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Study of Soil Properties on Various Slopes in the Cultivation of 15-Year-Old People's Rubber Plants in Janji Village, Bilah Hulu District, Labuhanbatu Regency

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Abstract−Erosion is a primary factor reducing soil productivity in perennial cropping systems, particularly smallholder rubber plantations. This condition is commonly found on sloping lands lacking adequate conservation practices. This study aims to qualitatively assess erosion through analysis of changes in soil physical and chemical properties in a 15-year-old smallholder rubber plantation in Janji Village, Bilah Hulu Sub-district, Labuhanbatu Regency. The research employed a descriptive survey method with a transect approach across three slope positions: summit, mid-slope, and valley. Observed parameters included soil pH, clay fraction, organic C content, and bulk density. The results revealed clear differences in soil properties at each slope position, indicating active erosion processes. At the summit, low pH values (average 4.38), clay fraction of 35.33%, organic C of 1.956%, and bulk density of 0.346 g/cm³ were found, reflecting significant topsoil loss and nutrient leaching. The mid-slope showed characteristics of a transport zone with the highest clay fraction (38.66%) and organic C of 1.060%. Meanwhile, the valley acted as a deposition zone with higher pH (5.26) and the greatest bulk density (0.366 g/cm³). This variation confirms that erosion influences the spatial distribution and quality of soil material in smallholder rubber gardens. This study underscores the need to implement soil conservation techniques such as organic mulch, cover crops, and contour planting patterns to minimize erosion rates in smallholder rubber cultivation systems.

Keywords: Soil Erosion; Smallholder Rubber; Slope Gradient; Soil Properties; Soil Conservation

1. INTRODUCTION

Land use change and increased intensification of tropical plantation crop cultivation are strategic issues in sustainable development, as they directly relate to goals of managing productive land, soil conservation, and improving smallholder farmer welfare. Economic pressures to meet plantation commodity demand often drive land expansion and management intensification, which, if not supported by sustainable practices, can degrade soil quality, accelerate erosion rates, and disrupt ecosystem functions supporting production and other environmental services (Cahyo et al., 2024; Chen, 2024).

This situation reinforces the urgency of research linking production aspects with soil conservation to formulate cultivation practices that maintain productivity while minimizing environmental impacts. Rubber (*Hevea brasiliensis*) is a vital commodity for millions of smallholder farmers in tropical and subtropical regions. However, recent studies indicate that its cultivation impacts on soil quality are significantly influenced by management patterns, stand age, and the presence of intercropping or agroforestry systems (Sun et al., 2021; Hong et al., 2024). The conversion of natural forest to monoculture rubber plantations has been proven to significantly alter soil physical, chemical, and biological properties, including reduced infiltration and increased erosion vulnerability. Conversely, agroforestry systems and inter-row ground cover can enhance soil resistance to degradation (Sun et al., 2021; Cahyo et al., 2024), making stand age and management practices key determinants of erosion risk in smallholder rubber gardens.

Hydrologically, the shift from natural vegetation to rubber plantations also affects soil water retention capacity. Under certain conditions, water retention and infiltration decrease, increasing surface runoff and erosion risk, especially in high rainfall areas and on moderate to steep slopes (Chen, 2024; Sun et al., 2021). Recent research also identifies that erosion hotspots are often located on relatively open planting rows. Therefore, the use of mulch, biomass residues, or leguminous cover crops has proven effective in suppressing runoff and soil loss (Perron et al., 2024). These findings highlight the importance of field evaluations based on ground cover conditions and organic residue management for erosion mitigation. From agroecological and soil microbiology perspectives, monoculture and intercropping systems in rubber show differences in root structure and microbial community composition. Integrating food crops or increasing inter-row vegetation cover can potentially improve soil physical and biological properties, enhance aggregate stability, and reduce erosion vulnerability (Hong et al., 2024). Changes in soil microbes and increased organic carbon are closely linked to soil structural robustness, so management that maintains surface organic matter contributes to increased productivity while reducing erosion risk (Hong et al., 2024; Sun et al., 2021).

In the context of smallholder gardens, socio-economic dynamics such as limited capital, labor, and access to technology influence farmers' ability to adopt soil conservation technologies. Technical interventions like planting leguminous cover crops, spreading residues, or constructing silt pits must consider ease of adoption and direct economic benefits perceived by farmers (Cahyo et al., 2024). Therefore, sustainability assessments of smallholder rubber cultivation need to include ecological, economic, and social indicators so that technical recommendations are not only effective but also widely applicable and acceptable. Plant age significantly influences soil biophysical and structural characteristics. A 15-year-old rubber garden, categorized as middle-aged, often undergoes management changes like pruning and opening new rows, which can affect erosion rates compared to younger or very old gardens (Xu et al., 2025; Perron et al., 2024). Consequently, research focusing on 15-year-old smallholder rubber gardens is crucial for identifying erosion vulnerability and appropriate conservation intervention opportunities. Specifically, Janji Village in Bilah Hulu Sub-district, Labuhanbatu Regency, represents smallholder rubber gardens in the lowland areas of North Sumatra with socio-economic characteristics and management patterns typical of local communities. However, qualitative studies on erosion patterns in middle-aged smallholder rubber gardens in this location remain limited.

This research gap hinders the formulation of contextual conservation strategies suited to local farmer needs. Studies assessing causal factors, erosion distribution patterns, and mitigation options will provide the necessary scientific basis to support sustainable rubber garden management. Considering these dynamics, this research aims to qualitatively assess erosion in 15-year-old smallholder rubber cultivation in Janji Village by identifying erosion hotspots, management practices contributing to erosion or its prevention, and formulating realistic conservation recommendations for smallholders. The findings are expected to serve as a reference for local policies and technical guidelines supporting the ecological, economic, and social sustainability of smallholder rubber production (Cahyo et al., 2024; Perron et al., 2024; Hong et al., 2024; Chen, 2024; Sun et al., 2021).

2. RESEARCH METHODS

This study was conducted from May to September 2025 in Janji Village, Bilah Hulu Sub-district, Labuhanbatu Regency, North Sumatra Province, in a ±15-year-old smallholder rubber garden. Site selection was based on the dominance of smallholder rubber gardens, variations in ground cover conditions, and indications of surface erosion visible on planting rows and inter-rows.

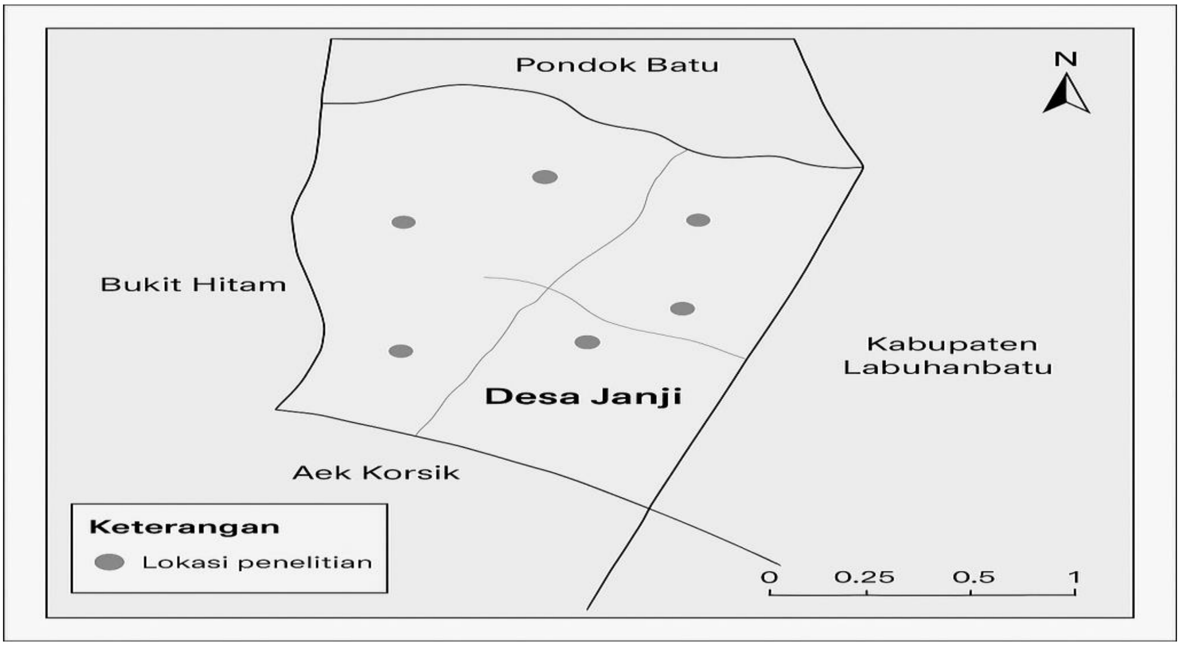

Figure 1. Administrative Map of Research Locations

Janji Village within the scope of Bilah Hulu Sub-district and Labuhanbatu Regency. Geographic coordinates: Approximately 2°12'--2°16' N and 99°52'--99°55' E. Boundary: North of Pondok Batu Village, south of Aek Korsik Village, west of Bukit Hitam Village, east of Pangkatan Sub-district.

The materials used in this research were: 15-year-old smallholder rubber plantation land, surface soil samples (0--20 cm), field documentation materials (observation sheets, interview forms), Base map imagery: DEMNAS (30 m) and BIG administrative boundaries. Handheld GPS for coordinate determination, Clinometer for slope gradient measurement, Soil sampler (ring sample) and small hoe for soil sampling, GIS software (ArcGIS/QGIS) for mapping, Field camera for documentation, Tape measure and measuring tape. These tools meet field observation standards for surface erosion studies as used in rubber garden erosion research by Perron et al. (2024) and soil hydrology studies by Chen et al. (2024).

This study used a qualitative-descriptive approach, emphasizing field observation, soil biophysical characteristics, and interpretation of surface conditions potentially causing erosion. The qualitative approach is suitable for research requiring a comprehensive understanding of erosion phenomena within ecological, social, and technical contexts. The qualitative method aligns with soil ecology study frameworks as used by Hong et al. (2024), Ali et al. (2025), and Liu et al. (2023), which evaluate soil conditions through field interpretation, interviews, and analysis of physical and biological characteristics. Data were obtained through three techniques:

a. Direct field observation, to describe actual erosion patterns, land cover, surface soil conditions, water pathways, and root structure.
b. Soil biophysical measurements, including aggregates, slope gradient, infiltration (visual), surface stability, and organic matter condition.

Preparation Stage: Literature review related to erosion in rubber gardens and soil biogeophysical factors (Chen et al., 2024; Ali et al., 2025; Hong et al., 2024), Creation of a working map using DEMNAS data and administrative boundaries, Determination of observation points based on slope variation and ground cover.

Field Observation**,** Establishment of at least 6 observation plots: Gentle slope plot (0--8%), Moderate slope plot (8--15%), Open inter-row plot, Plot with ground cover. Recording surface soil conditions, cracks, erosion paths, and small rills. Noting surface cover intensity (mulch, litter, cover crops). Measuring physical parameters: Slope gradient (clinometer), Surface texture (standard FAO manual visual), Depth of eroded solum (if present). This approach follows field erosion assessment methods used by Perron et al. (2024).

Soil Sampling**,** Collection of surface soil samples (0--20 cm) from each plot. Laboratory analysis of soil properties: Soil pH, Organic C, Aggregate structure, Moisture content. This method aligns with soil aggregate research in rubber gardens by Ali et al. (2025) and Liu et al. (2023).

3. RESULTS AND DISCUSSION

Analysis of Soil pH Results at Different Slope Positions, Soil pH measurements at three slope positions (summit, mid-slope, and valley) showed significant variation in acidity levels, reflecting differences in nutrient leaching, organic matter accumulation, and erosion dynamics in each landscape segment. pH values at the summit ranged from 4.19--4.64 with an average of 4.38, indicating this area tends to have more acidic soil conditions. This acidity is generally caused by more intensive leaching processes at the summit, where rainfall and surface flow remove basic cations such as Ca^{2+}, Mg^{2+}, and K^{+} (Sofyan, 2020).

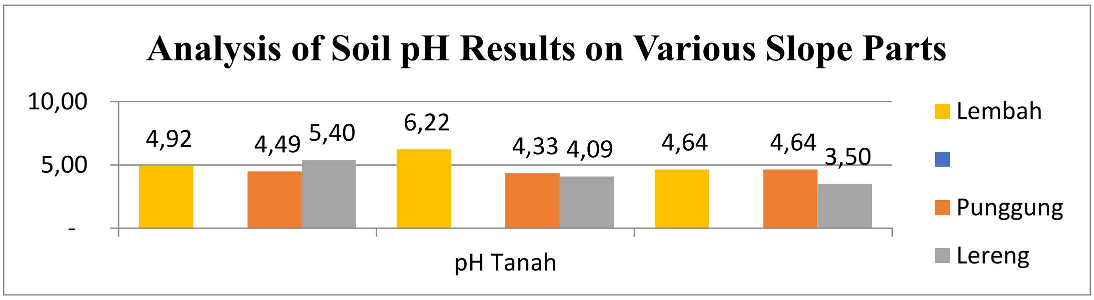

Figure 2. Analysis of Soil pH Results on Various Slope Parts

Summit positions typically have shallower soil layers and are more erosion-prone, resulting in lower pH buffering capacity. At the mid-slope, pH values ranged from 3.50--5.40 with an average of 4.33, slightly lower than the summit. This high variability indicates a combination of leaching and organic matter accumulation from upper parts. Nevertheless, acidity remains dominant, which may indicate high soil erosion rates, especially in smallholder rubber cultivation systems without adequate conservation measures (Harahap & Siregar, 2021).

Extreme acidity reaching pH 3.50 can disrupt soil microbial activity and inhibit the availability of essential nutrients like P and Mo (Brady & Weil, 2017). In contrast to the previous two positions, the valley showed higher pH values of 4.92--6.22 with an average of 5.26. This pH falls into the acidic to slightly acidic category and is relatively more neutral compared to other areas. This is due to the accumulation of organic matter, erosion sediments, and basic cations carried from upper slopes through runoff and surface erosion processes (Utami et al., 2022). This condition is common in valleys as depositional areas, leading to relatively better soil fertility. In rubber cultivation, more moderate valley pH conditions potentially support root growth and latex productivity. Overall, this pH distribution pattern shows that erosion intensity and soil material movement significantly influence soil chemical properties, especially in rubber cultivation on sloping land. Lower pH in upper and mid-slope sections indicates that erosion has removed organic-rich topsoil, leaving more acidic horizons. This aligns with findings that sloping lands without conservation measures experience soil quality degradation due to chronic erosion (Lal, 2019). Therefore, soil conservation interventions such as cover crops, contour ridges, or organic mulch are essential to maintain soil quality in 15-year-old smallholder rubber cultivation in Janji Village.

Analysis of Clay Fraction Results at Different Slope Positions, Clay fraction data at three slope positions summit, mid-slope, and valley show soil texture distribution patterns closely related to erosion dynamics, deposition, and leaching processes on sloping landscapes. The clay fraction value at the summit ranged from 32-40% with an average of 35.33%, indicating this section tends to have medium to high clay content. Relatively high clay content at the summit may indicate that erosion processes in this location have not completely removed the more clayey sub-horizon (Utami & Handayani, 2020). However, high clay content can also reflect eluviational processes moving fine particles downslope when surface erosion becomes more intense (Lal, 2019).

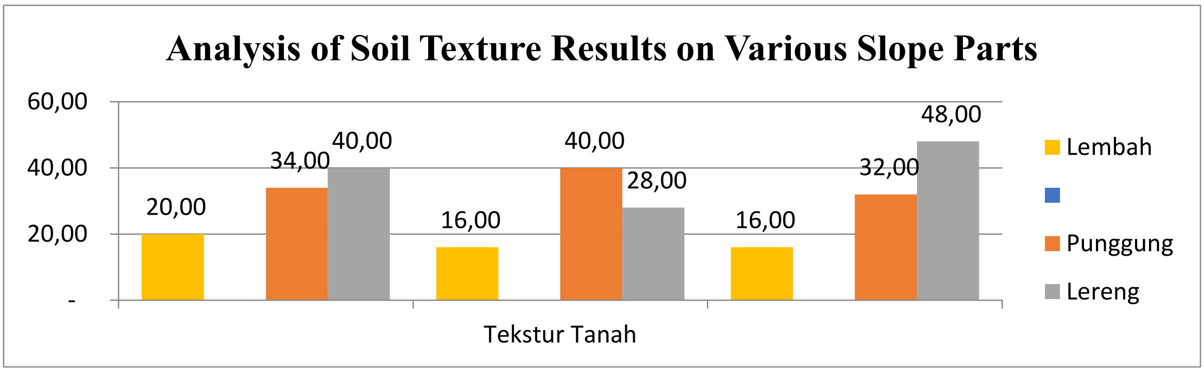

Figure 3. Analysis of Soil Texture Results on Various Slope Parts

At the mid-slope, the clay fraction ranged from 28-48% with an average of 38.66%, the highest value compared to the other two positions. This indicates that the mid-slope is a transitional zone receiving fine particle (clay) accumulation from the summit through surface runoff while undergoing deposition before particles reach the valley. The highest clay value (48%) shows illuviation, the accumulation of clay particles in specific soil layers often occurring in sloping soils experiencing chronic erosion (Brady & Weil, 2017). In smallholder rubber ecosystems, this condition is typically worsened by minimal ground cover, increasing soil erodibility and accelerating fine particle translocation. In contrast to the two previous positions, the valley showed much lower clay content of 16--20% with an average of 17.33%. The low clay fraction in the valley indicates that this area receives more coarse material (sand or silt) rather than clay fractions. This can occur when erosion in upper sections transports not only clay particles but also lighter material first, while clay particles are carried further or remain in the mid-slope (Sari et al., 2021).

Additionally, sufficiently strong water flow in the valley can suspend and carry clay particles further, leaving behind predominantly coarse fractions. This condition matches the characteristics of depositional areas with high sedimentation dynamics, where fine fractions are often sorted by water flow energy (Poesen & Lavee, 2020). Overall, the clay fraction distribution from summit → mid-slope → valley shows a typical pattern of sloping areas experiencing surface erosion. High clay content at the summit and mid-slope reflects source erosion and translocation zones, while the valley acts as a deposition zone for coarser material. This finding further strengthens the evidence that rubber cultivation without adequate soil conservation measures increases soil degradation risk, characterized by texture changes, decreased clay fraction in the valley, and increased structural damage in upper slopes.

Analysis of Soil Organic-C Results at Different Slope Positions, Organic C content is one of the most important indicators for assessing soil quality, especially on sloping lands prone to degradation. Organic C data from the summit, mid-slope, and valley show a pattern of decreasing organic matter content corresponding to increasing erosion intensity, thus depicting soil degradation dynamics in smallholder rubber agroecosystems. At the summit, organic C content ranged from 1.49--2.31% with an average of 1.956%, indicating this area has the highest organic matter content compared to the other two positions.

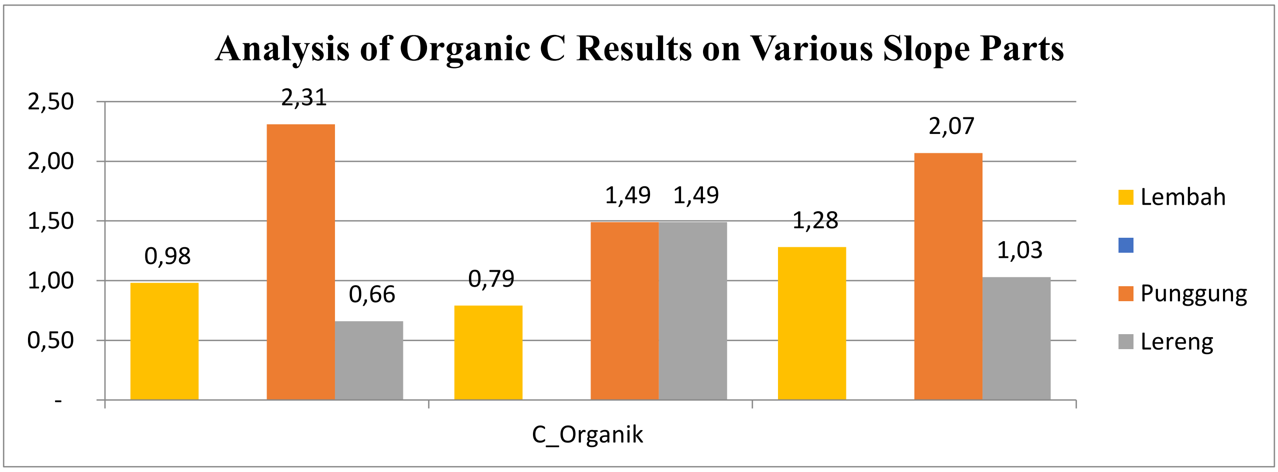

Figure 3. Analysis of Organic C Results on Various Slope Parts

The high organic C content at the summit can be linked to the relatively more preserved topsoil layer, despite erosion pressure. Organic matter is typically more abundant in upper horizons, so when erosion is not too extreme, organic

C content in this part remains relatively high (Lal, 2019). Additionally, leaf litter from rubber trees can add organic inputs to the soil surface (Mulyani & Sarwani, 2020).

Conversely, at the mid-slope, organic C values ranged from 0.66--1.49% with an average of 1.060%, showing a significant decrease compared to the summit. This confirms that the mid-slope is the most active zone for soil material translocation, where organic matter from the top layer is easily transported by surface runoff. This causes the soil to become poor in organic matter and more prone to compaction and reduced infiltration (Brady & Weil, 2017). In rubber land without adequate soil conservation measures, sheet erosion and rill erosion can quickly remove topsoil rich in organic C.

In the valley section, organic C content ranged from 0.79--1.28% with an average of 1.016%, slightly higher than the mid-slope but still lower than the summit. This indicates the valley functions as a deposition zone, where eroded material from upper slopes settles. However, the deposited material does not always include organic fractions, as lighter organic matter can be carried further by water flow or decompose faster due to moist conditions (Poesen & Lavee, 2020).

Therefore, although the valley is a depositional area, it is not always the zone with the highest organic C content. Overall, this pattern shows that erosion intensity has a strong correlation with declining soil organic C. Low organic C content in the mid-slope and valley indicates soil degradation due to topsoil loss.

This finding aligns with reports that erosion is a primary cause of soil organic matter decline in sloping plantation lands in tropical regions (Sujana et al., 2021). Thus, applying soil conservation techniques like organic mulch, cover crop planting, and surface runoff management becomes crucial to maintain organic matter stability in the 15-year-old smallholder rubber cultivation system in Janji Village.

Analysis of Soil Bulk Density Results at Different Slope Positions, Bulk density (BD) is an important parameter for assessing soil compaction levels and overall soil physical condition. BD values are influenced by organic matter content, soil texture, biota activity, and erosion intensity. Variation in BD across three slope positions—summit, mid-slope, and valley—provides insight into the dynamics of soil structural change due to erosion in smallholder rubber plantations. At the summit, BD values ranged from 1.256--1.258 g cm^{-3} with an average of 1.258 g cm^{-3}.

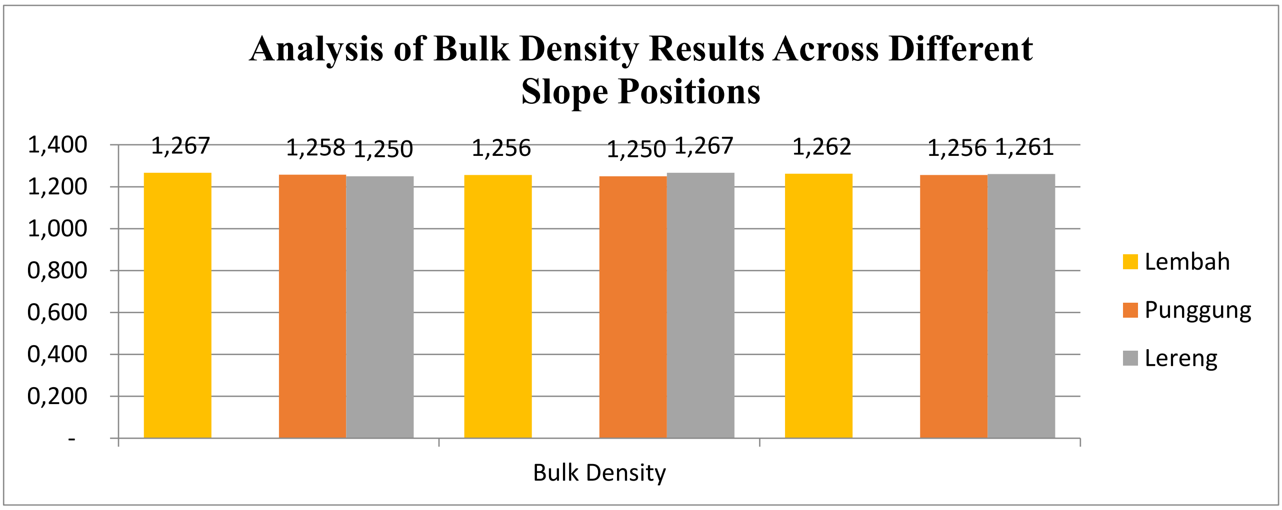

Figure 4. Analysis of Bulk Density Results Across Different Slope Positions

This value falls into the moderate category, indicating that soil at the summit does not experience extreme compaction despite direct exposure to surface runoff. The relatively high organic C content at the summit (compared to the other two positions) also supports soil aggregate stability, preventing excessive compaction (Lal, 2019). The relatively stable soil structure in this section potentially aids infiltration, although the summit is the most vulnerable zone to topsoil loss. At the mid-slope, BD ranged from 1.258--1.267 g cm^{-3} with an average of 1.260 g cm^{-3}, slightly lower than the valley but relatively similar to the summit. The mid-slope is a zone of flow and sediment transport, so soil structure in this area often changes due to sheet and rill erosion. However, BD does not sharply increase because some fine material is carried away by erosion before compaction occurs (Brady & Weil, 2017).

Nevertheless, low organic matter in the mid-slope indicates the soil is more prone to compaction if not managed properly. In the valley, BD ranged from 1.256--1.267 g cm^{-3} with an average of 1.262 g cm^{-3}, the highest value among all slope positions. This shows that the valley has greater compaction potential compared to the other two sections. This compaction can occur due to the accumulation of eroded sediments mixed with coarser fractions having higher density (Poesen & Lavee, 2020). Additionally, valley areas tend to have high moisture, hindering soil organism activity and accelerating compaction. Higher BD values in the valley can reduce soil porosity, decrease water infiltration, and potentially increase surface flow during high rainfall periods. Overall, differences in BD across slope positions show that erosion intensity affects soil structure and compaction. The relatively uniform yet slightly increasing BD in the valley illustrates that erosion not only removes topsoil but also moves heavier material downslope. This condition aligns with findings that deposition processes can increase bulk density in valley areas (Sujana et al., 2021). In smallholder rubber cultivation systems, increased soil compaction in the valley and decreased organic matter in the mid-slope are important indicators of soil degradation due to erosion.

4. CONCLUSION

Soil chemical and physical properties differ significantly across slope positions, indicating erosion dynamics and soil material relocation. At the summit, pH values ranged from 4.19--4.64 (average 4.38); clay fraction 35.33%; organic C 1.956%; and bulk density 0.346 g/cm³. These values reflect high leaching and nutrient loss, resulting in lower soil quality compared to mid-slope and valley areas. At the mid-slope, soil pH was slightly lower (average 4.33), clay fraction higher (38.66%), organic C 1.060%, and bulk density 0.260 g/cm³. This condition indicates an erosion transport zone, where soil from upper parts is transported and partially deposited. The higher clay fraction shows accumulation of fine particulates due to translocation processes. In the valley, soil pH increased significantly (average 5.26), clay fraction was lower (17.33%), organic C 1.016%, and bulk density was highest (0.366 g/cm³). This confirms the valley as a deposition zone, where soil eroded from upper slopes accumulates. Increased pH and bulk density strengthen indications that accumulated soil tends to be denser but has different biological activity. Overall, the pattern of changing soil properties from summit–slope–valley demonstrates active erosion, especially in 15-year-old smallholder rubber areas lacking conservative management. Variations in clay fraction, organic C, and pH confirm that soil transport and deposition processes affect soil quality spatially across the slope transect. Implementation of soil conservation techniques is essential, particularly on summit and mid-slope areas showing signs of topsoil loss. Conservation practices like organic mulch, cover crop planting, or silt pit construction are highly recommended. Organic matter management needs enhancement, given organic C values < 2% across all slope positions. Adding compost, manure, or biochar can improve aggregate stability and reduce erosion risk. Reorganization of rubber planting rows following contour patterns (contour planting) is important to interrupt surface flow velocity. Rubber-based agroforestry systems can also be an alternative for long-term soil quality improvement. Periodic monitoring of soil property changes, especially during the rainy season, is needed to ensure erosion dynamics can be addressed early. Further analyses like aggregate stability, permeability, and infiltration can strengthen mitigation steps. Smallholder rubber garden managers need training in soil conservation, considering most smallholder rubber cultivation practices still inadequately address conservation aspects.

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