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CHARACTERISTICS OF SOIL AND VEGETATION IN POST-LANDSLIDE AREA OF BONGLO VILLAGE, LUWU, SOUTH SULAWESI

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ABSTRACT

A landslide is a natural event characterized by the significant downslope movement of rock and soil masses. This corresponds to the recent landslide that occurred in Bastem, which also resulted in casualties. This study aims to analyze soil and vegetation characteristics in the landslide-affected area of Bonglo Village, Bastem Utara District, Luwu Regency. The research applied a purposive sampling method across nine plots (three in landslide areas and six in vegetated areas). Soil samples were analyzed for texture, permeability, bulk density, plasticity, organic matter, and pH, while vegetation was assessed using the Importance Value Index (IVI). Results revealed variations in soil texture, namely sandy loam, loamy sand, clay loam, and sandy clay loam. Permeability was highest in P2 (165.3 cm/hr) and P3 (78.6 cm/hr), and lowest in P5 (0.6 cm/hr). Bulk density ranged from 1.03 g/cm³ (P4) to 1.75 g/cm³ (P2). Soil plasticity varied from highly plastic to slightly plastic. The highest organic matter content was found in P2 (2.06%). The observed soil pH ranged from 6.0 to 6.9, indicating slightly acidic to near-neutral conditions that are generally favorable for plant growth and microbial activity.Vegetation was dominated by Pinus at the tree level (IVI 67.97%) and ferns at the seedling level (IVI 32.44%). These findings emphasize the role of soil physical properties and vegetation in slope stability and highlight the importance of bio-physical-based mitigation strategies in landslide-prone areas.

Keywords: Soil Characteristics; Landslide; Vegetation; Importance Value Index

INTRODUCTION

Natural disasters are natural events that can occur either suddenly or gradually, at any time and in any place, causing both material and non-material losses (Beach, 2021; Muzani et al., 2022). Such disasters often occur as a result of natural phenomena or a series of natural events, including earthquakes, tsunamis, floods, cyclones, and landslides, which can cause severe damage and threaten human safety.

According to Donati et al., (2023), mass movements, commonly referred to as landslides, are natural processes in which soil and rock masses move significantly from their original position to a lower location. The primary trigger is high-intensity rainfall, combined with unstable land conditions. Temme, (2021) further explains that landslides occur when soil layers, rocks, or other materials on a slope shift and move suddenly downward in a relatively short time with large volumes. Several factors influencing landslide occurrence, including rainfall intensity, slope gradient, land use, and soil characteristics.

Soil characteristics are the distinctive traits that differentiate one soil type from another. According to Robinson et al., (2022), these characteristics can be observed through soil physical properties such as texture, bulk density (BD), porosity, permeability, and plasticity. Soil physical properties strongly affect the availability of water, air, and nutrients and indirectly influence plant growth. Physical properties also affect changes in soil structure, aggregate stability, and porosity, all of which contribute directly to landslide susceptibility (Saputra et al., 2022).

A major landslide occurred in Bonglo Village, Bastem Utara District, Luwu Regency, in February 2024. According to the National Disaster Management Agency (BNPB) of Palopo City, the primary causes of the landslide were intense rainfall and unstable soil structure. Heavy rainfall is a major landslide trigger, as it increases the soil infiltration rate (Batumalai et al. 2023; Liu, et al. 2021). This occurs due to vegetation feedback acting indirectly and over the long term, whereby rainfall shapes soil properties, leading to denser and more luxuriant vegetation, increased root abundance, biopores, and soil fauna activity, thereby enhancing infiltration capacity, despite high rainfall, as commonly observed in forest soils. However, detailed information on the soil structure has not yet been described, making further investigation necessary. Based on these conditions, it is essential to conduct research on soil characteristics in the landslide-affected area of Bonglo Village, Bastem Utara District, Luwu Regency. The results are expected to provide valuable data and information to government agencies for mitigation and rehabilitation efforts along the landslide-prone Bonglo Trans road corridor.

MATERIALS AND METHODS

The study area is located in Bonglo Village, North Bassesangtempe District, Luwu Regency (Figure 1) from January to February 2025, one year after the landslide disaster. The total of research area is approximately 1.5 ha (15,000 m²). The landscape is predominantly characterized by moderate to very steep slopes. The presence of surface rocks is relatively low, with only a few rocks scattered across the study area. The vegetation growing at the site mainly consists of naturally regenerated understory plants in a former plantation area, along with a mixture of cultivated plantation species such as clove and cacao. Overall, the landscape reflects secondary forest conditions on abandoned plantation land, influenced by natural succession following previous land-clearing activities. Generally, area of Bonglo Village, Luwu Regency experiences high rainfall, which is characteristic of mountainous areas in South Sulawesi, with an estimated

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annual average ranging from 2,500 to 3,000 mm per year. The area frequently experiences cloudy weather to light rainfall, with temperatures ranging between 19–28 °C.

Sampling areas were determined using a purposive sampling method, based on the presence of representative soil and vegetation conditions. Soil physical properties were analyzed from samples collected in three landslide plots and six vegetated plots around the landslide area. Two types of soil samples were taken at each point: disturbed and undisturbed samples. Disturbed soil samples were used to analyze organic matter content, soil texture, and soil plasticity, while undisturbed samples were used to analyze soil permeability (Aji, et al. 2021; Xiao et al. 2022). Soil samples were collected at a depth of 0–30 cm. Vegetation data were collected by establishing six plots measuring 20 × 20 m, with subplots of 2×2m. Vegetation parameters observed included plant species, number of individuals per species, diameter, and total tree height. Soil sampling and vegetation data collection were carried out based on the illustrated plot design.

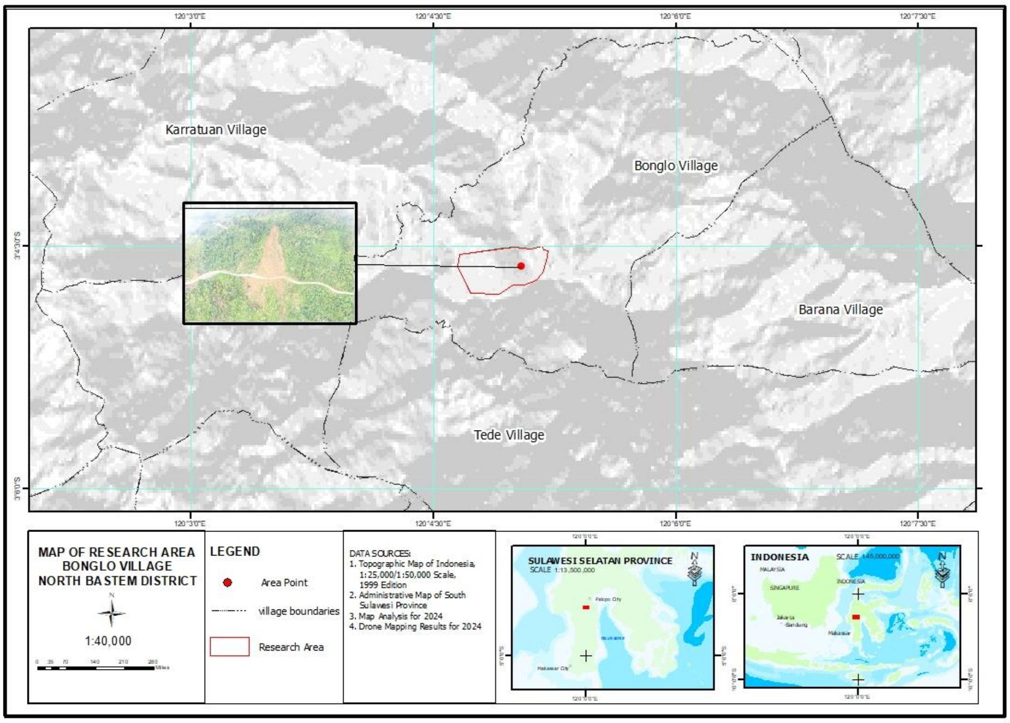

Figure 1. Research Location

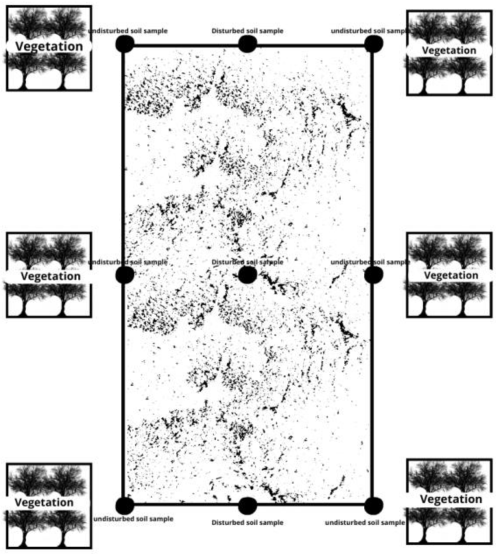

Figure 2. Illustration of soil sampling (●) and vegetation data collection (Vegetation)

Data Analysis

The soil characteristics

These were analyzed in the laboratory, and the results were presented in tabular form.

Tabel 1. Parameter dan Metode Analisis Contoh Tanah

No	Parameter	Unit	Analytical Method
1	Bulk density	g/cm³	Gravimetric method using ring sampler and electric balance
2	Permeability	cm/h	Saturation method according to de Boodt (1967) based on Darcy's Law (LPT, 1974)
3	Soil consistency	–	Direct field observation and measurement
4	Particle density	g/cm³	Gravimetric method using ring sampler and electric balance
5	Soil Organic	%	Method developed by Pons *et al.*

Sumber: Pusat Penelitian Tanah Bogor, 1983

Vegetation Data

Vegetation data collected were processed to obtain the Importance Value Index (IVI), which aims to determine the dominance of plant species present in the landslide-affected area. The calculation of vegetation analysis followed the method of Soerianegara and Indrawan (2005), as follows:

Density (D) and Relative Density (RD)

$$Density(D) = \frac{Number\ of\ individuals\ of\ a\ species}{Area\ of\ the\ plot}$$

$$Relatife\ Density\ (RD) = \frac{Density\ of\ a\ species}{Total\ density\ of\ all\ species} x\ 100\%$$

a) Frequency (F) dan Relative Frequency (RF)

$$Frequency(F) = \frac{Number\ of\ plots\ in\ which\ a\ species\ occurs}{Total\ number\ of\ plot}$$

$$Relative\ Frequency\ (RF) = \frac{Frequency\ of\ species}{Total\ frequency\ of\ species} x\ 100\%$$

b) Dominance (D) dan Relative Dominance (RD)

$$Dominance\ (D) = \frac{\Sigma\ Basal\ area\ of\ species}{Total\ area\ of\ the\ sample\ plot}$$

$$Relative\ Dominance\ (DR) = \frac{Dominance\ of\ species}{Total\ dominance\ of\ all\ species} x\ 100\%$$

c) Importance Value Index (IVI)

IVI = RD (%) + RF (%) + RDo (%)
(pole and tree stages (mature phase))

IVI = RD (%) + RF (%)
(seedling and sapling stages (regeneration phase))

Where:
IVI = Importance Value Index
RD = Relative Density
RF = Relative Frequency
RDo = Relative Dominance

RESULT AND DISCUSSION

Soil Characteristics in the Landslide-Affected Area

Based on the analysis of soil samples conducted at the Soil Chemistry and Fertility Laboratory, Department of Soil Science, Faculty of Agriculture, Hasanuddin University, the results are presented in Table 2.

Table 2. Characteristic of Soil in the landslide-affected area

Plot	Texture	Description	Organic Matter (%)	pH	Structure	Plasticity	Bulk Density (g/cm³)	Permeability (cm/hr)	Category
P1	Sandy Clay Loam	Moderately Fine	1.85	6.8	Sub-angular blocky	Very plastic	1.06	7.5	Moderately Rapid
P2	Sandy Loam	Coarse	2.06	6.0	Crumb	Slightly plastic	1.75	165.3	Very Rapid
P3	Loamy Sand	Moderately Coarse	1.75	6.0	Granular	Plastic	1.45	78.6	Very Rapid
P4	Clay Loam	Moderately Fine	1.63	6.9	Angular blocky	Plastic	1.03	4.7	Moderate
P5	Sandy Clay Loam	Moderately Fine	1.05	6.0	Angular blocky	Plastic	1.23	0.6	Moderately Slow
P6	Sandy Clay Loam	Moderately Fine	1.47	6.0	Sub-angular blocky	Very plastic	1.25	8.7	Moderately Rapid
DA	Sandy Clay Loam	Moderately Fine	1.33	6.4	Platy	Slightly plastic	1.43	2.1	Moderate
DB	Sandy Clay Loam	Moderately Fine	1.48	6.2	Sub-angular blocky	Plastic	1.43	2.8	Moderate
DT	Sandy Clay Loam	Moderately Fine	1.25	6.8	Sub-angular blocky	Slightly plastic	1.43	4.8	Moderate

Notes: *DA = upper soil sample, DB = middle soil sample, DT = lower soil sample*

Based on observations conducted across nine plots, three plots (DA, DB, and DT) were affected by landslides, while the remaining six plots (P1–P6) were classified as unaffected. Soil texture analysis, based on the United States Department of Agriculture (USDA) classification system, identified four texture classes: sandy loam (P2), loamy sand (P3), clay loam (P4), and sandy clay loam with moderately fine characteristics (P1, P5, P6, DA, DB, and DT). The results show that the landslide-affected plots were generally dominated by sandy clay loam textures. However, since the analyzed material in the affected plots consisted of mixed landslide deposits rather than undisturbed natural soil, the observed texture may reflect transported and redeposited materials. In general, soils with higher clay content or finer textures tend to exhibit reduced permeability and increased water retention, which may contribute to slope instability under conditions of prolonged or intense rainfall. Therefore, while finer-textured soils may be associated with greater landslide susceptibility, further analysis is required to establish a direct causal relationship. According to Cortez, (2025); Luino et al., (2022), landslides can be triggered by soil characteristics, especially finer-textured soils with irregular particle sizes and higher water retention, particularly on steep slopes. Clay soils exhibit properties that change significantly depending on weather conditions.

Also reported that less compact soils, such as clay, have a higher potential for landslides, particularly during rainfall events (Abanco et al., 2021). Such soils are highly susceptible to ground movement, as they become soft when wet and crack during dry seasons. These changes make clay soils more prone to movement, thereby increasing landslide risks, as observed in the soil samples from plots DA, DT, and DB. However, even though plots P1, P5, and P6 also exhibited moderately fine structures, these plots did not experience landslides. One distinguishing factor among these plots was the amount of vegetation present. DA, DB, and DT represent soil sampling points located within the landslide-affected area. Prior to the landslide event, these locations had vegetation cover similar to that of the surrounding plots (P1–P6). The vegetation conditions before the landslide were generally comparable across all plots, consisting of naturally regenerated understory vegetation mixed with plantation species. After the landslide occurred, the vegetation at DA, DB, and DT was disturbed or removed due to slope failure. Therefore, the presence or absence of vegetation alone cannot be considered the determining factor in preventing landslides at P1, P5, and P6. Other factors such as slope gradient, soil physical properties, soil saturation, and rainfall intensity likely played a more significant role in influencing slope stability.

Vegetation contributes to soil stability through its root systems, which bind soil particles together, enhance water infiltration, and reduce surface runoff (Witno et al. 2024). Therefore, although the physical characteristics of clay soils can increase landslide susceptibility, the presence of vegetation serves as an effective mitigating factor by maintaining soil ecosystem balance, preventing erosion, and ultimately reducing landslide risks.

Soil Permeability

Based on Table 2, the soil permeability values in the landslide-affected area indicate that Plots P2 and P3 had very rapid permeability rates, measuring 165.3 cm/hr and 78.6 cm/hr, respectively. This suggests that the soils in these plots have a very high capacity to transmit water, which may reduce soil stability and increase the risk of landslides, particularly during periods of high rainfall. This condition is associated with the coarse texture of P2 and the moderately coarse texture of P3, both of which influence the soil's ability to drain water. Soil permeability is the capacity of soil to transmit water and air through its pores. This ability is strongly influenced by soil physical properties, such as particle size, texture, and structure (Bryk & Kołodziej, 2021). The coarser the soil texture, the higher the soil permeability, as water and air can more easily move through larger pore spaces; conversely, finer-textured soils exhibit lower permeability.

The lowest permeability was found in Plot P5, with a value of 0.6 cm/hr, categorized as moderately slow. Soils with low permeability tend to retain water; however, under certain conditions, this may lead to surface water accumulation, thereby increasing landslide susceptibility. This finding aligns with Rahman et al., (2022), who stated that fine-textured soils with slow or low permeability have reduced infiltration rates, which increases the risk of waterlogging and flooding, potentially triggering landslides. Permeability thus plays a crucial role in regulating soil water dynamics; soils with higher permeability allow greater infiltration rates (Zhou et al., 2025).

Bulk Density

Based on Table 2, the bulk density measurements across several plots in the landslide-affected area varied between 1.03 g/cm³ and 1.75 g/cm³. The highest bulk density was recorded in Plot P2, with a value of 1.75 g/cm³, indicating possible soil compaction due to erosion processes, which may have caused the loss of soil structure and an increase in soil density. According to Imtiaz et al. (2024); Ogorek et al. (2025), high bulk density values indicate denser soils, which reduce the soil's capacity to retain and transmit water, and hinder root growth. Compacted soils restrict root penetration, thereby negatively affecting nutrient uptake by plants.

The lowest bulk density values were found in P1 (1.06 g/cm³) and P4 (1.03 g/cm³), suggesting that these soils had better structure with greater pore space, allowing for optimal water movement, air circulation, root growth, and nutrient absorption. Bulk density serves as an indicator of soil compaction: the denser the soil, the higher the bulk density, which corresponds to greater resistance to water infiltration and root penetration. Conversely, lower bulk density facilitates water infiltration into soil pores and enhances oxygen availability in the soil (Eng et al. 2025).

Soil Plasticity

Table 2 presents the classification of soil plasticity across various plots in the landslide-affected area, ranging from very plastic to slightly plastic. This variation reflects differences in the physical and mechanical properties of the soils, which may influence their susceptibility to landslides. Soils in Plots DA, DT, and DB exhibited slightly plastic to plastic characteristics, influenced by their clay texture, indicating relatively low structural strength. This condition is caused by high air content leading to soil shrinkage, while the cohesion of fine soil particles promotes saturation during heavy rainfall, resulting in landslides in these plots. According to Chen et al., (2024); Utkarsh & Jain, (2024), clay soils have very low bearing capacity, show high plasticity and cohesion, and possess significant shrink-swell potential. Soil moisture plays an important role in the characteristics of clay soils. At high moisture levels, clay expands as soil pores become fully saturated, while at low moisture levels or during dry conditions, clay soils shrink and crack.

Soil plasticity in the study area was influenced by soil texture, specifically the high clay content. According to Gaspar et al., (2022) reported that soil plasticity is strongly affected by clay content: the higher the clay content, the greater the soil's plasticity; conversely, soils with lower clay content exhibit lower plasticity. Although soils in the landslide-affected plots showed plastic characteristics, not all plots in the study area experienced landslides. This difference is largely due to the presence of vegetation, which acts as a stabilizing factor that mitigates soil shrinkage. In areas with good vegetation cover, landslides were less frequent, whereas areas with sparse vegetation experienced landslides more often. Vegetation cover significantly influences slope stability, particularly in steep areas, as root depth and strength determine the capacity of plants to reduce landslide risk.

Soil Organic Matter

Based on Table 2, the organic matter content across the observed plots ranged from 1.05% to 2.06%, indicating relatively low and fairly uniform levels throughout the study area. Plot P2 showed the highest organic matter content (2.06%), whereas Plot P5 recorded the lowest value (1.05%). The differences among plots, however, are relatively small, suggesting that organic matter distribution is generally homogeneous across the site.

Plots DA, DB, and DT are classified as landslide-affected areas. The soil in these plots represents landslide material that was displaced from the upper slope and subsequently redeposited. Despite this, the organic matter content in DA, DB, and DT is not markedly different from that in the other plots (except P2). This may indicate that the displaced material originated from surface or near-surface soil layers that already contained comparable levels of organic matter. In addition, post-landslide vegetation regeneration and litter input may have contributed to maintaining organic matter levels in these areas.

Therefore, the relatively similar organic matter content between landslide-affected and unaffected plots suggests that organic matter alone cannot explain landslide occurrence in this study area. Landslide susceptibility is more likely influenced by the interaction of multiple factors, including slope gradient, soil physical properties, hydrological conditions, and rainfall intensity.

According to Saco et al., (2021), the higher the organic matter content in soil, the greater its ability to delay landslide events. This is because organic matter contributes significantly to improving soil structure and stability, enhancing water retention, and strengthening soil aggregates. These processes improve soil bearing capacity, thereby reducing landslide risk, particularly in areas prone to mass movement. Consequently, the management and enhancement of soil organic matter should be considered a strategic measure in landslide risk mitigation, especially in previously degraded areas.

Soil pH

Soil pH represents the concentration of hydrogen ions in the soil solution and is an important indicator of soil chemical conditions. It plays a significant role in regulating nutrient availability, microbial activity, and plant growth. Based on Table 2, the pH values across all plots ranged from 6.0 to 6.9, indicating slightly acidic to nearly neutral soil conditions. Plots P2, P3, P5, and P6 had pH values of 6.0, while P1 and DT showed slightly higher values (6.8), and P4 recorded the highest pH (6.9). The landslide-affected plots (DA, DB, and DT) exhibited pH values between 6.2 and 6.8, which are also within the slightly acidic to near-neutral range.

These pH conditions are generally favorable for plant growth, as most essential nutrients are adequately available within this range. Unlike strongly acidic soils, the solubility of potentially toxic elements such as aluminum (Al) and iron (Fe) is relatively limited under slightly acidic to near-neutral conditions, reducing the risk of toxicity to plants. The abundance of Al and Fe elements can inhibit plant growth and act as toxins (Tang et al., 2023). Moreover, soil microbial activity involved in organic matter decomposition and nutrient cycling tends to function optimally within this pH range.

Therefore, based on the observed data, soil acidity does not appear to be a limiting factor for vegetation growth in the study area, nor does it represent a primary driver of landslide occurrence. Instead, other factors such as soil physical properties, slope gradient, and hydrological conditions may play a more dominant role in influencing slope stability.

Vegetation in the Landslide-Affected Area

Tree Layer Vegetation

The Important Value Index (IVI) indicates the ecological significance of a plant species and highlights its role within the forest community. Based on the calculation of Relative Density (RD), Relative Frequency (RF), and Importance Value Index (IVI), the tree vegetation composition in the landslide-affected area is presented in Table 3.

Based on Table 3, the species with the highest Importance Value Index (IVI) was *Pinus*, with an IVI of 67.97%, Relative Density (RD) of 17.27%, Relative Frequency (RF) of 9.38%, and Relative Dominance (RDo) of 41.32%. This indicates that *Pinus* is the most dominant species at the tree layer compared to other species. Such dominance suggests that *Pinus* possesses a high adaptability to post-landslide site conditions. According to Indrajaya & Handayani. (2008), *Pinus* genetically has strong potential as a landslide control species because it possesses several ecological traits: (i) reducing net rainfall through high interception capacity, (ii) reinforcing slopes with long and deep root systems, (iii) reducing water load through high evapotranspiration, and (iv) maintaining slope stability due to its balanced stem weight, which contributes to increased shear resistance in landslide-prone areas. In addition, pine resin as its main product ensures the economic value of maintaining pine stands, thereby supporting its role in landslide control.

In contrast, the species with the lowest IVI was *Anthocephalus macrophyllus*, with an IVI of 8.38%, RD of 0.91%, RF of 3.13%, and RDo of 4.34%. According to Karmila *et al*. (2019), species with high IVI values tend to have a more even distribution and greater abundance compared to other species. Conversely, species with low IVI values generally have restricted distribution and lower population density.

Seedling Layer Vegetation

The analysis of seedling layer vegetation in the landslide-affected area revealed a varied level of species dominance at the regeneration stage. The results are presented in Table 4.

Based on Table 4, the plant species with the highest Importance Value Index (IVI) was *Pteridophyta* (32.44%). This indicates that *Pteridophyta* contributes significantly to the vegetation structure in the area, with a Relative Density (RD) of 22.69% and a Relative Frequency (RF) of 9.76%. According to Akbar *et al.,* (2023), Pteridophytes are widely used as ornamental plants, vegetables, and medicinal ingredients. However, indirectly, the presence of Pteridophytes also contributes to the maintenance of forest ecosystems, including soil formation, protecting the soil from erosion, and facilitating the decomposition of forest litter. Conversely, the species with the lowest IVI was *Coffee* with 2.66%, having a Relative Density (RD) of 0.22% and a Relative Frequency (RF) of 2.44%. This indicates that *Coffee* has a very limited dominance in the area. Such low values reflect that *Coffee* contributes insignificantly to ecosystem stability. This condition is caused by several factors, including competition with more adaptive species and its inability to adjust to local environmental conditions. It has been emphasized that species exhibiting a low Importance Value Index (IVI) exert only limited ecological influence and demonstrate relatively weak adaptability to their habitat conditions (Muhammad *et al.* 2025; Ullah dkk. 2022). Consequently, *Coffee* cannot optimally function in maintaining ecosystem balance, particularly in soil cover and preventing erosion and landslides. Species dominance in a given habitat demonstrates their capacity to utilize the majority of available environmental resources.

Table 3. Tree layer vegetation analysis in the landslide-affected area

No	Species	Relative Density (RD, %)	Relative Frequency (RF, %)	Relative Dominance (RDo, %)	Importance Value Index (IVI, %)
1	Pinus merkusii	17.27	9.38	41.32	67.97
2	Muntingia calabura	16.36	9.38	3.25	28.99
3	Dillenia serrata	6.36	6.25	0.89	13.51
4	Mimosa pudica	7.27	9.38	2.22	18.87
5	Ficus Septica	3.64	6.25	0.27	10.16
6	Psidium guajava	3.64	6.25	0.30	10.18
7	Anthocephalus macrophyllus.	0.91	3.13	4.34	8.38
8	Syzygium aromaticum	14.55	3.13	0.00	17.67
9	Gliricidia sepium	10.91	9.38	1.21	21.50
10	Casuarina junghuhniana	5.45	9.38	5.86	20.68

Table 4. Seedling layer vegetation analysis in the landslide-affected area

No	Species	Number of Individuals	Relative Density (RD, %)	Relative Frequency (RF, %)	Importance Value Index (IVI, %)
1	Imperata cylindrica	129	14.21	9.76	23.96
2	Coffee (*Coffea sp.*)	2	0.22	2.44	2.66
3	Psidium guajava	12	1.32	4.88	6.20
4	Pteridophyta	206	22.69	9.76	32.44
5	Pinus merkusii	4	0.44	2.44	2.88
6	Dipteris conjugata	76	8.37	4.88	13.25
7	Melastoma malabathricum	138	15.20	14.63	29.83
8	Chromolaena odorata	146	16.08	14.63	30.71
9	Ficus Septica	54	5.95	9.76	15.70
10	Dicranopteris flexuosa	41	4.52	7.32	11.83
11	Anthocephalus macrophyllus.	60	6.61	7.32	13.93
12	Ageratum conyzoides	12	1.32	7.32	8.64
13	Gliricidia sepium	28	3.08	4.88	7.96

CONCLUSION AND SUGGESTION

Conclusion

This study indicates that variations in soil texture, permeability, bulk density, plasticity, organic matter, and pH may influence slope stability in Bonglo Village. The observed soil pH ranged from 6.0 to 6.9, indicating slightly acidic to near-neutral conditions that are generally favorable for plant growth and microbial activity. Therefore, soil acidity does not appear to be a limiting factor or a primary trigger of landslides in the study area. Although some plots exhibited relatively higher bulk density and moderately fine textures, the occurrence of landslides cannot be attributed to a single soil property. Several plots with similar physical and chemical characteristics remained stable, suggesting that slope failure is controlled by the interaction of multiple factors rather than by individual parameters alone. Vegetation, particularly *Pinus* at the tree layer and Pteridophyta at the seedling layer, likely contributes to slope reinforcement through root binding, improved soil structure, and surface protection against erosion. Overall, slope stability in the study area appears to result from the combined interaction of soil physical–chemical properties, slope gradient, hydrological conditions, rainfall intensity, and vegetation cover. These findings highlight the importance of integrating soil characteristics, topography, and vegetation management in landslide mitigation strategies, rather than attributing slope stability to a single controlling factor.

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Suggestion

Future research should incorporate long-term monitoring of soil chemical dynamics and vegetation succession to better understand temporal changes in landslide susceptibility. Expanding the study to include hydrological factors, such as rainfall intensity and groundwater fluctuations, would improve predictive accuracy. The use of high-resolution remote sensing and geotechnical modeling is also recommended to integrate spatial variability of soil–vegetation interactions for more comprehensive landslide risk assessments and mitigation planning.

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