2 to 147 mV in K4H5, indicating prevailing oxidizing conditions that favor nutrient mineralization and microbial activity (Miele et al., 2023). Together, these chemical properties — pH, EC, and Eh — provide a nuanced picture of nutrient availability, salinity risk, and redox-driven transformations, all of which are critical for optimizing fertility management and crop selection in these plantation soils. Based on these findings, dolomite liming is recommended to correct soil acidity, while site-specific fertilization and organic amendments can help manage salinity and enhance microbial activity under oxidizing conditions.

Table 3. Soil pH, EC, and Redox Test Results

Sample Code	**pH**		**EC (µS/cm)**	**Redoxs (mV)**
	H_2O	**KCl**		
K4H1	5.47	4.66	93.5	132
K4H2	5.61	4.54	13.1	128
K4H3	5.99	4.28	26.8	135
K4H4	5.35	4.15	17.4	144
K4H5	5.69	4.15	6.8	147

Notes: Laboratory test results for Land Resources at UPN Veteran East Java; *K4 = Site code for the Pulosari Dua plantation location in Bareng Wonosalam District; *H = Horizon (H1 refers to the Ap, H2 to the AB, H3 to the Bt1 H4 to the Bt2, H5 to the BC)

3.3. Organic Carbon

The organic carbon and corresponding organic matter values for each sampling horizon are presented in Table 4. Table 3 summarizes the soil organic carbon (SOC) and calculated organic matter (OM) contents across the five sampling horizons. SOC ranged from 0.77 % in sample K4H1 to 3.61 % in sample K4H5, with OM values of 1.32 % and 6.23 %, respectively. The low SOC at K4H1 likely reflects limited organic inputs and higher erosion on steeper slopes. In contrast, the elevated SOC at K4H5 can be attributed to greater residue return and reduced leaching on gentler terrain. Soil organic carbon is a key driver of aggregate stability, porosity, water retention, and nutrient-holding capacity, all of which support root growth and microbial activity (Yulina & Ambarsari, 2021). To raise SOC in low-carbon areas, incorporating organic amendments such as compost, green manure, or livestock manure can enhance carbon pools, improve soil structure, and stimulate beneficial soil biota (Arifiati & Nuraini, 2017; Sertua et al., 2014).

Figure 1 further illustrates the mean SOC values across horizons, with error bars representing standard deviations from three replicate measurements. The graphical presentation highlights a transparent vertical gradient, with SOC increasing from the surface horizon (K4H1) to the deepest horizon (K4H5). Notably, SOC in K4H5 exceeded the widely cited 2 % benchmark for tropical mineral soils, while the upper horizons remained below this threshold. This comparison underscores the need for targeted management: low-SOC horizons require organic inputs to restore soil quality, whereas high-SOC horizons highlight the potential of residue retention and reduced disturbance to sustain carbon stocks.

Table 4. Soil Organic Carbon Test Results

Sample Code	C-Organic (%)	Organic Matter (%)
K4H1	0.77	1.32
K4H2	1.04	1.79
K4H3	1.31	2.25
K4H4	1.00	1.72
K4H5	3.61	6.23

Notes: Laboratory test results for Land Resources at UPN Veteran East Java; *K4 = Site code for the Pulosari Dua plantation location in Bareng Wonosalam District; *H = Horizon (H1 refers to the Ap, H2 to the AB, H3 to the Bt1 H4 to the Bt2, H5 to the BC)

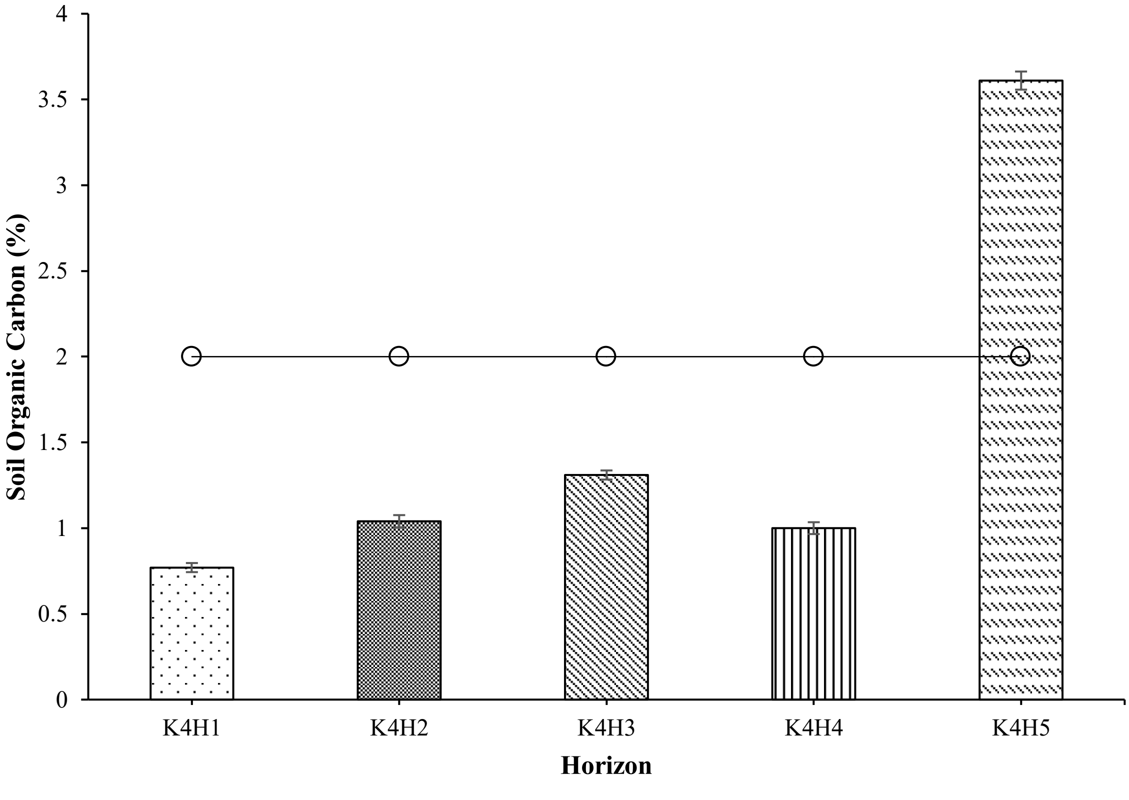

Figure 1. Soil organic carbon by horizon

3.4. Total Nitrogen

To assess the soil's nitrogen status, total nitrogen (N-total) was measured on air-dried, <2 mm sieved samples using the Kjeldahl digestion–distillation method. This technique quantifies both organic and ammonium nitrogen, offering a comprehensive indicator of the soil's nitrogen reserves available for plant uptake and microbial turnover. The total nitrogen content directly correlates with organic matter levels and potential mineralization rates, making it a key metric for evaluating soil fertility and informing nutrient management. The N-total values for each horizon across the five sampling points are presented in Table 5.

As shown in Table 5, total nitrogen content ranged from 0.06 % in samples K4H4 and K4H5 to 0.08 % in sample K4H2. The highest N-total at K4H2 likely reflects greater inputs of nitrogen-rich residues or organic amendments, combined with reduced leaching losses on gentler slopes. In contrast, the lower values at K4H4 and K4H5 may result from intensive cultivation practices, higher denitrification rates under wetter conditions, or limited organic inputs. Soil nitrogen is lost through volatilization, leaching, plant uptake, and microbial immobilization (Dewi & Setiawati, 2018), so maintaining or increasing N-total in depleted areas can be achieved by incorporating leguminous cover crops, applying compost or manure, and adopting no-till practices to bolster nitrogen stocks and support sustainable crop production (Mazzoncini et al., 2011).

Table 5. Total Nitrogen Test Results

Sample Code	N-Total (%)
K4H1	0.07
K4H2	0.08
K4H3	0.07
K4H4	0.06
K4H5	0.06

Notes: Laboratory test results for Land Resources at UPN Veteran East Java; *K4 = Site code for the Pulosari Dua plantation location in Bareng Wonosalam District; *H = Horizon (H1 refers to the Ap, H2 to the AB, H3 to the Bt1 H4 to the Bt2, H5 to the BC)

3.5. Available Phosphorus

The available phosphorus values for each sampling horizon are summarized in Table 6. The available phosphorus data, presented in Table 6, demonstrate significant variation across the five soil samples, ranging from 3.30 ppm in sample K4H4 to 22.68 ppm in K4H1. These values reflect the soil's capacity to supply phosphate readily accessible to plants, a critical nutrient for root development, flowering, and energy transfer. K4H1 recorded the highest P-available level (22.68 ppm), likely due to favorable pH conditions, active organic matter decomposition, or mineral sources releasing phosphorus into the soil solution. In contrast, K4H4 exhibited the lowest P value (3.30 ppm), suggesting stronger P fixation, possibly due to the prevalence of aluminum and iron oxides in acidic environments or lower biological activity inhibiting mineralization (Mwende Muindi, 2019).

Table 6. Available Phosphorus Test Results

Sample Code	P (ppm)
K4H1	22.68
K4H2	6.71
K4H3	4.77
K4H4	3.30
K4H5	14.12

Notes: Laboratory test results for Land Resources at UPN Veteran East Java; *K4 = Site code for the Pulosari Dua plantation location in Bareng Wonosalam District; *H = Horizon (H1 refers to the Ap, H2 to the AB, H3 to the Bt1 H4 to the Bt2, H5 to the BC)

The moderate P concentrations found in K4H2 (6.71 ppm), K4H3 (4.77 ppm), and K4H5 (14.12 ppm) point to varied phosphate dynamics influenced by horizon depth, clay content, and organic matter distribution. The Bray and Olsen methods were used appropriately, based on pH: Bray for acidic samples and Olsen for neutral to alkaline profiles, ensuring an accurate representation of plant-available phosphorus (Ara et al., 2018).

To assess nutrient sufficiency, the measured P-available values were compared with established critical phosphorus thresholds for tropical crops, typically ranging from 10 to 20 ppm for Olsen P and 15 to 25 ppm for Bray P (Hazelton & Murphy, 2025; Jalali et al., 2025). Samples below 10 ppm, such as K4H2, K4H3, and K4H4, fall below the critical range and may benefit from phosphorus fertilization or organic amendments to stimulate microbial release and enhance availability. In contrast, samples above 15 ppm, including K4H1 and K4H5, exceed the sufficiency threshold and require only maintenance fertilization to prevent luxury uptake or environmental runoff. This comparison provides a clearer basis for evaluating soil fertility status and guiding site-specific phosphorus management strategies.

From a management standpoint, soils with P-available values below 10 ppm may benefit from phosphorus fertilization or organic amendments (e.g., compost or manure) to stimulate microbial release and improve availability. Those with values above 15 ppm, such as K4H1 and K4H5, require maintenance fertilization only to avoid luxury uptake or environmental runoff. In future cultivation, attention to soil pH, organic inputs, and erosion control will help maintain optimal phosphorus supply for sustainable crop production (Balemi & Negisho, 2012; Shah & Wu, 2019). Integrating these findings with the observed SOC and moisture gradients reinforces the importance of horizon-based nutrient management, where each layer's physical and chemical properties inform tailored interventions to optimize plant growth and long-term soil health.

3.6. Exchangeable Cations, CEC, and Base Saturation

The resulting values for each horizon at our single sampling point are presented in Table 7. As shown in Table 7, exchangeable potassium (K) ranged from 0.11 to 0.23 cmol kg⁻¹, classified as low, while exchangeable sodium (Na) ranged from 0.40 to 0.56 cmol kg⁻¹, also low. Exchangeable calcium (Ca) was high, varying between 3.69 and 7.06 cmol kg⁻¹, whereas exchangeable magnesium (Mg) showed a wide range from –2.17 to 6.31 cmol kg⁻¹. CEC values lay between 9.15 and 12.93 cmol kg⁻¹ (low to moderate), and base saturation spanned 53.51 % to 117.11 % (high).

Table 7. Test Results for Exchangeable Base Cations, Cation Exchange Capacity (CEC), and Base Saturation (BS)

Sample Code	K- (cmol·kg⁻¹)	Na	Ca	Mg	CEC	BS (%)
K4H1	0.23	0.56	4.00	2.13	12.93	53.51
K4H2	0.15	0.40	4.05	4.62	11.97	76.99
K4H3	0.17	0.60	3.69	4.91	9.18	102.14
K4H4	0.11	0.48	7.06	2.40	10.05	54.56
K4H5	0.12	0.49	3.79	6.31	9.15	117.11

Notes: Laboratory test results for Land Resources at UPN Veteran East Java; *K4 = Site code for the Pulosari Dua plantation location in Bareng Wonosalam District; *H = Horizon (H1 refers to the Ap, H2 to the AB, H3 to the Bt1 H4 to the Bt2, H5 to the BC)

The low K indicates that potassium availability in the study soils is limited, necessitating supplemental potassium fertilization (Khatimah et al., 2024). Low Na values (< 1.0 cmol kg⁻¹) indicate no salinity problems and generally good soil quality. The contrasting Ca and Mg levels suggest an imbalance in essential cations, which may impair fertility. Soils rich in Ca but deficient in Mg often benefit from dolomite applications, which raise Mg levels without substantially increasing pH (Nabiollahi et al., 2017). The low to moderate CEC reflects a limited capacity to retain and supply cations, typically due to low clay and organic matter contents, suggesting a need for organic or clay-based amendments to enhance nutrient-holding capacity (Hailegnaw et al., 2019). High base saturation indicates that most exchange sites are occupied by nutrient cations, which can improve soil structure and root activity but may also necessitate balanced fertilization to maintain long-term nutrient equilibrium (Sahbudin et al., 2020). These findings collectively support a site-specific soil management approach that focuses on potassium supplementation, dolomite application, and the integration of organic amendments to improve fertility and sustain plantation productivity.

The measured CEC and base saturation (BS) values provide diagnostic support for soil classification under Soil Taxonomy. Horizons with BS values exceeding 35 % and moderate-to-high CEC align with Alfisol criteria, particularly where argillic horizon development is evident. Conversely, profiles with a BS below 35% and weak horizon differentiation are more consistent with the Inceptisol classification. These interpretations are consistent with morphological observations and support the preliminary taxonomic assignment presented in Table 7.

3.7. Texture

The distribution of soil texture classes across the genetic horizons is presented in Table 8. The texture data in Table 8 show four horizons (K4H1, K4H3, K4H4, K4H5) classified as silty clay or clay, with clay fractions ranging from 42% to 71%, and one horizon (K4H2) as silty clay loam. High silt and clay contents enhance water-holding capacity and nutrient retention by providing large surface areas and strong particle cohesion, thereby improving soil quality. However, when clay exceeds 40 %, pore continuity is reduced, leading to slower infiltration rates, poorer aeration, and potential compaction under wet conditions (Hadi Pratiwi et al., 2022). The silty clay loam horizon (K4H2), by contrast, offers a more favorable balance of permeability and moisture storage, which can support more uniform root development.

Fine textures also confer erosion resistance, as clay acts as a binding agent that stabilizes aggregates (Dewanti et al., 2024). Yet excessive clay can impede root penetration and limit microbial activity by restricting oxygen flow (Mulyono et al., 2019). Previous research describes silty clay soils as sticky and moldable, forming firm clods that resist breakdown but may compact under the weight of machinery or foot traffic. To optimize physical conditions in these plantation soils, integrating organic amendments (e.g., compost or green manure) or coarse-textured materials (e.g., sand or biochar) can increase macroporosity, improve structure, and maintain the moisture-retention benefits of the native fine texture (Jiang et al., 2017; Mondal et al., 2020).

Table 8. Texture Test Result

Sample Code	% Fraction			Total	Texture Class
	Sand	Silt	Clay		
K4H1	8	50	42	100	Silty Clay
K4H2	8	55	37	100	Silty Clay loam
K4H3	4	43	52	100	Silty Clay
K4H4	4	25	71	100	Clay
K4H5	4	31	65	100	Clay

Notes: Laboratory test results for Land Resources at UPN Veteran East Java; *K4 = Site code for the Pulosari Dua plantation location in Bareng Wonosalam District; *H = Horizon (H1 refers to the Ap, H2 to the AB, H3 to the Bt1 H4 to the Bt2, H5 to the BC)

3.8. Soil Permeability

The results of the soil's permeability are summarized for each sample in Table 9. Permeability rates were classified as fast, moderate, or slow based on USDA Soil Survey criteria, where saturated hydraulic conductivity (ksat) values exceeding 5.0 cm/hr are considered fast, 1.0–5.0 cm/hr are moderate, and those below 1.0 cm/hr are slow (USDA, 2017). The permeability data in Table 9 show a clear decline in hydraulic conductivity with increasing clay content.

Table 9. Soil Permeability Test Results

Sample Code	Permeability (cm h^{-1})	Class
K4H1	17.95	Fast
K4H2	3.67	Moderate
K4H3	0.36	Slow
K4H4	0.45	Slow
K4H5	0.20	Slow

Notes: Laboratory test results for Land Resources at UPN Veteran East Java; *K4 = Site code for the Pulosari Dua plantation location in Bareng Wonosalam District; *H = Horizon (H1 refers to the Ap, H2 to the AB, H3 to the Bt1 H4 to the Bt2, H5 to the BC)

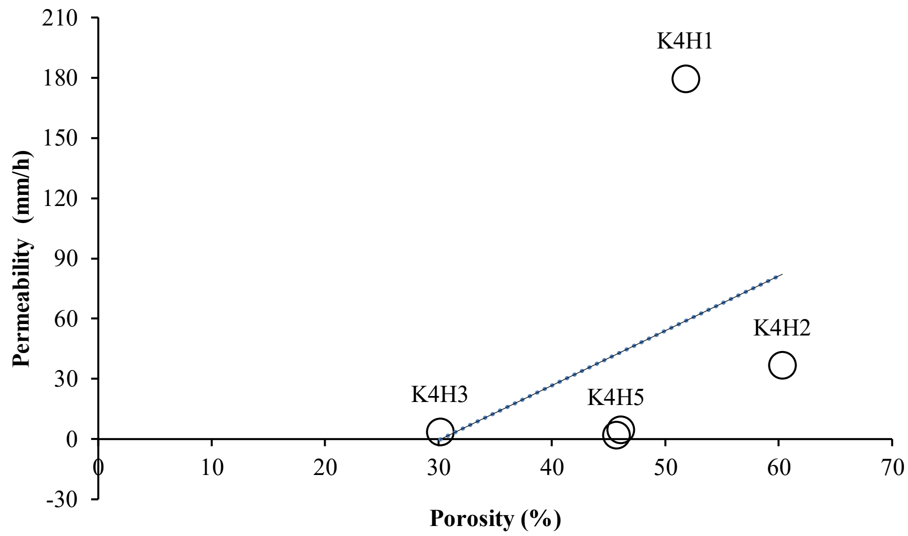

Figure 2. Relationship between soil porosity and infiltration rate across horizons

Sample K4H1 (42 % clay) exhibited the highest rate (17.95 cm h^{-1}, classified as fast), reflecting its coarser pore network and greater macroporosity. In contrast, K4H5 (65% clay) recorded the lowest Ks (0.20 cm h^{-1}, slow), consistent with its fine-textured matrix, which restricts pore continuity and water movement. Intermediate horizons (K4H2–K4H4) fell into moderate to slow classes, mirroring their silty clay or silty clay loam textures. Such variability influences drainage, aeration, and root zone moisture. High-permeability zones may require moisture-retentive amendments to prevent drought stress. In contrast, low-permeability areas are at risk of waterlogging and may benefit from enhanced macropore creation through the use of organic amendments or deep ripping (Qi & Knappett, 2022). The scatter plot between total porosity and infiltration rate yielded a low coefficient of determination (R^2 = 0.155), indicating a weak linear relationship (Figure 2). While porosity is theoretically linked to water movement, the low R^2 suggests that other factors, such as soil structure, texture, and biological activity, also influence water movement; therefore, porosity alone cannot serve as a reliable indicator.

3.9. Bulk Density, Particle Density, and Total Porosity

The values obtained for each genetic horizon are summarized in Table 10. Bulk density values ranged from 1.23 g cm^{-3} (K4H2) to 1.52 g cm^{-3} (K4H3). The highest bulk density in K4H3 reflects its dense, fine-textured structure and lower organic matter content, which reduces pore volume. Conversely, K4H2's lower bulk density corresponds to its silty clay loam texture and higher aggregate stability, which preserve more pore space.

Table 10. Bulk Density, Particle Density, and Porosity Test Results

Sample Code	Bulk Density (g/cm^3)	Particle Density (g/cm^3)	Total Porosity (%)
K4H1	1.25	2.59	51.80
K4H2	1.23	3.09	60.32
K4H3	1.52	2.18	30.16
K4H4	1.39	2.59	46.06
K4H5	1.42	2.62	45.68

Note: *K4 = Site code for the Pulosari Dua plantation location in Bareng Wonosalam District; *H = Horizon (H1 refers to the Ap, H2 to the AB, H3 to the Bt1 H4 to the Bt2, H5 to the BC)

Particle density varied markedly, with K4H2 peaking at 3.09 g cm^{-3}, likely due to coarse fragments or mineral enrichment, and K4H3 dropping to 2.18 g cm^{-3}, suggesting increased organic or micro-porous fractions. Total porosity mirrored these trends: K4H2 exhibited the highest porosity (60.32 %), supporting excellent aeration and water movement, while K4H3's low porosity (30.16 %) indicates limited macropores and potential risks of compaction and impeded root growth. The measured particle density values ranged from 2.18 to 3.09 g/cm^3, which is unusually wide for mineral soils. Values exceeding 3.0 g/cm^3 may indicate the presence of heavy minerals such as magnetite or hematite, while those below 2.3 g/cm^3 suggest elevated organic matter content or lightweight mineral fractions. These anomalies warrant further verification through mineralogical analysis or cross-checking with organic matter data to confirm the source of variation.

These findings highlight the joint influence of texture and organic matter on soil physical quality. Horizons with high bulk density and low porosity may benefit from organic amendments or reduced tillage to restore structure, whereas well-structured horizons should be managed to maintain their porosity advantages (Di Giuseppe et al., 2016; Hailegnaw et al., 2019). To improve physical conditions in compacted horizons such as K4H3, the integration of compost, cover crops, and minimal tillage practices is recommended to enhance porosity, reduce bulk density, and support healthy root development.

3.10. Soil Morphological Characteristics

The detailed horizon descriptions are summarized in Table 11. The clear, abrupt to smooth boundaries between Ap–AB and AB–Bt1 horizons indicate distinct pedogenic zones of organic mixing versus clay translocation. The Ap horizon's weak, coarse crumb structure and moderate root penetration reflect active bioturbation and organic matter enrichment. Transitioning to Bt1 and Bt2, the angular blocky structure and visible clay coatings on ped faces confirm the presence of an argillic horizon formed by illuviation. Reduced root abundance and coarser consistency in Bt2 and BC horizons indicate less biological activity and an increasing influence of the parent material. The silty clay to clay textures, coupled with dense, angular peds at depth, align with measured low permeability and high bulk density, underscoring restricted water movement and root growth in subsoil layers (Wei et al., 2015). Management should focus on maintaining surface structure through organic amendments while addressing potential compaction and drainage limitations in deeper horizons.

Table 11. Soil Morphological Characteristics

Horizon	Depth (cm)	Texture	Color (Munsell moist)
Ap	0–27	Silty clay	7,5 YR 6/4
AB	27–50	Silty clay loam	5 YR 5/8
Bt 1	50–91	Silty clay	2,5 YR 4/6
Bt 2	91–160	Clay	7,5 YR 6/6
BC	160–180	Clay	5 YR 5/8

Note: *K4 = Site code for the Pulosari Dua plantation location in Bareng Wonosalam District; *H = Horizon (H1 refers to the Ap, H2 to the AB, H3 to the Bt1 H4 to the Bt2, H5 to the BC)

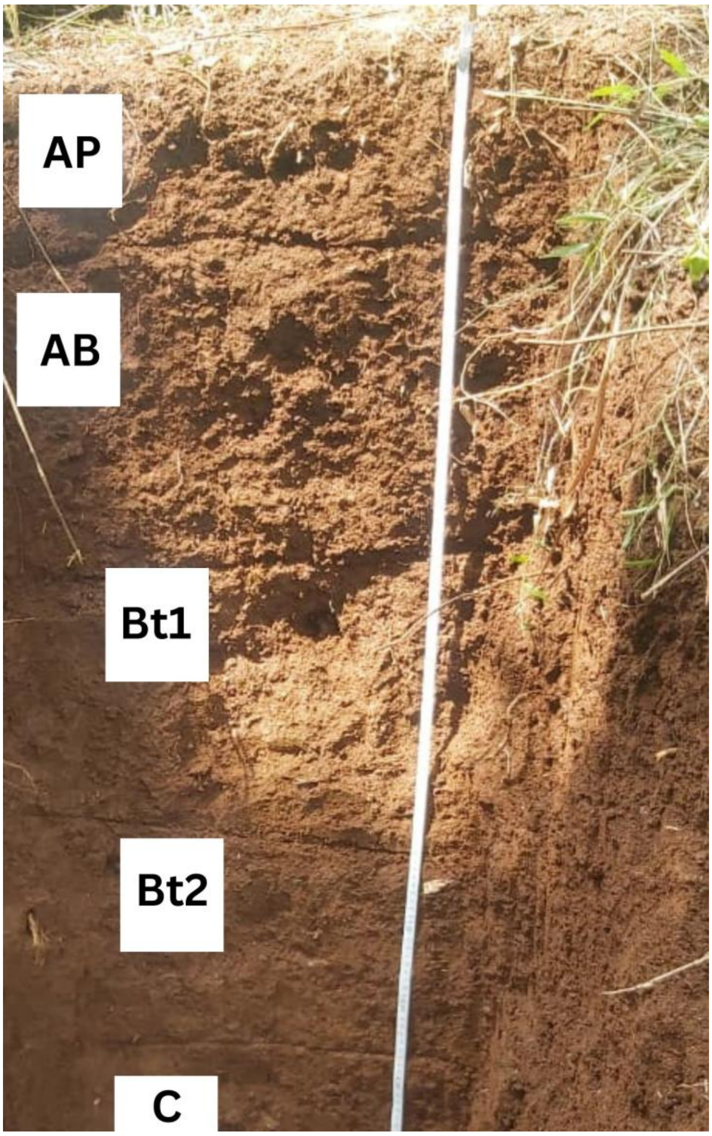

Figure 3. Field photographs of soil horizons (K4H1–K4H5)

These morphological features were further compared with profiles from nearby volcanic landscapes, such as those described by Anggraeni and Suryaningtyas (2017) in Sukabumi and also Suparman and Gunawan (2000) in Garut. Unlike the studied profile, which exhibits a shallow Mollic epipedon and moderately developed Argillic horizon, adjacent volcanic soils typically show deeper organic accumulation, stronger horizon differentiation, and lower base saturation. This contrast highlights the uniqueness of the Wonosalam profile within the regional volcanic context, which is shaped by microtopography, parent material, and land-use history. To enhance clarity and support horizon designation, representative photographs of each horizon (Figure 3) are recommended, illustrating color transitions, structural features, and the distinctness of boundaries. Thin-section micrographs could further reveal micromorphological evidence of clay illuviation and mineral composition, thereby strengthening the diagnostic basis for classification.

3.11. Soil Classification

The resulting taxonomic assignment is summarized in Table 12. To classify the soil profile at the UPN Experimental Farm in Wonosalam, we applied the USDA Soil Taxonomy framework. Surface-horizon properties, including a Mollic epipedon (0–27 cm) with 53 % base saturation, were used to define the epipedon, while subsurface attributes established the endopedon. The profile exhibits an Argillic endopedon, as evidenced by Bt horizons showing clay illuviation: oriented clay bridges spanning sand grains, thin clay films coating pore walls, and clay skins on both vertical and horizontal ped faces. These features fulfill all Argillic horizon criteria and testify to lessivage, the downward translocation of clay.

Table 12. Soil Classification at the Research Site

Taxonomic Category	Taxon Name	Description
Epipedon	Mollic	Base saturation of 53 % within the upper 0–27 cm
Endopedon	Argillic	Accumulation of clay in Ap, AB, Bt1, Bt2, and BC horizons
Order	Alfisol	Presence of an argillic horizon (clay ≥ 35 %)
Suborder	Udalfs	Udic moisture regime
Great Group	Hapludalf	Udalfs members without additional distinguishing features
Subgroup	Typic Hapludalfs	Typical representatives of the Hapludalf Great Group
Family	Clay	High clay content across all horizons, with evidence of clay illuviation and accumulation

Combined with clay contents of≥ 35% and base saturation above 50%, these illuvial signatures qualify the soil as an Alfisol. Its udic moisture regime places it in the Udalfs suborder. The absence of kandic, natric, or fragipan horizons and no lithic contact assigns it to the Hapludalf great group and the Typic Hapludalfs subgroup. Uniformly high clay contents across all horizons justify assigning this soil to the clay family. Typic Hapludalfs are recognized for their high nutrient reserves, strong cation-exchange capacity, and robust base saturation, characteristics that underpin their inherent fertility (Boxiang Zhang et al., 2025). To maintain the classification stability and long-term fertility of Typic Hapludalfs, management should focus on preserving horizon integrity and minimizing erosion, particularly in sloping areas where surface loss and horizon truncation are common risks.

To reinforce the classification, the profile was compared across multiple systems. Under the Indonesian soil classification (PPT), the profile corresponds to Tanah Mediteran, characterized by an argillic horizon and base saturation exceeding 50%. This alignment confirms consistency with the USDA Alfisol designation. According to the WRB system, the soil qualifies as a Haplic Luvisol (Clayic, Mollic), reflecting the presence of an argillic horizon, high clay content, and a mollic surface layer. The convergence of classifications across the USDA, PPT, and WRB frameworks underscores the diagnostic reliability of the observed features. It supports the broader applicability of these features in regional and international soil mapping.

4. Conclusion

The Pulosari plantation soil profile is characterized by fine textures (silty clay to clay), acidic pH (5.35–5.99), moderate to high moisture retention (6.2–20.8%), and distinct clay illuviation in the subsurface horizons. Hydraulic conductivity decreases sharply with depth (17.95–0.20 cm h^{-1}) due to reduced macroporosity in clay-rich Bt layers, while bulk density (1.23–1.52 g cm^{-3}) and total porosity (30.16–60.32%) reflect corresponding textural variations. High base saturation (53.5–117.1%) and cation exchange capacity (9.15–12.93 cmol kg^{-1}) indicate strong nutrient-holding capacity in the upper horizons. Morphological features such as clay coatings, ped structures, and root distribution confirm the presence of an Argillic endopedon formed by lessivage, classifying the soil as a Typic Hapludalf (Alfisol, Udalfs, Hapludalf, Clay family) — a fertile soil type with robust nutrient reserves. To sustain its productivity, management should incorporate organic matter additions, liming to balance Ca–Mg ratios and stabilize pH, structural improvements through coarse amendments or reduced tillage, and targeted K fertilization. These strategies will preserve soil structure, enhance water dynamics, and maintain long-term fertility for plantation crops in Wonosalam's hilly terrain.

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