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Morphological and Physicochemical Comparison of Sandy Soils under Horticultural Monoculture on the Erosional Slope of Gamalama Volcano, Ternate Island

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ABSTRACT

This study investigated the morphological and physicochemical characteristics of sandy soils under horticultural monoculture on the erosional slopes of Mount Gamalama Volcano, Ternate Island. Volcanic activity of Gamalama Volcano has contributed to the formation of young sandy soils, which are often characterized by rapid weathering and low fertility. The region is dominated by steep topography, and the history of active volcanoes further complicates soil management. In addition, intensive horticultural monoculture with 2-3 month crop rotations exacerbates soil fertility degradation, leading to erosion and nutrient loss. Given the challenges posed by these conditions, there is an urgent need to understand soil physical and chemical properties to develop effective land management strategies. We created three soil profiles located in the erosional zone of a regional slope of Mount Gamalama. Soil profile observations were made by characterizing soil morphology, and then at each soil depth, detailed soil physicochemical property parameters were analyzed according to USDA standards. The results showed that soils on the erosional slopes of Gamalama have low fertility and poor water holding capacity, which significantly limits agricultural productivity. In addition, the lack of organic matter and high susceptibility to erosion exacerbate the degradation process. These findings highlight the critical need for improved agricultural management techniques.

Keywords: Active volcanoes, conservation, land degradation, regional slopes, soil physicochemical

INTRODUCTION

Mount Gamalama is an active volcano that occupies a large part of Ternate Island, contributing to the island ecosystem and agricultural landscape (Hidayat et al., 2022). Volcanic activity frequently supplies new soil parent material with a sandy fraction; however, this material is susceptible to weathering (Ahmad *et al*., 2020). The sandy soils that predominate on erosional slopes pose significant challenges to agricultural land due to their low fertility, limited water-retention capacity, and susceptibility to erosion. These problems are particularly evident in volcanic landscapes, where the interplay between geomorphological processes and agricultural activities gives rise to distinctive soil physical and chemical characteristics (Noviyanto *et al*., 2020). One of them is the soil characteristics on the erosional slopes of Mount Gamalama Volcano, whose physicochemical properties are changing as a result of agricultural activities. The region exhibits a combination of steep topography, an active volcanic history, and intensive horticultural monoculture practices, along with a 2–3 month crop rotation.

Volcanic landscapes, such as those on Ternate Island, are characterized by sandy soils with distinct morphological and physicochemical properties that vary according to topographic position. These soils exhibit high drainage rates, low organic matter content, and limited nutrient availability, which negatively impact their agricultural productivity (Saputra *et al*., 2022). Furthermore, erosion processes on sloping terrains exacerbate soil degradation by depleting nutrient-rich layers and destabilizing soil structure, posing significant challenges to sustainable land management (La Manna *et al*., 2018). Understanding soil properties and their degradation patterns is essential for developing effective soil conservation strategies in areas where horticultural monoculture dominates. However, there is still a lack of comprehensive studies that specifically examine the extent and severity of soil degradation under monocultural horticultural systems on volcanic slopes, particularly in the context of long-term sustainability. Previous research has established that intensive horticultural land use, particularly under monoculture systems, accelerates soil degradation by depleting organic matter, reducing soil fertility, and increasing erosion rates (Kassa *et al*., 2017; Chatterjee *et al*., 2022; Hartati *et al*., 2023). Despite this, limited studies have provided detailed morphological and physicochemical analyses of these soils across different slope gradients to assess degradation severity and its implications for horticultural productivity. Additionally, while soil conservation techniques are well documented, their applicability and effectiveness in volcanic sandy soils under monoculture remain inadequately explored. Addressing these knowledge gaps is crucial for devising land management practices to sustain productivity while mitigating further degradation (Osman, 2014; Narayanan & Ma, 2024).

Therefore, this study aims to (1) analyze the morphological and physicochemical characteristics of sandy soils under horticultural monoculture across different slope gradients on Ternate Island, (2) identify patterns and severity of soil degradation with slope position and land use intensity, and (3) evaluate the implications of these degradation patterns for crop productivity and soil conservation practices. By bridging these knowledge gaps, this research will provide valuable insights into the sustainability of horticultural monoculture on volcanic landscapes and inform strategies for improved land management.

MATERIALS AND METHODS

The research was carried out on Ternate Island, North Maluku Province, Indonesia. Administratively, the research was conducted in Loto Village, West Ternate District, Ternate City, North Maluku Province, Indonesia (**Figure 1**). Geomorphological conditions are volcanic with geological formations of Quaternary age. The results of direct measurements in the field of topography in Loto Village are divided into three classes, namely sloping (8 - 15%), moderately steep (15 - 25%) and steep (25 - 40%). Based on the results of rainfall analysis from the Meteorology, Climatology and Geophysics Agency, the average rainfall in the study area varies between 2,000 - 2,300 mm / year. The lithological composition in the study area is Holocene volcanic rock formation (andesite breccia, andesite - basalt lava, and tuff).

The materials used are Ternate Island Administration Map Scale 1:50,000, Ternate Island Land Use Map Scale 1:50,000, Ternate Island Slope Map Scale 1:50,000, and Geological Map Scale 1:250,000 Ternate Sheet. Then the tools used in this research include Global Positioning System (GPS), Meter, Dagger Knife, Munsell Soil Color Chart Book, Camera, Hoe, Shovel, and Office Stationery.

Soil sampling

Soil sampling was based on micro-slope differences measured directly at the study site. Three soil profiles (P1, P2, P3) were investigated in the field. The three soil profiles (P1, P2, P3) were identified in the field using standards from the USDA Field Book Procedures for Describing and Sampling Soils (Soil Survey Staff, 2024). The type of observation at the research site is divided into two observations, namely physiographic conditions which include landform, parent material, slope, and land use. Meanwhile, identification of soil morphology includes soil solum, soil texture, soil structure, soil consistency, rooting zone. Soil sampling for laboratory analysis was conducted at an effective depth of 0 - 30 cm and 30 - 60 to determine the performance of horticultural crops. Soil physicochemical analysis was conducted based on laboratory measurement standards of the Agricultural Instrument Standardization Agency of the Ministry of Agriculture. Soil physicochemical analysis includes analysis of bulk density (ring method), particle density (pycnometer method), soil porosity, soil texture (hydrometer method) with based on the principle of sedimentation or deposition of soil grains in water. The texture classification criteria based on USDA classification including, clay (Φ: <0.002 mm), silt (Φ: 0.05 mm - 0. 002 mm) and sand (Φ: 2 mm - 0.05 mm), soil pH (1:5) (electrometric method; pH meter), soil organic carbon (Walkley & Black method), soil total nitrogen (Kjeldahl Titrimetric method), soil P_2O_5 content (Olsen method; Spectrophotometer), soil K_2O content (AAS method), exchangeable cations (K, Ca, Mg, C, Mg), and Soil CEC (Percolation method NH4OAc 1 M, pH7 + NaCl 10%; Titrimetric).

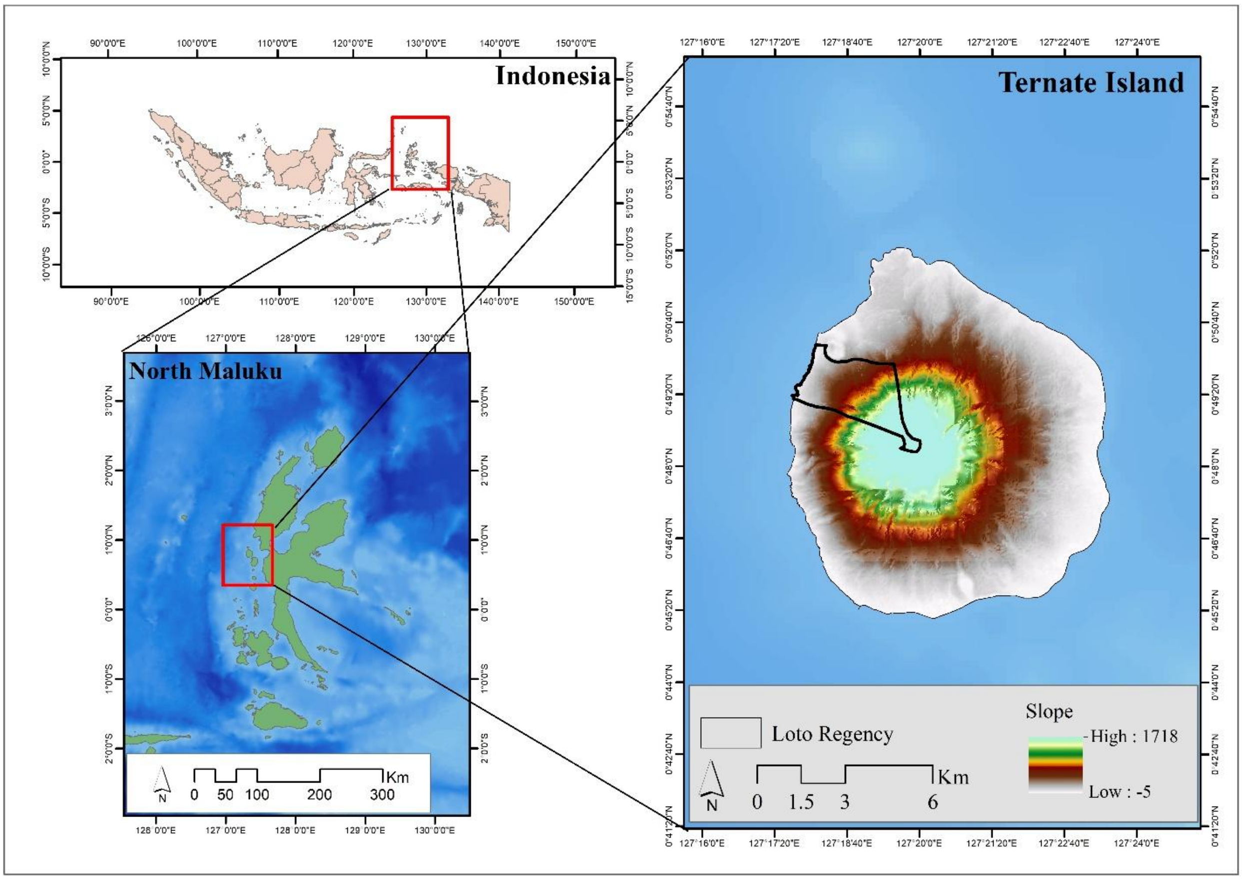

Figure 1. Administrative Map of the Research Area

RESULTS

Soil morphological characteristic

A total of three soil profiles were observed in the field, and the results indicate that the soil type at the research site belongs to the Inceptisols order, specifically the Eutrudepts group (**Table 1**). The classification was determined based on criteria established by the United States Department of Agriculture (USDA). The soil layers have undergone progressive development through elluviation and illuviation, forming the Bw (cambic) horizon (**Figure 2**). This horizon exhibits physical and chemical changes resulting from soil development (Mulyadi & Makhrawie, 2023). Additionally, the Bb horizon was identified in P3, indicating a deposition process involving fresh coarse material (Φ: 2 mm - 0.05 mm) from the upper slope. The thick solum (>60 cm) at the study site is attributed to periodic eruptions of Gamalama Volcano, leading to multiple horizon formations over time.

Soil thickness is also influenced by the sedimentation of volcanic ash material, which gradually develops into a soil body (Noviyanto, 2024). The composition of magma during eruptions affects the formation of soil mineral composition (Nurcholis *et al*., 2019; Aji *et al*., 2020, 2024). Soil texture in the field is generally coarse (Φ: 2 mm - 0.05 mm) and medium (Φ: 0.05 mm - 0.002 mm). The determination of soil texture serves as an indicator of soil development levels (Aji *et al*., 2024). Furthermore, the soil structure in the field has formed clods, which is indicative of a well-aggregated structure with sufficient pore spaces. Soil consistency across the three profiles is relatively sticky, highlighting the influence of soil texture on structural integrity. Rooting in the field is primarily within the micro and meso classes, reflecting the density level and penetration capacity of plant roots.

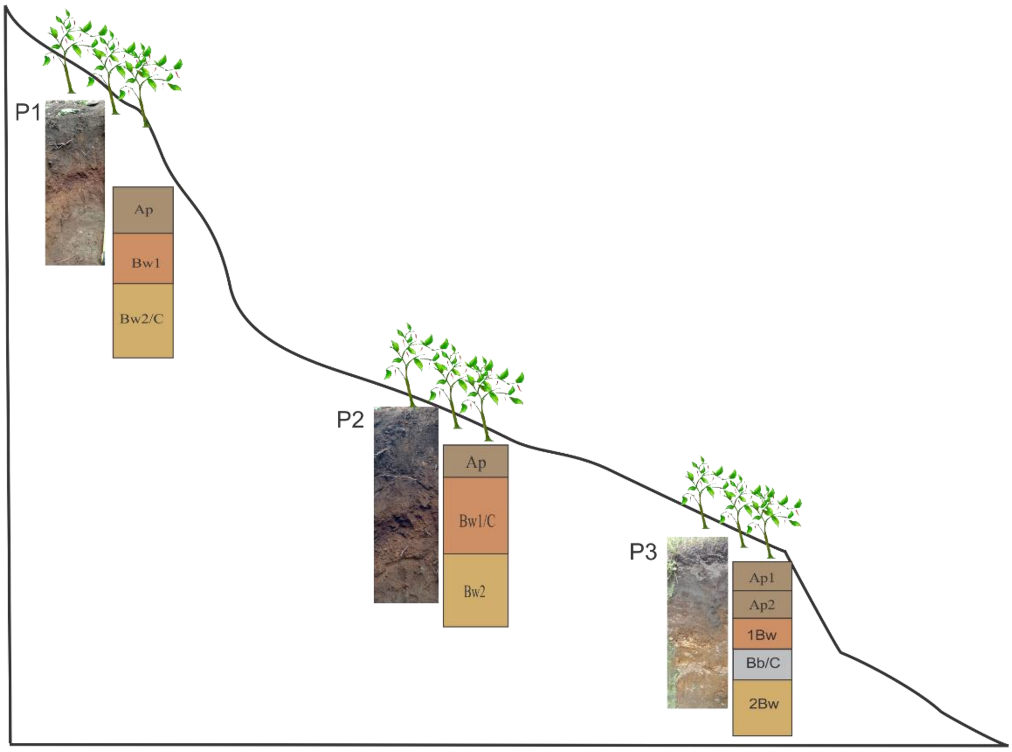

Figure 2. Illustration of Position of Soil Layer and Soil Horizon

Soil physicochemical properties

The physicochemical properties of the soil were analyzed in the laboratory, and the results are presented in **Tables 2** and **3**. The texture analysis confirms the dominance of a coarse texture (Φ: 2 mm - 0.05 mm) in the tillage layer, indicating incomplete pedogenesis. Geomorphological processes such as erosion are visibly active, particularly in profile 2, as evidenced by the soil distribution. This erosion process directly affects horticultural production by depleting plant nutrients in the processing layer. Bulk density values vary across profiles, providing insights into soil compaction levels. An increase in bulk density in profile 1 is attributed to illuviation, where materials accumulate in lower layers due to physical pedogenesis. Particle density values are relatively uniform across all three profiles, correlating with mineral type and humus content (Blake, 2008).

Low soil porosity was observed in profile 1 at a depth of 30-60 cm and in profile 2 at both depths, indicating limited air and water movement. Coarse soil texture is linked to low porosity due to the dominance of larger soil particles, which reduces total surface area (Φ: 2 mm - 0.05 mm). It is hypothesized that soil texture exerts a significant influence on several key aspects of soil quality, including nutrient holding capacity, drainage, aeration, susceptibility to soil compaction, irrigation, and soil erodibility (Swanson, 2018). Soil pH values in all profiles are neutral, likely due to fertilization with mature organic matter. The total nitrogen content is low to very low across all profiles, primarily due to evaporation, leaching, and erosion. Organic carbon content is highest in profile 1 at a depth of 30-60 cm, while other layers exhibit moderate to low values. The dry environment and high temperatures accelerate organic carbon decomposition, reducing soil fertility. Essential macronutrients, including P_2O_5 and K_2O, are present in low to very low concentrations, limiting plant growth.

Table 1. Soil Morphological Characteristics

Sample Code	Parent Material	Horizon	Solum (cm)	Texture	Color	Structure	Consistency	Root	Soil Classification (Groups)
P1	Weathering of Volcanic Ash	Ap	0 – 30	Loamy Sand	10YR1/2	Angular Blocky	Slightly sticky	Meso	Eutrudepts
		Bw1	30 – 70	Clayey Loam	7,5YR3/4	Angular Blocky	Slightly sticky	Meso	
		Bw2/C	70 – 110	Loamy Sand	10YR3/2	Angular Blocky	Slightly sticky	Micro	
P2	Weathering of Volcanic Ash	Ap1	0 – 43	Loamy Sand	10YR2/2	Granular	Slightly sticky	Micro	Eutrudepts
		Ap2	43 – 80	Sandy Loam	10YR3/2	Granular	Slightly sticky	Meso	
		1Bw	80 - 100	Clay Loam	10YR3/4	Subangular Blocky	Slightly sticky	Micro	
		Bb/C	100 – 150	Clay Loam	10YR3/5	Angular Blocky	Slightly sticky	Micro	
		2Bw	150 – 180	Silty Loam	10YR4/4	Angular Blocky	Slightly sticky	Meso	
P3	Weathering of Volcanic Ash	Ap	0 – 30	Sandy Loam	10YR2/2	Subangular Blocky	Slightly sticky	Meso	Eutrudepts
		Bw1/C	30 – 50	Sandy Loam	10YR3/6	Angular Blocky	Slightly sticky	Meso	
		Bw2	50 – 75	Loam	10YR3/4	Subangular Blocky	Slightly sticky	Meso	

Table 2. Soil physical properties

Sample Code	Solum (cm)	Texture (%)			Texture Class	Bulk Density ($g.cm^{-3}$)	Particle Density ($g.cm^{-3}$)	Porosity (%)
		Sand	Silt	Clay				
P1	0 – 30	66	19	15	Sandy loam	0,90	2,65	65,92
	30 – 60	64	23	13	Sandy loam	1,61	2,58	37,56
P2	0 – 30	90	3	7	Loamy Sand	1,89	2,56	26,25
	30 – 60	85	8	7	Loamy Sand	1,77	2,62	32,53
P3	0 – 30	74	17	9	Sandy loam	1,44	2,67	45,91
	30 – 60	61	23	16	Sandy loam	1,21	2,64	54,16

Table 3. Soil chemical properties

Sample Code	Solum (cm)	pH		Soil Organic Carbon (%)	Total Nitrogen (%)	Soil Organic Matter (%)	C/N Ratio	P_2O_5		K_2O (mg 100 g^{-1})	Cations can be exchanged (cmol (+) Kg^{-1})				CEC (cmol (+) Kg^{-1})	Base Saturation (BS) (%)
		H_2O	KCl					Available (ppm)	Potential (mg 100 g^{-1})		K	Ca	Mg	Na		
P1	0 – 30	7,4	6,4	2,85 (m)	0,49 (m)	4,93	5,82 (l)	17 (l)	75	14 (l)	0,18 (l)	5,04 (l)	1,31 (m)	0,18 (l)	10,87 (l)	61,73 (h)
	30 – 60	7,2	5,8	3,54 (h)	0,32 (m)	6,12	11,06 (m)	31 (m)	97	15 (l)	0,35 (m)	8,55 (m)	1,78 (m)	0,76 (h)	11,44 (l)	100 (vh)
P2	0 – 30	7,4	6,3	1,5 (l)	0,02 (vl)	2,60	75 (h)	21 (m)	73	57 (h)	0,26 (l)	3,99 (l)	0,82 (l)	0,3 (l)	5,26 (l)	102,09 (vh)
	30 – 60	7	5,8	1,16 (l)	0,13 (l)	2,01	8,92 (l)	12 (vl)	57	12 (l)	0,14 (l)	2,93 (l)	0,04 (vl)	0,22 (l)	4,63 (vl)	71,92 (h)
P3	0 – 30	7,3	6,3	1,55 (l)	0,17 (l)	2,68	9,12 (l)	12 (vl)	57	24 (m)	0,29 (l)	6,26 (m)	2,35 (h)	0,32 (l)	7,58 (l)	121,64 (vh)
	30 – 60	7,2	5,9	1,07 (l)	0,11 (l)	1,85	9,73 (l)	14 (vl)	30	45 (h)	0,64 (h)	7,14 (m)	0,33 (vl)	0,43 (m)	12,99 (l)	65,74 (h)

Note: (vl): Very Low; (l): Low; (m): Moderate; (h): High; (vh): Very High

The decline in macronutrients is attributed to high metal chelation processes involving Al and Fe (Brady & Weil, 2016). The cation exchange capacity (CEC) values at the study site are low to very low, indicating a limited nutrient-holding capacity. CEC is influenced by clay content, organic matter decomposition, and soil pH, all of which contribute to the overall fertility status. The base saturation (BS) values range from 60-121%, correlating positively with soil pH levels. Higher soil pH results in greater base saturation due to the presence of exchangeable cations such as Ca^{2+}, Mg^{2+}, and K^{2+}. While high base saturation in some layers suggests nutrient availability, the overall depletion in the topsoil necessitates immediate soil restoration. The combination of erosion, low organic matter content, and reduced macronutrient levels presents challenges for sustainable horticultural production in the study area.

DISCUSSION

The morphological characteristics of soil profiles (P1, P2, and P3) reveal significant horizon differentiation caused by volcanic deposits from Mount Gamalama eruptions. Geological and geomorphologic processes are the key to understanding the origin of soil body parent material distribution (Riyanto *et al*., 2022). The presence of Bw horizons in all profiles indicates soil development influenced by pedogenetic processes over time. This finding aligns with studies highlighting the role of volcanic eruptions in shaping soil morphology through periodic ash deposition and sedimentation (Arifin *et al*., 2022). The presence of buried horizons (Bb) in P2 signifies active geomorphic processes driven by slope deposition. Similar characteristics have been reported in volcanic toposequence zones, such as Mount Tangkuban Parahu, where distinct soil layers form due to different soil formation stages (Hakim *et al*., 2024). These morphological variations directly impact soil physicochemical properties, influencing horticultural productivity. The deep solum observed in the profiles (>60 cm) results from historical volcanic activity depositing thick layers of ash, which later transformed into soil components (Noviyanto, 2025).

The blocky granular and subangular structures observed suggest moderate soil aggregation, providing favorable conditions for root penetration and water movement (Chen *et al*., 2022). These structural properties are critical for sustaining horticultural crops by enhancing aeration and water retention. However, the coarse soil texture dominated by sand fractions presents limitations in water-holding capacity and nutrient retention (Yatno & Zauyah, 2016). Coarse soil texture, with sand proportions ranging from 66-85%, contributes to low porosity values of 26-65%, which reduces water retention (Hartati *et al*., 2023). Bulk density values range between 0.90 and 1.89 g/cm^3, highlighting potential compaction at specific horizons. This compaction can impede root development and water infiltration, necessitating management interventions. Soil improvement strategies such as organic matter incorporation can enhance soil structure and water storage efficiency (Eshetu & Wogi, 2024).

Neutral pH values (7.2-7.4) provide a conducive environment for microbial activity and nutrient bioavailability. However, low organic carbon (0.56-3.54%) and total nitrogen (0.05-0.17%) levels indicate poor soil fertility, exacerbated by high temperatures and rapid organic matter decomposition. The depletion of P_2O_5 and K_2O exacerbates nutrient deficiencies, negatively impacting horticultural productivity (Riyanto *et al*., 2022). Similar studies in Ethiopia show that soil and water conservation measures influence organic matter retention and fertility status (Mohammed *et al*., 2019). CEC values range from 8.01 to 16.40 cmol(+)/kg, reflecting limited nutrient retention capacity due to high sand content and low organic matter (Yost & Hartemink, 2019). Base saturation (60-121%) positively correlates with pH, indicating that exchangeable cations originate from volcanic mineral weathering (Meitasari *et al*., 2024). Although base saturation suggests available nutrients, erosion-induced depletion requires targeted soil management.

Erosion significantly affects soil productivity in the study area, particularly in P2, where steep slopes accelerate nutrient loss. Geomorphic processes further reduce soil fertility, limiting root zone development and nutrient availability (Costantini *et al*., 2018). Sustainable land management practice on volcanic landscapes can be approached in a variety of time frames, ranging from the short term to the long term. Implementing soil conservation techniques such as contour farming, mulching, and cover cropping can mitigate erosion and improve soil stability (Srivastava *et al*., 2024). Long-term sustainability requires integrating organic matter addition, drip irrigation, and slow-release fertilizers (Avianto *et al*., 2024). Agroforestry and terracing can further enhance soil conservation, reducing erosion and maintaining long-term soil health. These strategies are essential for improving soil productivity and ensuring the sustainability of horticultural monoculture on the slopes of Mount Gamalama.

CONCLUSION

This study revealed that sandy soils on the erosional slopes of Gamalama Volcano, Ternate Island, exhibit advanced pedogenesis influenced by volcanic activity, resulting in the development of thick solums and horizons, including cambered horizons (Bw) and buried horizons (Bb). These soils, classified as Eutrudepts below Inceptisols, have a coarse texture indicating incomplete pedogenesis and high susceptibility to erosion. Physicochemical properties such as low porosity, bulk density variations, and limited organic carbon and nutrient content highlight challenges in soil fertility and water retention. Although the soil has a neutral pH, which allows nutrient availability, the loss of nitrogen, phosphorus and potassium through erosion and leaching remains a critical limitation for horticultural monocultures. These findings emphasize the need for conservation strategies such as incorporation of organic matter, contour farming, and agroforestry to reduce erosion and improve soil fertility.

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