



Andosols property dynamics under intensive tea cultivation in West Java: Implications for sustainable management

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ABSTRACT

Despite its significant economic value, tea cultivation in Indonesia is experiencing a continuous decline in plantation area, primarily due to changes in land use. Soil fertility degradation and reduced yields present a significant threat to the long-term sustainability of tea production. A comprehensive understanding of the dynamic nature of tea plantation soil properties is essential for developing sustainable land management strategies aimed at enhancing and maintaining the productivity and sustainability of healthy tea cultivation. This study investigates the properties of Andosols formed from andesite tuff in a heavily managed tea plantation in Cisarua, Bogor, West Java, Indonesia. Four vertical soil profiles and ten composite soil samples were collected from depths of 0-20 cm and 20-40 cm across varying tea vigor and slope class gradients in block plantations. The ongoing production of tea on Andosols has led to significant chemical decline, evidenced by decreased organic matter, increased acidity, reduced cation exchange capacity, and compromised andic properties. The observed rise in base saturation primarily indicates a reduction in CEC, rather than an improvement in fertility. The observed patterns indicate progressive soil weathering and reduced resilience in monoculture systems. Restorative management, which encompasses the incorporation of organic matter and a balanced nutrient supply, is essential for maintaining soil functionality and securing long-term tea productivity. This article synthesizes key findings regarding soil properties, anthropogenic impacts, and strategies for sustainable management. Understanding these dynamics is crucial for optimizing good soil management practices and enhancing tea productivity in volcanic areas.

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1. INTRODUCTION

The tea plant (*Camellia sinensis* L.) ranks among the most extensively consumed beverages worldwide. The annual demand for tea in Indonesia has risen, attributed to its high export value. The total area of tea plantations in the country has been experiencing a decline over time (Manumono & Listiyani, 2023; Pratiwi & Andriyani, 2021). This paradox highlights the critical necessity to reinforce the sustainability of the national tea industry.

This scenario necessitates robust backing from land resources, the development of human capital, and a resilient

ecosystem within the tea industry. A crucial factor is the accessibility of current research regarding soils in tea plantation areas. The tradition of tea research in Indonesia extends back to the colonial era (Alatas & Wan Sulong, 2020). The focus has evolved from agronomy and climate studies to encompass productivity, thereby becoming the predominant area of national research on tea (Anjarsari et al., 2019; Anjarsari et al., 2024; Febriantika et al., 2022; Heryana & Rokhmah, 2021; Ramadhan et al., 2023; Siahaan et al., 2024; Surbakti & Irsal, 2024; Umiyati et al., 2024; Wulansari,

Athallah, et al., 2022; Wulansari & Huga, 2024; Wulansari, Pranoto, et al., 2022). However, research on soil characteristics in tea plantations—generally situated in volcanic landscapes—remain limited. The studies address the factors affecting tea plant growth only in part. The existing research on the factors affecting tea plant growth in a holistic manner remains insufficient. This identified gap is critical, as soil properties are essential for the long-term sustainability of tea cultivation.

The research was conducted at the Ciliwung Tea Plantation in the Cisarua District, Bogor Regency, West Java Province, situated in a volcanic area. This location represents the most extensive tea plantation within Bogor Regency. In addition, limited research exists regarding the correlation between local soil characteristics and the vigor of tea plants. Previous studies on pedogenesis have shown that the soils in the study area originate from andesitic and slightly basaltic parent materials and are currently in an early stage of weathering, as evidenced by limited pedogenic development (Wahyudin, 1989). Marianti et al. (2021) reported that altitude significantly affects soil properties more than slope factors in tea plantations located in Central Java. Furthermore, landform position as a geographical feature significantly role in ecosystem services and soil quality (Ahmadi Mirghaed & Sour, 2022). (Arifin et al., 2022) identified the main factors influencing the formation of volcanic soils—particularly Andisols—as the type of parent material, climate, and eruption age, which collectively influence the extent of soil development. Climatic factors, including increased annual rainfall and decreased annual temperature, can influence soil properties and types (Azurianti et al., 2022; Hu et al., 2021).

Recent studies have highlighted the relationship between environmental factors, soil characteristics, and the health of tea plants in intensive cultivation. Long-term tea monoculture in West Java has been associated with the degradation of soil organic matter, leading to reduced fertility and a decline in tea productivity (Wulansari & Pranoto, 2018). The ongoing depletion of nutrients and loss of organic matter diminish the resilience of Andisols, which were initially well-suited for tea cultivation. In China, analogous trends have been noted, with the overuse of chemical fertilizers leading to accelerated soil acidification, disrupted nutrient balances, and a consequent decline in both tea yield and quality (Wang et al., 2025; Ye et al., 2022). Soil acidification presents a significant concern, as tea cultivation necessitates slightly acidic soils (pH 4.5–5.5). However, the overuse of nitrogen fertilizers frequently results in soil pH falling below these optimal thresholds. Ye et al. (2022) demonstrated that substituting a part of chemical fertilizers with organic amendments mitigated acidification and improved tea yields, highlighting the importance of balanced management in maintaining soil health.

The age of the plantation is another significant factor influencing outcomes. Wang et al. (2024) showed that soil organic carbon in tea plantations exhibits a unimodal pattern: younger plantations accumulate organic carbon, whereas older plantations show significant declines, indicating long-term depletion of soil resources. This finding has significant implications for Indonesia, where numerous tea estates are several decades old and consequently more vulnerable to soil

degradation. Soil physical and thermal properties, alongside chemical changes, are essential in influencing plant vigor. Research conducted in Sri Lanka demonstrated that organic amendments improved soil water retention, reduced thermal conductivity, and stabilized aggregate structure in Ultisols, thereby fostering a more conducive environment for tea roots (Vidana Gamage et al., 2025). The findings indicate that organic inputs may enhance the resilience of volcanic soils, enabling them to better withstand climatic stresses, despite being derived from a different soil order.

These findings highlight that the sustainability of tea plantations cannot be assessed solely through yield statistics or climatic factors; it is essential to also consider the underlying dynamics of soil properties. Intensive tea plantations consistently stress soils, leading to organic matter depletion, nutrient imbalances, and acidification that collectively diminish plant vigor. The transition from young to mature plantations presents further challenges associated with the decline of soil organic carbon and the loss of soil resilience. The interplay of chemical, physical, and biological degradation poses a serious risk to the long-term viability of tea production, particularly in West Java, where plantations are typically managed intensively, and soils are derived from volcanic materials.

Improving tea plantation productivity requires soil development and management strategies that consider soil capacity and functional characteristics (Wulansari, Pranoto, et al., 2022). Volcanic soils possess distinctive properties that enhance their ability to support agricultural practices and demonstrate significant potential for carbon sequestration in terrestrial ecosystems (Muslim et al., 2025; Zhu et al., 2017). Fiantis et al. (2023) demonstrated that cultivation on volcanic soils affects the geochemical properties of the soil, especially the carbon and phosphorus content. Research examining the relationship between tea plant vigor, intensive plantation management, and pedogenetic processes in volcanic soils derived from tuff and andesitic breccia is limited.

This study investigates the dynamics between soil properties and tea plant vigor, evaluating the implications for land management in tea plantations. This study assesses the impact of long-term intensive tea cultivation on the variations in the physical, chemical, and mineralogical properties of volcanic soils. By addressing this gap, this study enhances the understanding of the impact of intensive management on soil development and plant health, while also exploring how improved management strategies can sustain soil fertility and tea productivity moving forward.

2. MATERIAL AND METHODS

2.1. Site Description

The research was conducted at the Ciliwung Tea Plantation in Cisarua District, Bogor Regency, West Java Province, Indonesia, from November 2023 to March 2024. Figure 1 shows the distributions of soil sampling sites within the Ciliwung Tea Plantation, located at approximately 6° 41' 00" S and 107° 00' 00" E. The research site has an elevation ranging from 1,363 to 1,560 meters above sea level (m asl). This study employed descriptive statistics to summarize and interpret the soil property data collected from the sampling sites.

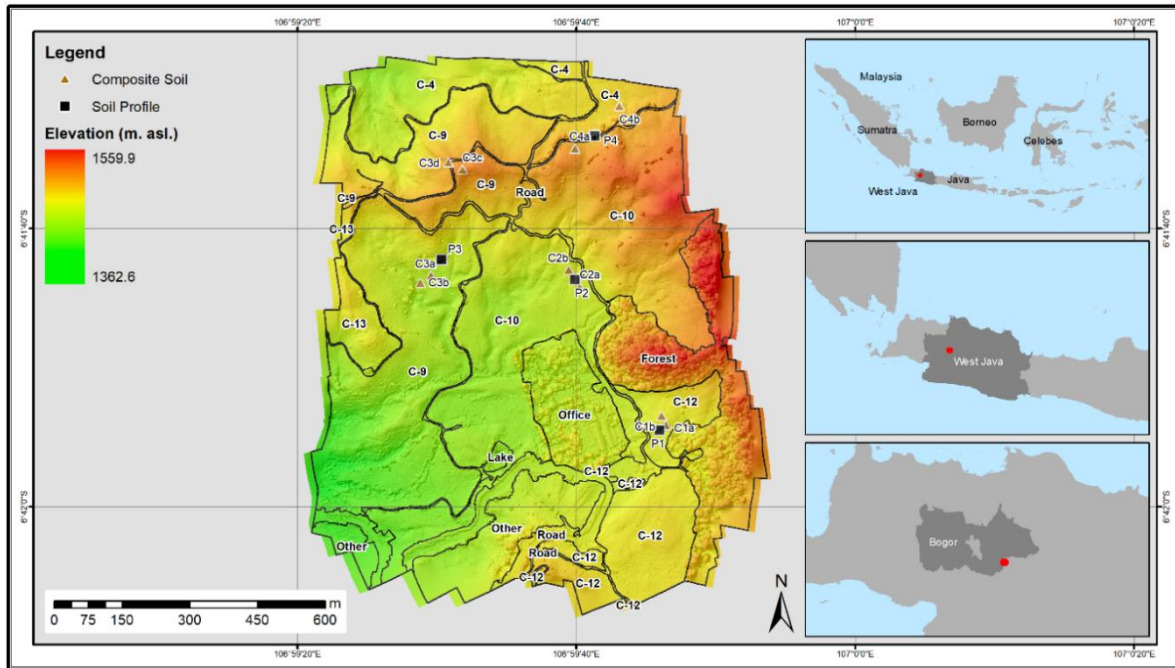


Figure 1. Location of the study site.

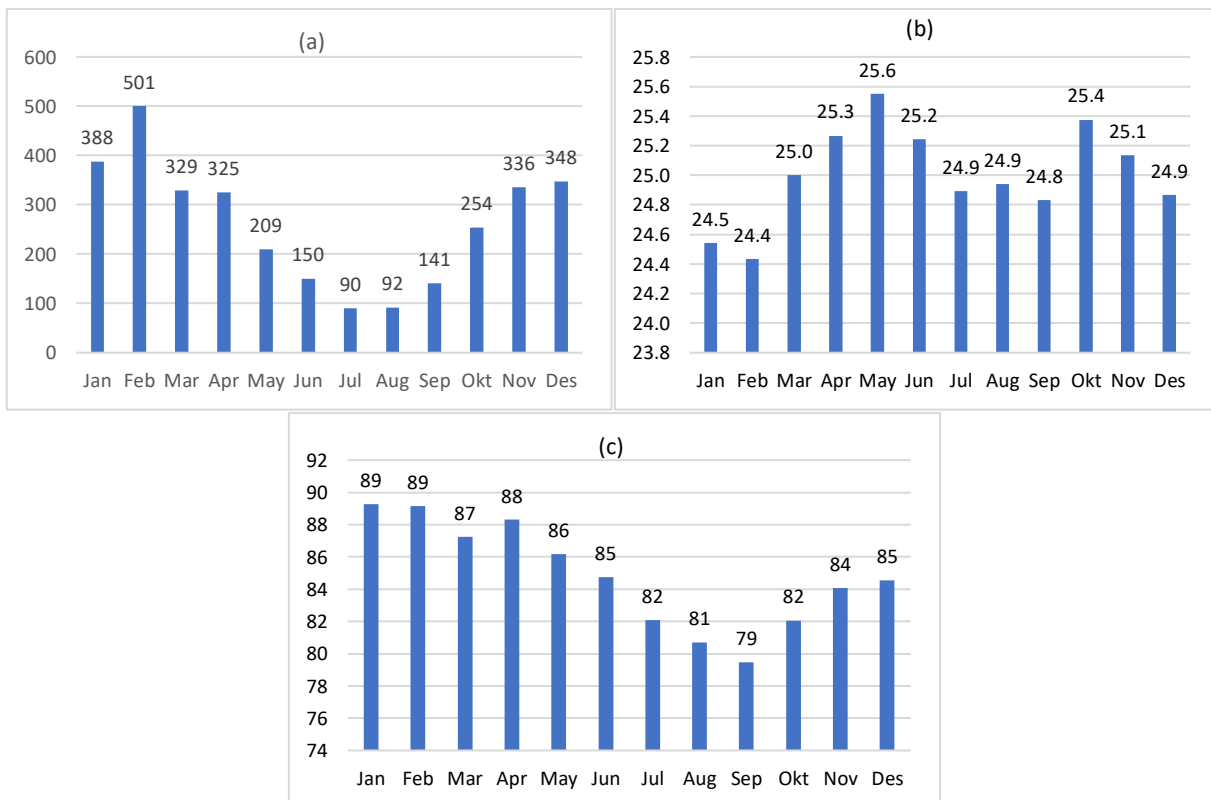


Figure 2. Climate data for the study site: (a) Rainfall average (mm month⁻¹): period 2010-2023; (b) Air Temperature average (°C): period 2011-2022; (c) Air Humidity average (%): period 2011-2022.

2.2. Climate Data Collection

Climate data for the research location were obtained from the Bogor Regency Statistics Agency covering the period from 2010 to 2023 (BPS, 2023). The study site exhibits a humid tropical climate characterized by an annual precipitation of 3,164 mm. The rainy season extends from October to May, featuring peak average rainfall in February at 500.7 mm month⁻¹, while July and August record the lowest rainfall,

approximately 90.3 mm month⁻¹ and 92.1 mm month⁻¹, respectively (Fig. 2). The mean temperature at the study site varies between 24 to 25 °C. No significant temperature variations occur between the rainy and dry seasons (Fig. 2). In the rainy season, the research site exhibits air humidity levels ranging from 84–89%, whereas in the dry season, these levels drops to between 80–79%. Air humidity peaks in January and February, whereas it reaches its lowest levels in August and September (Fig. 2).

2.3. Lithology

The parent material at the study site is identified based on the geology map of Bogor, utilizing secondary data from [Effendi et al. \(1998\)](#). The geological map indicates that the research area is composed of parent rock material, specifically andesite and andesite breccia. The parent material identified in the study was andesitic tuff rock.

2.4. Soil Sampling

The study was conducted in four designated blocks (C-4, C-9, C-10, and C-12) within the tea plantation area ([Fig. 1](#)), encompassing an area of 98 ha. Soil profile observations and soil sampling were performed in each block. This study utilized four vertical soil profile samples, composite soil samples collected from 10 points surrounding the soil profile observation, and ring soil samples taken from the top layer of the soil profile. Four soil samples were selected according to varying tea health conditions (vigor), aspect, elevation, and slope position. The health conditions of the tea plants were categorized as follows: healthy tea plants on slopes of 3-8% (P1) and 30-40% (P4), rejuvenated healthy tea plants on slopes of 8-15% (P2), and unhealthy tea plants on slopes of 8-15% (P3). The samples comprised those taken from each layer of the soil profile, composite soil samples (disturbed), and soil samples from rings (undisturbed). All soil samples were analyzed using various methods, reflecting the differing vigor of tea plants.

Soil profiles were constructed with dimensions of 2 m in length, 1 m in width, and 1.5 m in depth; however, variations in depth may occur depending on the presence of the C layer/parent material, as well as the specification of the soil

order control section. The parameters observed in the soil profile consist of: solum depth, horizon boundaries, horizon thickness, plant rooting, field soil texture, soil color, soil structure, soil consistency, field soil pH, slope position, slope class, and elevation ([Soil Survey Staff, 2022](#); [Sukarman et al., 2017](#)).

Composite samples were collected from the topsoil layer at depths of 0–20 cm and 20–40 cm at various locations, subsequently combined into a single sample with two repetitions. Composite sampling was used to acquire more representative soil chemical data. A ring sample, representing an undisturbed soil sample, has been collected from the topsoil at a depth of 0-20 cm. [Table 1](#) presents methods for physical, chemical, and mineral analysis. Legacy soil data from published [Wahyudin \(1989\)](#) and [Muslim et al. \(2025\)](#). The data sites near the Ciliwung Plantation, assumed to be comparable, exhibit similar soil chemical values corresponding to tea plantations with equivalent land use. [Table 1](#) presents various methods for physical, chemical, and mineral analysis. In addition, we analyzed the correlations between soil characteristics—including base saturation, cation exchange capacity (CEC), and organic C and N—and tea yield through Pearson correlation analysis.

2.5. Soil Classification

The soil classification used in this study follows the outline in the USDA Soil Taxonomy book ([Soil Survey Staff, 2022](#)). The National Soil Classification System ([Subardja et al., 2014](#)) and World Reference Base for Soil Resources (WRB) by FAO ([IUSS Working Group WRB, 2015](#)) serve as equivalents.

Table 1. Methods for analyzing chemical, physical, and mineral properties of soil.

No	Soil analysis	Methode
Soil physical		
1	Soil texture (sand, silt, clay)	Pipette (Kurnia et al., 2022)
2	Water holding capacity	<i>Alhricks</i> (Kurnia et al., 2022)
3	Bulk volume	Soil sample ring/ <i>core method</i> (Kurnia et al., 2022)
4	Soil colors	Munsell soil color chart book
Soil chemical		
1	Soil pH reaction (H ₂ O dan KCl) ratio 1:5	pH meter (Eviati et al., 2023)
2	NaF pH ratio 1:5; 1 dan 60 minutes	Solution NaF 7,7 (Eviati et al., 2023)
3	Organic Carbon	Walkey dan Black (Eviati et al., 2023)
4	Total-N	Kjeldahl (Eviati et al., 2023)
5	Soil Cation Exchangeable Capacity	Extraction NH ₄ OAc 1 N pH 7,0 (Eviati et al., 2023)
6	Base saturation	Extraction NH ₄ OAc 1 N pH 7,0 (Eviati et al., 2023)
7	Exchangeable cations (Ca, Mg, K, Na)	Extraction NH ₄ OAc 1 N pH 7,0 (Eviati et al., 2023)
8	Total K ₂ O	Extraction HCl 25% (Eviati et al., 2023)
9	Total P ₂ O ₅	Extraction HCl 25% (Eviati et al., 2023)
10	P ₂ O ₅ available	Extraction <i>Bray 1</i> dan <i>Olsen</i> (Eviati et al., 2023)
11	K ₂ O available	Morgan Wolf (Eviati et al., 2023)
12	Retention P	Blackmore (Eviati et al., 2023)
13	Exchangeable Al and H	Extraction KCl 1 N (Eviati et al., 2023)
Soil mineral		
1	Clay minerals	XRD
2	Sand minerals	Polarizing microscope with counting line (Buurman, 1990)

Table 2. Soil morphology of soil profiles.

Pedon/ Horizons	Solum (cm)	MSSC	Soil Color (moisture)	Soil Structure	Consistency (wet & moisture)	Horizon Boundary
P1 Alic Hapludands						
Ap	0-18	7.5YR 3/3	Dark brown	2, vf, sb	s, p, fr	-
Bw1	18-49	7.5YR 2.5/3	Very dark brown	3, f, sb	vs, vp, fr	c, sm
Bw2	49-105	7.5YR 3/4	Reddish dark brown	3, f, sb	vs, vp, fr	gr, sm
Bw3	105-129	5YR 3/4	Brownish yellow	2, f, sb	vs, vp, fr	d, sm
Bw4	129-150	7.5YR 3/3	Dark brown	2, f, sb	vs, vp, fr	c, sm
P2 Alic Hapludands						
Ap	0-14	7.5YR 3/2	Dark brown	1, f, sb	ss, sp, fr	gr, sm
Bw1	14-42	7.5YR 4/3	Brown	1, f, sb	ss, sp, fr	c, sm
Bw2	42-82	7.5YR 4/4	Brown	1, f, sb	ss, sp, fr	c, sm
Bw3	82-142	7.5YR 4/4	Brown	2, m, sb	s, p, t	gr, sm
Bw4	142-170+	7.5YR 7/6; 7.5YR 4/6	Reddish yellow; Strongly brown	2, m, sb	s, p, t	-
P3 Alic Hapludands						
Ap	0-18	7.5YR 3/3	Dark brown	1, f, sb	ss, sp, fr	c, sm
Bw1	18-48	7.5YR 4/4	Brown	1, f, sb	ss, sp, fr	c, sm
Bw2	48-82	7.5YR 5/6	Strongly brown	1, f, sb	s, p, fr	d, sm
Bw3	82-124	7.5YR 5/6	Strongly brown	2, m, sb	s, p, t	d, sm
Bw4	124-170+	7.5YR 6/6; 7.5YR 7/3	Reddish yellow; Pink	2, m, sb	s, p, t	-
P4 Acrudoxic Hapludands						
Ap	0-16	7.5YR 3/2	Dark brown	1, f, sb	so, po, fr	c, w
Bw1	16-46	7.5YR 4/4	Brown	1, f, sb	ss, sp, fr	c, w
Bw2	46-85	7.5YR 4/3	Brown	1, f, sb	ss, sp, fr	d, sm
Bw3	85-155	7.5YR 4/4	Brown	2, m, sb	s, p, t	d, sm
Bw4	155-170+	7.5YR 4/4; 7.5YR 4/3; 5YR 5/6	Brown; Brown; Yellowish red	2, m, sb	s, p, t	-

Notes: soil structure (level of development: 1= weak, 2= moderate, 3= strong; size: vf = very fine, f = fine, m = moderate; shape: sb = subangular blocky); consistency (so= non sticky, ss= slightly sticky, s= sticky, vs= very sticky, po= non plastic, sp= slightly plastic, p= plastic, vp= very plastic, fr= friable, t= firm), horizon boundary (c= clear, gr= gradual, d= diffuse, sm= smooth, w= wavy).

3. RESULTS

3.1. Soil Morphology Characteristics

The research site exhibited a deep solum, supported by four soil profiles, each exceeding 150 cm in depth, as indicated in Table 2. The depths were determined according to the deepest observable pedogenic horizon. All profiles exhibited dark brown topsoil (7.5YR 3/2 to 7.5YR 3/3) (Table 2), indicating a relatively elevated concentration of soil organic matter. Profile P1 exhibited greater color variation relative to other profiles, characterized by a significant darker horizon at a depth of 18 cm to 49 cm compared to the surface layer. The soil matrix exhibited colors varying from reddish dark brown to brownish yellow within the depth range of 49 cm to 129 cm. The observed reddish and yellowish colors indicate the presence of iron oxide minerals, such as hematite, goethite, and lepidocrocite. Yellowish hues were observed in subsoil layers at depths greater than 120 cm in additional profiles. The varied colors observed in profile P1 suggest a more developed soil formation, presumably linked to enhanced structural development relative to the other profiles. This is evidenced by its well-developed structure and significant clay accumulation, which is also indicated by its

higher bulk density. Profile P3 exhibited a distinct contrast, characterized by a dark upper horizon and a lighter lower horizon (Fig. 3), indicative of variations in organic matter content. In wet conditions, soil consistency varied from slightly sticky to sticky in profiles P2, P3, and P4, whereas profile P1 exhibited a consistency ranging from sticky to very sticky, indicating a higher clay content. In moist conditions, the soil exhibited friability. The horizon boundaries across all profiles exhibited variability, ranging from distinct and gradual to diffuse and smooth.

3.2. Soil Physical Properties

The physical properties of all soil profiles are presented in Table 3. The values of bulk density (Bd) and particle density (Pd) exhibited an inverse relationship with total porosity. Bd exhibited low (0.58-0.73 g cm⁻³) values, while total porosity is consistently high (63.25-68.55 %). Profile P1 exhibited the highest values of Bd and Pd, followed by P3, whereas P2 and P4 exhibited similar and comparatively lower values. Profiles P2 and P4, characterized by lower Bd and Pd, exhibited increased total porosity. In contrast, P1, with higher Bd and Pd, had the lowest total porosity.

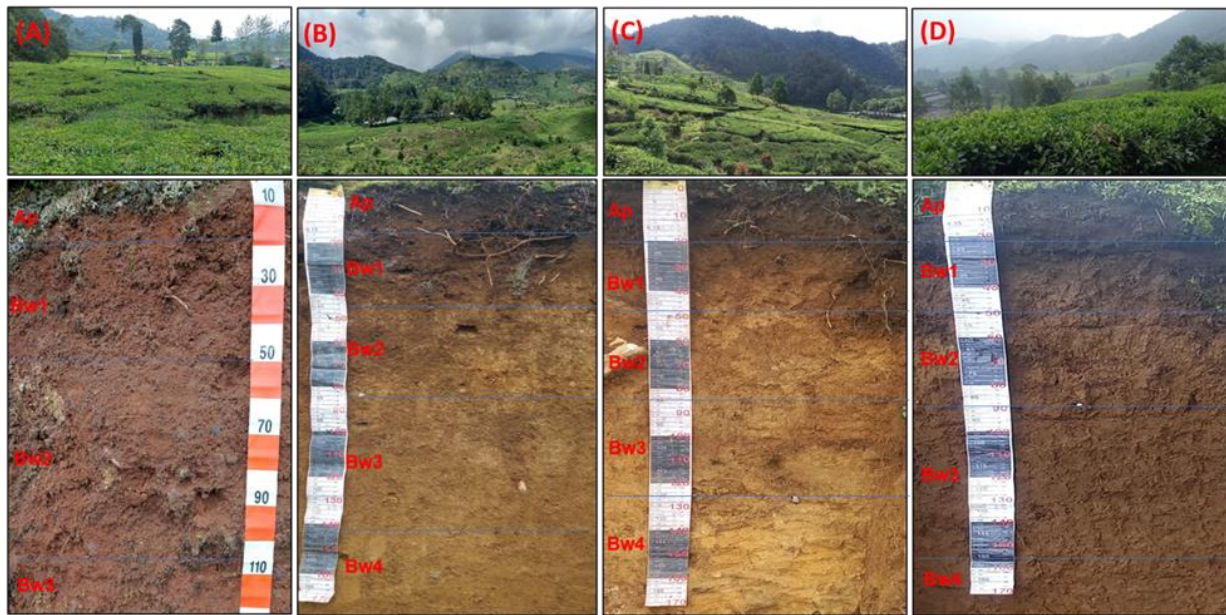


Figure 3. Landscape and soil profile at study site (A= soil profile P1, B= soil profile P2, C= soil profile P3, and D= soil profile P4).

Table 3. Physical properties of the topsoil horizon.

Pedon	Water content (% volume)	Bulk density (BD) g cm ⁻³	Particle density (PD)	Total porosity (%)	Water content				Aeration pores		Available water (%)
					pF1	pF 2	pF2.54	pF 4.2	Fast	Slow	
					----- % volume -----						
P1	39.70	0.73	1.97	63.25	56.30	47.10	43.45	26.90	16.15	3.65	16.55
P2	49.65	0.58	1.80	67.65	60.40	49.90	43.45	26.35	17.75	6.45	17.10
P3	44.15	0.65	1.90	66.10	55.80	47.15	39.90	23.30	18.95	7.25	16.60
P4	48.15	0.58	1.85	68.55	58.40	41.90	35.65	23.20	26.65	6.25	12.45

Bd and Pd reflect the proportion of solid material within the soil, whereas total porosity represents the void present between soil particles. Bulk density and porosity variations are significantly influenced by the soil particle-size distribution, or texture (Table 4a). P1 exhibited a higher bulk density and lower porosity due to its clay loam texture, which is characterized by a predominance of fine particles. P4 exhibited reduced bulk density and increased porosity attributed to its sandy loam texture, characterized by a higher proportion of coarse particles. In contrast, P2 and P3 exhibited a silty loam texture, indicating an intermediate condition relative to P1 and P4.

Fast aeration pores are characterized by larger pore spaces exceeding 28.8 microns in diameter, whereas slow aeration pores are defined by smaller pore spaces ranging from 8.6 to 28.8 microns. Table 3 indicates that profile P4 exhibited the highest percentage of fast aeration pores compared to all profiles. Conversely, profile P1, characterized by a higher Pd, exhibited a reduced percentage of fast aeration pores. Profile P3 exhibited the highest percentage of slow aeration pores, whereas profile P1 displayed the lowest percentage. The highest availability of water was observed in P2, succeeded by P3, P1, and P4.

The soil water retention curves (SWRC) presented in Figure 4 demonstrate notable variations in pore-size distribution and water holding capacity across the four pedons, which are critical factors influencing soil physical

quality and crop productivity. All four pedons exhibited low bulk densities (0.58–0.73 g cm⁻³) and high total porosities (63.25–68.55%), characteristics of volcanic andic soils abundant in amorphous minerals such as allophane and imogolite; however, their water dynamics varied considerably. The findings indicate that soil water availability is influenced more by pore architecture than by total porosity.

Pedon 2 (P2) demonstrated the highest volumetric water content at all matric potentials, achieving a plant-available water content (PAWC) of 17.10%. This indicates an optimal distribution of macropores and micropores, enhancing both drainage and water retention. The findings are consistent with earlier research indicating that well-aggregated soils characterized by moderate clay content and stable structure enhance soil water retention while maintaining adequate aeration (Dexter, 2004).

Conversely, Pedon 4 (P4), which demonstrated the highest total porosity at 68.55%, experienced significant water loss at higher matric potentials, resulting in the lowest PAWC of 12.45%. This suggests a prevalence of macropores and a coarser texture, facilitating infiltration and aeration while diminishing water storage capacity. This observation aligns with the findings of Jiang et al. (2020) and Harefa (2025) which indicate that coarse-textured soils exhibit greater susceptibility to drought stress.

Table 4a. Properties of chemical soil.

Pedons/ Horizons	Solum (cm)	Soil Texture				pH		NaF		C	N	C/N	P ₂ O ₅	K ₂ O	P ₂ O ₅	K ₂ O
		Sand	Silt	Clay	Class	H ₂ O	KCl	1'	60'	----- % -----	----- mg 100g ⁻¹ -----		----- ppm -----			
		----- % -----														
P1 (Alic Hapludands, Tea Plantation)																
Ap	0-18	23	39	38	Clay loam	4.43	3.82	11.02	11.61	3.43	0.27	12.92	73.96	6.37	9.67	54.34
Bw1	18-49	24	35	41	Clay	4.37	3.84	10.95	11.57	3.23	0.26	12.61	70.49	5.85	9.51	50.72
Bw2	49-105	19	41	40	Silty clay loam	4.62	3.83	11.15	11.67	3.27	0.25	13.14	76.76	6.10	2.75	49.99
Bw3	105-129	28	41	31	Clay loam	4.85	3.76	10.73	11.37	1.08	0.11	9.82	69.18	4.68	3.72	39.08
Bw4	129-150	25	46	29	Clay loam	4.76	3.84	11.18	11.67	2.42	0.21	11.77	53.59	6.97	3.44	66.26
P2 (Alic Hapludands, Tea Plantation)																
Ap	0-14	30	68	2	Silty loam	4.50	4.20	11.40	11.7	5.72	0.84	7.00	67.00	8.00	4.40	73.00
Bw1	14-42	26	71	3	Silty loam	4.90	3.90	11.00	11.6	2.81	0.4	7.00	53.00	7.00	1.70	66.00
Bw2	42-82	30	58	12	Silty loam	4.90	3.90	11.00	11.5	0.98	0.12	8.00	73.00	6.00	0.60	58.00
Bw3	82-142	33	57	10	Silty loam	5.00	3.80	11.10	11.6	1.20	0.15	8.00	69.00	3.00	1.10	29.00
Bw4	142-170+	35	50	15	Loam	5.00	3.90	11.40	11.7	1.09	0.15	7.00	72.00	3.00	2.10	24.00
P3 (Alic Hapludands, Tea Plantation)																
Ap	0-18	42	42	16	Loam	4.80	4.50	11.60	11.8	6.69	1.16	6.000	63.00	6.00	2.50	57.00
Bw1	18-48	26	51	23	Silty loam	5.20	4.00	11.20	11.6	2.03	0.27	8.000	76.00	4.00	0.60	38.00
Bw2	48-82	35	51	14	Silty loam	5.20	3.80	10.70	11.2	0.97	0.1	10.000	111.00	3.00	0.80	33.00
Bw3	82-124	32	44	24	Loam	5.00	3.70	10.70	11.2	0.84	0.12	7.000	80.00	3.00	0.60	29.00
Bw4	124-170+	44	35	21	Loam	5.20	4.00	10.40	10.9	0.45	0.06	8.000	219.00	4.00	0.60	38.00
P4 (Acruoxic Hapludands, Tea Plantation)																
Ap	0-16	69	30	1	Sandy loam	4.70	4.60	11.60	11.7	6.99	0.98	7.00	78.00	4.00	15.30	38.00
Bw1	16-46	68	30	2	Sandy loam	4.90	4.80	11.50	11.7	3.61	0.49	7.00	168.00	4.00	4.30	38.00
Bw2	46-85	55	33	12	Sandy loam	5.60	5.00	11.30	11.6	2.46	0.18	14.00	120.00	3.00	5.10	29.00
Bw3	85-155	45	46	9	Loam	5.60	5.00	11.30	11.5	2.74	0.21	13.00	410.00	5.00	9.00	48.00
Bw4	155-170+	28	61	11	Silty loam	5.60	5.00	11.30	11.5	2.47	0.34	7.00	498.00	3.00	5.90	29.00
Composite																
C5a	0-20	34	53	13	Silty loam	4.80	4.49	11.40	11.7	4.46	0.29	15.50	48.27	15.96	2.00	142.50
C5b	20-40	38	41	21	Loam	4.60	3.97	11.40	11.8	3.64	0.25	14.50	94.20	11.05	3.360	95.44
C1a	0-20	33	48	19	Loam	4.10	3.70	10.80	11.2	2.87	0.35	8.00	148.00	26.00	24.60	232.00
C1b	20-40	33	54	13	Silty loam	4.40	3.80	11.00	11.3	2.82	0.37	8.00	61.00	30.00	10.00	269.00
C2a	0-20	68	30	2	Sandy loam	4.50	4.40	11.60	11.8	5.60	0.75	7.00	98.00	23.00	10.20	212.00
C2b	20-40	55	33	12	Sandy loam	4.30	4.20	11.60	11.8	6.20	1.06	6.00	125.00	14.00	11.20	132.00
C3a	0-20	42	34	24	Loam	4.50	4.20	11.60	11.8	5.47	0.76	7.00	63.00	16.00	4.20	156.00
C3b	20-40	36	43	21	Loam	4.40	4.00	11.50	11.7	5.13	0.93	6.00	104.00	14.00	6.40	132.00
C4a	0-20	68	28	4	Sandy loam	4.90	4.80	11.50	11.7	4.88	0.64	8.00	115.00	4.00	8.70	37.00
C4b	20-40	68	28	4	Sandy loam	4.90	4.80	11.60	11.7	5.07	0.73	7.00	123.00	3.00	11.00	32.00

Table 4b. Properties of chemical soil (continue).

Pedons/ Horizons	Solum (cm)	Ca	Mg	K	Na	Sum	CEC	Base Saturation	P Retention	Fe-ox	Al-ox	Al-ox + (1/2Fe-ox)	Al ³⁺	H ⁺
		cmol kg ⁻¹						%				cmol kg ⁻¹		
P1 (Alic Hapludands, Tea Plantation)														
Ap	0-18	0.70	0.30	0.10	0.13	1.23	32.39	3.80	-	-	-	-	21.71	0.94
Bw1	18-49	1.52	0.37	0.10	0.27	2.26	32.11	7.04	-	-	-	-	20.70	0.85
Bw2	49-105	1.41	0.35	0.09	0.29	2.14	30.82	6.94	-	-	-	-	18.43	0.80
Bw3	105-129	4.21	0.98	0.07	0.27	5.53	28.77	19.22	-	-	-	-	19.33	0.83
Bw4	129-150	3.33	0.76	0.13	0.27	4.49	31.63	14.20	-	-	-	-	17.79	0.72
P2 (Alic Hapludands, Tea Plantation)														
Ap	0-14	1.9	0.43	0.15	0.18	2.66	22.18	12.00	95.82	2.23	2.38	3.50	3.10	0.98
Bw1	14-42	3.79	1.1	0.14	0.36	5.39	13.63	40.00	95.82	3.14	2.00	3.57	5.49	0.71
Bw2	42-82	2.77	0.66	0.12	0.27	3.82	20.8	18.00	93.04	2.33	1.66	2.83	10.96	1.19
Bw3	82-142	2.59	0.69	0.06	0.35	3.69	19.17	19.00	95.59	2.77	2.02	3.41	15.43	1.99
Bw4	142-170+	2.21	1.12	0.05	0.4	3.78	25.75	15.00	93.04	2.48	2.29	3.53	12.14	2.2
P3 (Alic Hapludands, Tea Plantation)														
Ap	0-18	2.34	0.49	0.12	0.34	3.29	25	13.00	96.52	2.04	3.05	4.07	1.06	0.63
Bw1	18-48	10.8	2.47	0.08	0.24	13.59	30.62	44.00	93.04	2.27	1.31	2.45	3.69	1.03
Bw2	48-82	12.91	1.72	0.07	0.28	14.98	23.97	62.00	78.65	1.20	0.79	1.39	8.42	2.75
Bw3	82-124	7.95	1.25	0.06	0.28	9.54	31.26	31.00	87.47	1.38	0.82	1.51	16.59	1.35
Bw4	124-170+	7.37	1.34	0.08	0.23	9.02	32.19	28.00	79.35	0.43	0.62	0.84	22.91	4.69
P4 (Acruoxic Hapludands, Tea Plantation)														
Ap	0-16	1.35	0.22	0.08	0.44	2.09	19.41	11.00	96.75	1.62	4.08	4.89	0.88	0.25
Bw1	16-46	1.01	0.24	0.08	0.24	1.57	15.29	10.00	95.36	3.54	4.32	6.09	0.47	0.08
Bw2	46-85	1.38	0.37	0.06	0.15	1.96	15.99	12.00	96.75	4.63	4.73	7.05	0	0.5
Bw3	85-155	1.18	0.26	0.09	0.24	1.77	22.24	8.00	95.59	4.02	7.05	9.06	0	0.28
Bw4	155-170+	1.05	0.23	0.06	0.26	1.6	22.54	7.00	97.45	3.14	7.72	9.29	0	0.35
Composite														
C3c	0-20	1.49	0.26	0.26	0.21	2.22	21.20	10.47	-	-	-	-	0.59	0.42
C3d	20-40	1.65	0.35	0.17	0.25	2.42	23.37	10.36	-	-	-	-	8.37	0.45
C1a	0-20	1.23	0.57	0.49	0.27	2.56	35.78	7.00	90.95	1.23	1.21	1.83	20.96	8.03
C1b	20-40	6.35	1.46	0.57	0.31	8.69	24.67	35.00	89.79	1.46	1.26	1.99	14.83	4.6
C2a	0-20	2.16	0.7	0.45	0.27	3.58	22.53	16.00	95.13	1.36	2.56	3.24	1.77	0.31
C2b	20-40	2.06	0.55	0.28	0.24	3.13	24.76	13.00	95.82	1.56	2.91	3.69	2.69	0.71
C3a	0-20	1.54	0.46	0.33	0.34	2.67	23.88	11.00	95.82	2.18	2.98	4.07	2.92	1.03
C3b	20-40	3.37	0.87	0.28	0.24	4.76	29.41	16.00	93.97	1.70	1.89	2.74	7.41	1.13
C4a	0-20	1.16	0.24	0.07	0.19	1.66	17.9	9.00	96.52	2.94	4.08	5.55	0.36	0.36
C4b	20-40	1.05	0.2	0.06	0.24	1.55	15.96	10.00	96.05	2.56	3.91	5.19	0.48	0.25

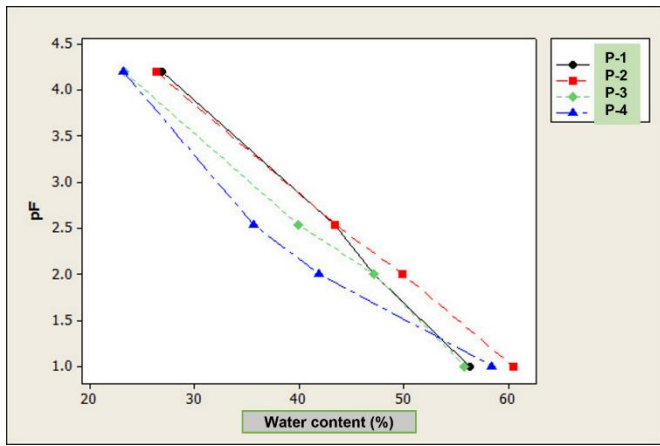


Figure 4. Curve depicting the relationship between soil water retention (pF) and water content.

Pedons 1 and 3 exhibited intermediate water retention curves (Fig. 4), with PAWC values of 16.55% and 16.60%, respectively, and aeration porosity greater than 18%. The characteristics indicate an advantageous soil structure and suitability for various cropping systems. The slope of the SWRC between pF 1 and pF 2.54 reflects gravitational drainage, whereas the stable water content observed at higher pF values (pF 2.54–4.2) in Pedons 1–3 implies efficient water retention in micropores.

These results underscore the necessity for tailored water management strategies at specific sites. Soils such as P4, characterized by high aeration and low water retention, may improve through practices that enhance micropore volume and organic matter content, such as biochar application, cover cropping, or residue mulching (Arif et al., 2021). P2 represents an ideal soil physical condition that can sustain intensive cropping systems while minimizing the risks of

waterlogging or drought. The findings reinforce the necessity of integrating SWRC data with bulk density and porosity measurements in the assessment of soil physical quality, as no singular parameter can comprehensively represent the complexity of soil hydraulic behavior.

The SWRC analysis demonstrated significant variability in water retention across the pedons, indicating variations in soil texture, structure, and pore connectivity. Comprehending these variations is crucial for developing accurate water management and soil conservation strategies, particularly in regions prone to variable rainfall and drought risk. Future research should incorporate SWRC characteristics with hydraulic conductivity measurements and crop performance data to strengthen the relationship between soil physical properties and agricultural productivity.

3.3. Chemical Properties of Soil

The soils at the research site predominantly displayed loam textures, specifically clay loam, silty loam, and sandy loam. The soil pH was primarily acidic, exhibiting values from 4.5 to 5.5 (Table 4a). Very acidic conditions (pH < 4.5) were observed in the topsoil of profile P1 and in several composite soil samples, such as C1a, C1b, C2b, and C3b. C1a and C1b were collected in proximity to P1. Soil profile data revealed that subsoil layers exhibited higher pH values compared to the topsoil, indicating base leaching, likely influenced by the high annual rainfall at the study site (approximately 3,164 mm year⁻¹). Increased sum of exchangeable cations with soil depth indicate evidence of base leaching. The soil pH measured in KCl solution revealed potential acidity, exhibiting values lower than those recorded in distilled water (pH H₂O). The pH measurement with NaF indicated the prevalence of non-crystalline minerals, specifically allophane and imogolite.

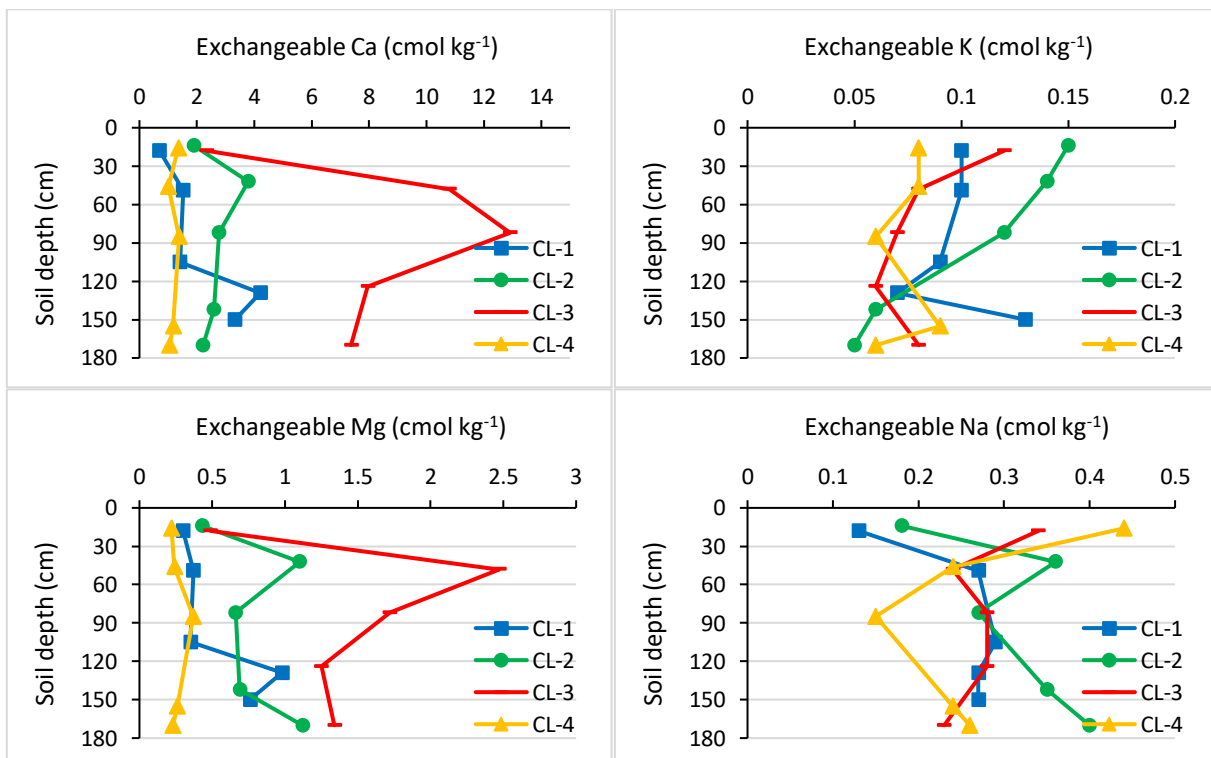


Figure 5. Exchangeable cations in soil profiles according to soil depth.

The organic carbon content in all soil profiles and composite samples exhibited variation, with most; classified as high (3–5%) to very high (>5%) (Table 4a). The maximum organic carbon content in the topsoil was found in profiles P3 and P4, at 6.69%, whereas the minimum was recorded in P1, at 3.43%. The composite soil samples support these findings, displaying trends aligned with the profile data. The composite samples exhibited the highest organic carbon content in C2b (20–40 cm depth), located near P2, whereas the lowest values (2.8%) were observed in C1a and Cb, both near P1. Profile data indicated a significant reduction in organic carbon content in the subsoil relative to the topsoil, with the exception of P1, which retained a relatively high organic carbon level (3.0%) at a depth of 105 cm. The organic carbon content at comparable depths in P2 and P3 was significantly lower, record at 1.2% and 0.84%, respectively. The total nitrogen content in all samples was under 1%, except for the

top layer of P3 and composite sample C2b, which exhibited N content of 1.16% and 1.06%, respectively (Table 4a). Nitrogen levels were strongly correlated with organic carbon, with more than 90% of the measured nitrogen existing in organic form. Both parameters indicate the organic matter content in the soil. The carbon-to-nitrogen (C/N) ratio indicates the relative amounts of organic carbon and nitrogen in the soil, where organic carbon levels consistently surpass those of nitrogen. A reduced C/N ratio indicates an accelerated release of nitrogen into the soil solution, thereby enhancing its availability for plant uptake (Brust, 2019). In this study, the majority of soil samples exhibited C/N ratios under 10. The highest C/N ratios were recorded in profile P1 (13–14) and in composite samples C3c and C3d (14–15). The lowest C/N ratio was recorded at 6, was found in the topsoil of profile P3 and in composite samples C2b and C3b.

Table 5. Comparative analysis of various chemical properties of the soil at the research site in relation to prior studies.

Soil Profile Horizons	pH H ₂ O						
	P1 ¹⁾	P2 ¹⁾	P3 ¹⁾	P4 ¹⁾	N3 ²⁾	W-1 ³⁾	W-2 ³⁾
I	4.43	4.50	4.80	4.70	4.52	5.02	5.00
II	4.37	4.90	5.20	4.90	4.59	5.15	5.20
III	4.62	4.90	5.20	5.60	4.54	5.26	5.43
IV	4.85	5.00	5.00	5.60	4.80	5.69	5.12
V	4.76	5.00	5.20	5.60	5.54	5.63	5.14
Organic matter (%)							
I	5.91	9.86	11.53	12.05	14.45	17.77	15.71
II	5.57	4.84	3.50	6.22	11.03	14.27	8.28
III	5.64	1.69	1.67	4.24	6.45	7.93	6.47
IV	1.86	2.07	1.45	4.72	4.45	7.14	8.05
V	4.17	1.88	0.78	4.26	2.86	8.50	5.55
C-organic (%)							
I	3.43	5.72	6.69	6.99	8.38	10.31	9.11
II	3.23	2.81	2.03	3.61	6.40	8.28	4.80
III	3.27	0.98	0.97	2.46	3.74	4.60	3.75
IV	1.08	1.2	0.84	2.74	2.58	4.14	4.67
V	2.42	1.09	0.45	2.47	1.66	4.93	3.22
Total Nitrogen (%)							
I	0.27	0.84	1.16	0.98	0.80	0.44	0.32
II	0.26	0.40	0.27	0.49	0.58	0.37	0.19
III	0.25	0.12	0.10	0.18	0.31	0.23	0.14
IV	0.11	0.15	0.12	0.21	0.26	0.19	0.19
V	0.21	0.15	0.06	0.34	0.19	0.22	0.12
Cation Exchangeable Capacity (cmol kg ⁻¹)							
I	32.39	22.18	25.00	19.41	20.17	41.79	42.79
II	32.11	13.63	30.62	15.29	15.39	37.41	41.78
III	30.82	20.80	23.97	15.99	10.48	32.41	43.75
IV	28.77	19.17	31.26	22.24	7.84	33.05	40.61
V	31.63	25.75	32.19	22.54	8.85	34.07	35.46
Base Saturation (%)							
I	3.80	12.00	13.00	11.00	7.36	9.55	7.62
II	7.04	40.00	44.00	10.00	5.31	9.94	5.12
III	6.94	18.00	62.00	12.00	8.72	8.45	5.44
IV	19.22	19.00	31.00	8.00	14.00	9.50	6.38
V	14.20	15.00	28.00	7.00	34.16	8.99	6.20

Notes: 1) Data from P1, P2, P3, P4 (Table 4a), 2) Muslim et al. (2025), 3) Wahyudin (1989).

The levels of exchangeable cations correlated with soil pH. The maximum exchangeable cation sum was recorded in profile P3, exhibiting a soil pH between 4.8 and 5.0. Profile P4, despite a higher subsoil pH of 5.6, demonstrated the lowest base cation levels across all profiles at comparable depths. The total exchangeable cations generally increased with soil depth, presumably as a result of cation leaching from the topsoil to the subsoil. Profile P4 displayed a distinct pattern, characterized by a decrease in exchangeable cation with depth. The location of P4 in a hilly area, coupled with dense tea vegetation and thick foliage, likely contributed to reduced rainfall infiltration and minimized leaching relative to the other profiles.

Figure 5 illustrates that calcium (Ca) and magnesium (Mg) concentrations were comparable across samples, with the highest concentrations observed in profile P3 and the lowest in profile P4. Profile data indicated that potassium (K) concentrations were highest in P2 and lowest in P4. Sodium (Na) concentrations exhibited consistency across all samples, with the peak concentration recorded in the topsoil of P4 (Fig. 5).

The soil CEC observed in this study varied between 15 to 35 cmol kg⁻¹. Profile P1 exhibited the highest CEC values, ranging from 28.77 to 32.39 cmol kg⁻¹, whereas profile P4 exhibited the lowest values, ranging from 15.29 to 22.54 cmol kg⁻¹. The composite soil samples reflected a consistent trend, with the highest CEC observed in C1a, located near P1, and the lowest values found in C4a and C4b, located near P4.

The soils at the study site typically demonstrated low base saturation levels (<50%), which correlated with elevated soil acidity. The maximum base saturation occurred in profile P3 at depths of 18–82 cm, with values between 44% and 62%. Subsequently, profile P2 exhibited a value of 40% at depths ranging from 14 to 42 cm, whereas the composite sample C1b, recorded a value of 35%. In contrast, all other samples exhibit a base saturation value below 20%.

Volcanic soils are characterized by high phosphate retention (>85%). Table 4b indicates that all soil profiles exhibited phosphate retention exceeding 90%, with the exception of the subsoil in profile P3. While P1 was not assessed for phosphate retention, composite samples C1a and C1b, located near P1, may act as representative indicators of its phosphate retention capacity.

Oxalate-extractable Fe (Fe-ox) and Oxalate-extractable Al (Al-ox) signify the existence of these elements in non-crystalline mineral forms. Fe-ox levels varied between 0.43% and 4.63%, with the highest concentrations observed in the subsoil of profile P4, reaching 4.02% to 4.63% at depths of 46 to 155 cm (Table 4b). The subsoil of profile P3 exhibited the lowest Fe-ox concentration, measured, at 0.43% within the depth range of 124–170 cm. The levels of Al-ox exhibited a comparable pattern, as both Fe-ox and Al-ox are associated to non-crystalline minerals such as allophane and ferrihydrite.

The acidic nature of volcanic soils leads to elevated levels of Al³⁺ and H⁺ saturation, particularly observed in profile P1 and composite samples C1a and C1b. In other areas, Al saturation was generally lower, as indicated by the comparatively low Al content in additional samples, especially in the surface layers. This condition is likely attributable to

liming practices implemented in other blocks but not in P1, resulting in a pronounced disparity. The saturation levels of Al and H were inversely related to soil pH, with lower pH values indicating higher saturation of Al and H.

The effect of tea plantations in this area was assessed by employing a comparative approach, utilizing legacy soil data from sites near the Ciliwung Plantation, which was presumed to be similar (Table 5). Over 36 years, the Andosols of Bogor beneath tea plantations have experienced significant alterations in their chemical properties. A discernible trend of soil acidification was observed, with pH decreasing from an average of 5.26 in 1989 (W1–W2) to 4.93 in 2024 (P1–P4, N3). Substantial decreases were observed in soil organic matter (–46.6%), organic carbon (–46.6%), and CEC (–41.7%), indicating a weakening of the soil's buffering capacity. These alterations align with prolonged leaching processes characteristic of humid tropical environments, further intensified by the ongoing use of acidifying nitrogen fertilizers in tea cultivation.

Base saturation increased from 7.7% to 18.0% during the same period; however, this increase does not signify an improvement in soil fertility. This indicates a relative increase resulting from the sharp decline in CEC. Consequently, while the percentage of exchange sites occupied by basic cations has risen, the total stock of nutrient cations has likely decreased or remained low. The total nitrogen content exhibited a slight increase from 0.24% to 0.35%, likely attributable to continuous fertilizer applications rather than an enhancement of soil organic matter reserves. These findings suggest that, despite ongoing nutrient inputs, the soil's inherent capacity to store and regulate nutrients has been diminished.

The chemical degradation observed in these Andosols indicates progressive weathering and soil aging, likely involving the transformation of short-range order minerals into more crystalline phases with reduced charge densities. The observed trajectory, along with declining organic matter inputs and intensified acidification, highlights a sustained decline in soil quality and resilience within monoculture tea systems. The findings emphasize the necessity for restorative soil management practices, including organic matter enrichment, and balanced nutrient applications, to mitigate adverse trends and maintain the productivity of tea plantations on Andosols.

These changes indicate potential mineralogical shifts from short-range order minerals to more crystalline phases, signaling the onset of andic property deterioration. These transformations indicate that Andosols, previously considered resilient due to their high CEC and organic matter content, are actually susceptible to rapid degradation under intensive monoculture practices. The findings highlight the urgency for restorative management aimed at rebuilding organic matter, mitigates acidification, and preserving the distinctive andic properties essential for the productivity of tea plantation soils.

3.4. Soil Mineralogical Properties

The sand fraction of the analyzed soils is primarily composed of rock fragments and weathered minerals (Table

6). Profile P1 exhibited the highest concentrations of weathered minerals and rock fragments, ranging from 22-29% and 49-60%, respectively. Small amounts of opaque minerals and quartz were identified, constituting less than <15% of the total composition. The presence of opaque minerals indicates that the analyzed soils originated from volcanic parent materials, whereas the low quartz content indicates that these soils have not experienced significant weathering or are still in the developmental stage. The analyzed soils contain easily weathered minerals, including labradorite, augite, and hypersthene, in small to moderate quantities. Profile P4 exhibited the highest concentrations of augite and hypersthene, ranging from 10-16% and 14-28%, respectively. The likely reason for this is that P4 has not experienced additional pedogenic development, leading to greater reserves of easily weathered minerals such as augite and hypersthene in comparison to other profiles. This interpretation is additionally reinforced by the comparatively limited structural development of P4 and its sand-dominated texture. The significant presence of these minerals indicates that the soil originated from intermediate andesitic or volcanic parent materials. The significant presence of weathered minerals and rock fragments, along with easily weathered minerals, illustrates the substantial nutrient reserves conducive to the growth and development of tea crops.

The mineral composition of the clay fraction in the analyzed soils exhibit considerable variability. Vermiculite is present in moderate quantities in Profiles P2 and P3, whereas

illite is observed in small to very small quantities in Profiles P2, P3, and P4. Non-crystalline or amorphous minerals, meta-halloysite, gibbsite, quartz, goethite, and magnetite are present in small to moderate quantities. Hydrated halloysite minerals are present in limited quantities in Profile P1, whereas cristobalite is detected in minimal quantities in both Profiles P1 and P3 (Fig. 6).

Meta-halloysite was identified through XRD peaks exhibiting d-spacings of 0.713 to 0.722 nm (order 1) and 0.347 to 0.350 nm (order 2) following treatments with Mg^{2+} , Mg^{2+} plus glycerol, and K^+ . Additionally, the peaks diminished after treatment with K^+ and heating at 550 °C (Fig. 6). Hydrated halloysite exhibits a d-spacing of 1.000 nm (order 1) and 0.447 nm (order 2) following treatments with Mg^{2+} , Mg^{2+} combined with glycerol, and K^+ . The peaks subsequently collapsed following K^+ treatment combined with heating at 550 °C. Vermiculite exhibits a d-spacing of 1.423 nm after treatments with Mg^{2+} , Mg^{2+} plus glycerol, and K^+ . The peaks collapse following a K^+ treatment combined with heating at 550°C, yielding a d-spacing of 1.011 nm. XRD analysis revealed the presence of illite, characterized by d-spacing of 1.000 to 1.015 nm (order 1), and 0.540 to 0.545 nm (order 2). After treatment with Mg^{2+} , Mg^{2+} plus glycerol, and K^+ gibbsite exhibits a d-spacing range from 0.482 to 0.489 nm. The peaks subsequently collapse following K^+ treatment combined with heating at 550 °C. Cristobalite, quartz, goethite, and magnetite exhibit d-spacings of 0.404 to 0.406 nm, 0.334 to 0.339 nm, 0.255 to 0.256 nm, and 0.238 to 0.239 nm, respectively, following all treatments.

Table 6. Properties of sand mineral.

Soil Samples	Hor.	Op	Zr	Kk	Kb	Kf	Lm	SiO ₂ -Or	Ze	Mw	Fb	Gv	An	La	Bi	Sa	Hh	Au	Hi	Ep	Tu	St	Ds	En	Sum
P1	I	9	-	-	-	-	-	1	-	29	49	sp	sp	1	-	-	-	3	7	1	-	-	-	-	100
	II	4	-	-	-	-	-	3	-	28	55	1	1	1	1	-	-	1	5	-	-	-	-	-	100
	III	6	-	-	-	1	-	1	-	26	58	3	-	sp	-	-	-	1	4	-	-	-	-	-	100
	IV	6	-	-	-	2	-	sp	-	24	60	2	-	-	-	-	-	2	3	-	1	-	-	-	100
	V	10	-	-	-	-	-	-	-	-	22	57	3	-	1	1	-	-	1	4	1	sp	-	-	-
P2	I	8	1	8	1	2	-	sp	-	5	42	1	sp	9	sp	-	1	9	11	1	-	-	-	1	100
	II	6	-	7	1	4	-	-	-	8	46	2	sp	10	sp	-	1	5	9	-	1	-	-	-	100
	III	7	sp	6	-	4	-	sp	-	13	43	-	1	12	-	-	sp	5	7	1	sp	-	-	1	100
	IV	8	-	9	2	7	-	-	-	12	40	sp	1	8	-	-	sp	5	8	-	sp	-	-	sp	100
	V	7	-	5	1	7	-	-	-	-	20	35	1	sp	9	-	-	5	9	sp	1	-	-	-	100
P3	I	6	-	5	sp	5	-	sp	sp	11	34	1	sp	12	sp	1	-	9	15	sp	1	-	-	-	100
	II	2	1	6	1	5	-	-	-	14	39	-	sp	11	sp	sp	-	7	13	-	sp	-	-	1	100
	III	5	-	6	-	9	1	sp	-	14	37	-	2	10	-	-	-	6	10	sp	sp	-	-	sp	100
	IV	4	sp	8	2	10	sp	-	-	17	28	sp	1	12	-	sp	-	8	9	1	sp	-	-	-	100
	V	6	-	7	-	9	1	-	-	19	23	-	sp	13	-	1	-	9	12	-	-	-	-	sp	100
P4	I	9	-	2	sp	2	-	1	-	8	24	1	-	4	sp	1	2	16	22	2	2	-	3	1	100
	II	11	-	3	-	3	-	-	-	7	26	-	-	5	sp	-	1	14	28	2	sp	-	sp	-	100
	III	14	-	3	sp	6	-	sp	-	10	25	1	-	7	-	1	sp	10	21	sp	sp	-	-	1	100
	IV	10	-	5	1	5	-	-	-	13	27	sp	-	4	sp	-	1	13	20	sp	-	sp	-	-	100
	V	9	-	4	1	7	-	sp	-	15	33	-	-	2	2	sp	-	10	14	1	1	-	-	-	100

Notes: sp = sporadic (found during orientation but not offensive line counting), (-) = not found, Op = Opaque; Zr = Zircon; Kk = Turbid quartz; Kb = Translucent quartz; Kf = Iron concretion; Lm = Limonite; SiO₂-Or. = SiO₂-Organic; Ze = Zeolite; Mw = Mineral weathered; Fb = Glassy rocks fragment; Gv = Volcanic glass; An = Andesine; La = Labradorite; Bi = Bitownite; Au = Augite; Sa = Sanidine; Hh = Green Hornblende; Hi = Hypersthene; Ep = Epidote; Tu =Tourmaline; St = Staurolite; Ds = Diopside; En = Enstatite.

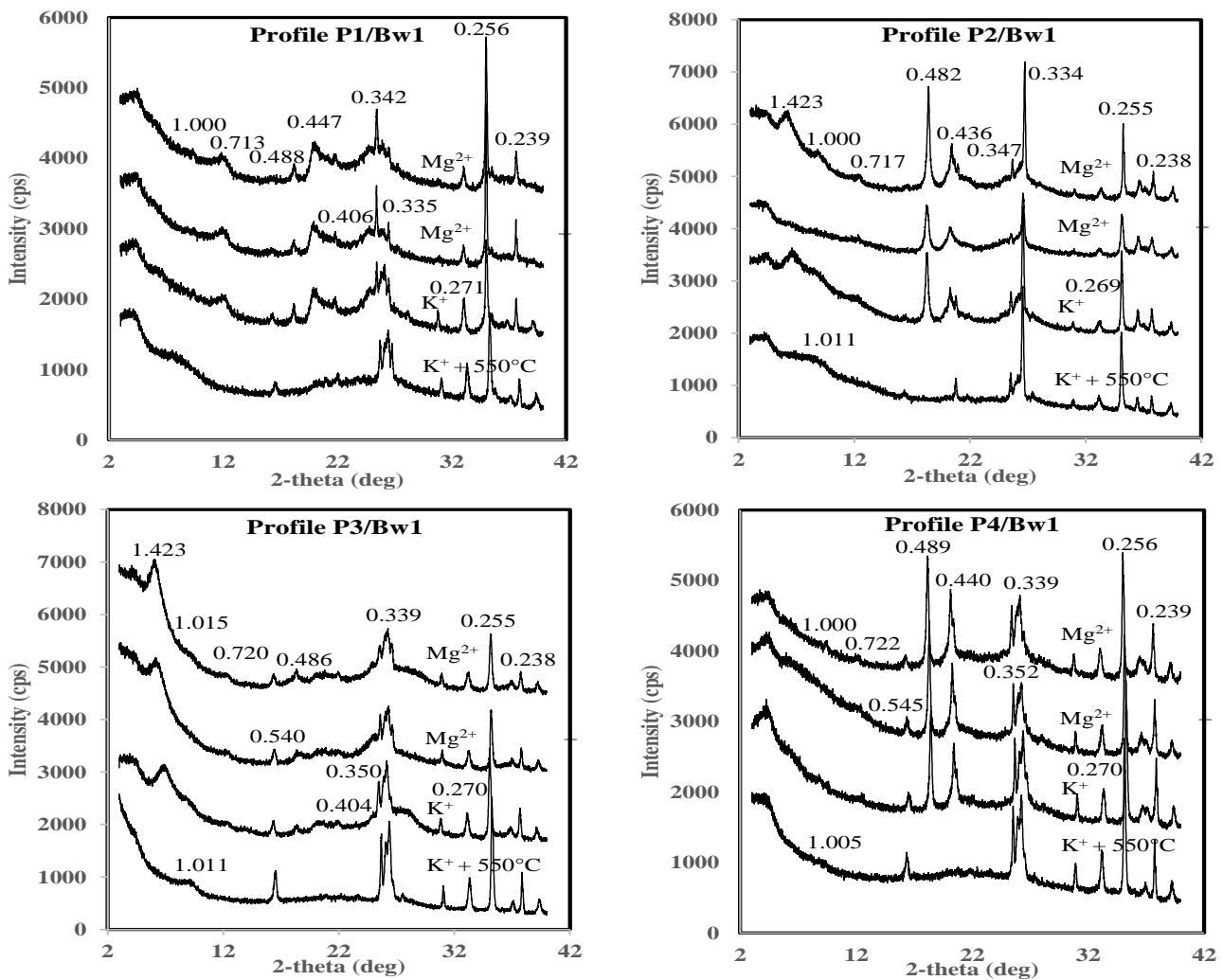


Figure 6. X-ray diffractogram of the analyzed soils subjected to Mg²⁺, Mg²⁺plus glycerol, and K⁺+heating at 550°C treatments.

3.5. Analysis of Climate Condition

Climate is a significant factor influencing soil formation (Weil & Brady, 2016). Figure 2 presents the results of monthly climate data measurements for the period 2011-2022, derived from BPS data (BPS, 2023). The minimum air temperature was recorded in February at 24.4°C, while the maximum was observed in May at 26.5°C. The mean temperature throughout the entire duration was 25.0°C. The Braak (1929) equation was employed to determine the minimum temperature corresponding to the elevation of each soil profile, resulting in a range of 17.3–17.7°C, with in an average of 17.6°C. The soil temperature at the research site was estimated using the equation from van Wambeke (1982) (Eq. 1).

$$T_s = T_a + 2.5^\circ C \dots\dots\dots [1]$$

where: Ts is soil temperature and Ta is the annual average air temperature.

The estimated annual average soil temperature, according to the equation, is 20.1°C. This condition aligns with the isohyperthermic soil temperature regime as outlined by the Soil Survey Staff (2022).

February recorded the highest rainfall at 500 mm month⁻¹, while July and August experienced the lowest, with 90 mm

month⁻¹ at 92 mm month⁻¹, respectively. The monthly average rainfall was 263.7 mm month⁻¹ leading to an annual average of 3,691.2 mm year⁻¹. The mean air humidity was 84.82%, with the peak recorded in January at 89.29% and the lowest in September at 79.47%. The research site exhibits an udic moisture regime (Soil Survey Staff, 2022).

The data indicated that the rainfall is classified as type A according to Schmidt and Ferguson (1951) classification system, characterized by a low ratio of dry months to wet months, with a Q value between 0.00 and 0.43. This indicates the absence of drought conditions for a duration of 90 consecutive days or longer at the research site. Ritung et al. (2011), highlight that tea plants thrive in temperatures ranging from 19 to 21°C, with annual rainfall between 2,500 and 4,000 mm, and air humidity below 70%. Ishak S et al. (2017) state that soil moisture is a crucial determinant of tea plant productivity, with an optimum humidity level of 87,2%. The climate conditions indicate that elevated rainfall contributes to the leaching of cations in the soil, attributed to high soil acidity levels at the research site.

3.6. Lithology

The research site, as indicated on a 1:100,000 scale geological map of Bogor, Java, is situated within the breccia

and lava formations of Mount Kencana and Mount Limo (Qvk). This area comprises Pleistocene-aged andesite and andesite breccia, such as andesine, labradorite, and hornblende, which are abundant in mineral nutrients (Effendi et al., 1998). Tan (1965) highlighted that Indonesian Andisols originated from diverse parent materials during the recent Pleistocene, predominantly consisting of andesitic tuffs.

3.7. Topography

The representative soil profile at the study site is situated in undulating to hilly terrain, with elevations ranging from 1,430 to 1,496 meters above sea level and a slope class exceeding 3 to over 40% (Table 7). Slope gradient influences surface runoff. This process results in the depletion of organic matter in the topsoil layer and may lead to surface erosion, such as sheet erosion. Marianti et al. (2021) stated that elevation significantly affects soil properties, surpassing the impact of slope on factors, such as CEC, total N, available P, or exchangeable K, and bulk density. Values of organic carbon, total nitrogen, and available phosphorus exhibited an increase with ascending profile position and slope class (P4 > P3 > P2 > P1). Conversely, values of soil CEC, available potassium, and BD diminished. Soil CEC, an important measure of soil fertility, exhibited the highest value at the lowest slope and elevation, specifically in P-1 soil profile. Li et al. (2025) find that higher slopes exhibit greater total nitrogen and available nutrient values than lower slopes, whereas soil CEC is maximized on the middle slope. Table 7 presents the location of each representative soil profile in relation to the topographic conditions of the study site.

3.8. Classification of Soil

Soil classification refers to the procedure outlined in the methodology section. The study's result classifies the soil according to the USDA Soil Taxonomy at the soil type level, identifying Alic Halpudands for soil profiles P-1, P-2, and P-3, and Acrudoxic Hapludands for soil profile P-4. As equivalents of the Soil Taxonomy, these soil types are classified as Andisol Distrik (soil profiles P-1, P-2, and P-3) and Andisol Okrik (soil profile P-4) in the National Soil Classification System. Meanwhile, in the FAO WRB system, they are classified as Dystric Alic Andosol and Dystric Acrudoxic Andosol.

4. DISCUSSION

This study's findings indicate that intensive tea cultivation affect the physical and chemical properties of soils. The implementation of cultivation and land management practices correlated with an increase in surface soil bulk

density. The bulk density values recorded in this study ranged from 0.58 to 0.73 g cm⁻³ which, while relatively low due to andic properties, were higher than those found under natural conditions, indicating the influence of cultivation practices. A study by Muslim (2024) in the Mount Gede-Pangrango area reported bulk density values ranging from 0.43 to 0.48 g cm⁻³ in undisturbed forest soils. Anda and Dahlgren (2020) reported analogous findings in Andisols from Mount Tangkuban Perahu, West Java, indicating that cultivated soils exhibited higher bulk density (0.5–0.8 g cm⁻³) than pine forest soils (0.4 g cm⁻³). This finding indicates that intensive land management for tea cultivation results in increased soil compaction, as reflected by higher bulk density values, which may subsequently affect soil physical quality. The increase in bulk density is attributed to the repeated foot traffic of farmers engaged in continuous tea harvesting activities. The lack of cover crops in various areas likely exacerbates soil compaction.

The rise in bulk density due to intensive cultivation practices was accompanied by a decrease in soil porosity. Pedon P1, exhibiting the highest bulk density, demonstrated reduced porosity in comparison to other soil profiles with lower bulk density. Soil organic carbon content also influenced both properties. Fukumasu et al. (2022) found that the content of organic matter has a significant impact on soil porosity. The present study demonstrated this relationship, with P1 exhibiting the lowest soil organic carbon in the surface layer at 3.43%, in contrast to the other three profiles, which ranged from 5.72% to 6.99%. Moreover, a significant reduction in organic carbon content was observed in intensively cultivated tea soils compared to natural conditions. Volcanic soils in forested or uncultivated areas exhibited 11.89% organic carbon in the surface layer (Muslim et al., 2025). The organic carbon content was lower than that of the forest soil; however, the organic matter content of these Andisols remained elevated. This resulted from the ongoing deposition of litter from pruning residues, which accumulate in the topsoil.

The high organic matter content in volcanic soils is primarily due to the stabilization of organic compounds by Al/Fe oxides and non-crystalline minerals, which are typical of these soils Beckstrom et al. (2025). Soil organic matter originating from shade plants and tea plant pruning offers numerous advantages in improving physical, chemical and biological properties of soil. The prior research indicated that organic matter derived from plants contributes to the availability of nitrogen, phosphorus, and exchangeable potassium and magnesium, while also enhancing CEC in the soil.

Table 7. Altitude, slope, topography, vegetation, and soil profile position.

Soil Profile	Altitude (m asl)	Slope class (%)	Topography	Vegetation	Coordinate	
					Latitude	Longitude
P-1	1430	3-8	Undulating	Healthy tea plants	-6.69904	106.99600
P-2	1434	8-15	Rolling	Rejuvenation tea plants	-6.69945	106.99600
P-3	1445	8-15	Rolling	Unhealthy tea plants	-6.69964	106.99600
P-4	1496	30-40	Hilly	Healthy tea plants	-6.69987	106.99600

Moreover, in Andisols, a significant correlation exists between soil organic carbon derived from soil organic matter, and available P, soil dry bulk density, and the microbial community. A correlation exists between available P and microbial community with CEC (Wulanningtyas et al., 2021).

Evidence of a decline in soil physical quality was observed through surface erosion, resulting from uniform vegetation cover and partially exposed areas utilized as footpaths. These conditions reduce soil protection from rainfall impact and runoff, consequently increasing topsoil loss. This process may result in the depletion of fine particles and organic matter, thereby reducing soil fertility and structural stability. The observed erosion is primarily sheet erosion, resulting in the transport of topsoil to lower or concave areas, which subsequently leads to deposition processes. Elevated precipitation and diverse landforms, ranging from undulating to hilly terrain, facilitate these geomorphic processes. Erosion can be assessed by examining the thickness of the topsoil layer, known as the epipedon. The epipedon thickness for profiles P1, P2, P3, and P4, based on morphological data (Table 2), is 18 cm, 14 cm, 18 cm, and 16 cm, respectively. The P1 soil profile in the topo sequence is situated at a lower elevation compared to the other profiles. The results indicate that profile P2 exhibits the thinnest epipedon relative to the other three profiles. This condition is likely a consequence of land use in the P2 profile, characterized by tea plants that have been pruned and replanted in response to pest and disease pressures. As a result, the land surface exhibits greater exposure relative to the other three profiles, which feature denser tea vegetation. The findings suggest that elevation and slope have minimal impact on erosion levels in the study area; instead, erosion is primarily influenced by the presence or absence of vegetative cover.

The intensive utilization of tea plantations impacts the chemical properties of the soil. A comparison of various soil chemical properties from prior studies near our research site indicates a notable increase in soil acidity, alongside reductions in organic carbon, CEC, and total nitrogen over a span of 36 years. Simultaneously, base saturation exhibits an upward trend while still adhering to the very low criteria (less than <20%).

The extensive use of nitrogen fertilizers leads to heightened soil acidity. Farmers intentionally sustain this acidity level without lime addition, as tea plants thrive best at a pH of 4.5–5.5 (Ritung et al., 2011). Maintaining soil acidity within this range can enhance production in tea cultivation. This condition contrasts with agricultural land utilized for horticulture, where farmers apply lime intensively, in soil pH beyond its natural level. Anindita et al. (2022) found that horticultural farmland on volcanic soils exhibited higher pH values than uncultivated forest soils.

The content of soil carbon and the clay fraction significantly affect soil CEC. Soils exhibiting elevated CEC demonstrate reduced vulnerability to nutrient depletion. Profile P1 demonstrates a greater clay content relative to other profiles, which aligned with its elevated CEC. Conversely, pedons P2 and P4 exhibited very low organic carbon contents, especially in the surface horizon, with values ranging from 1% to 2% (Table 4a), attributed to the leaching

of clay into the subsoil. The downward movement of clay indicates a decline in soil performance due to prolonged intensive land use.

Soil minerals were analyzed to assess weathering intensity, focusing on the quantity of easily weatherable minerals alongside physical and chemical properties. The presence of easily weathered minerals suggests potential nutrient reserves in volcanic soil accessible to plants. Yatno et al. (2021) observed that Andisols in Lembang District, West Java, exhibit both high porosity and substantial nutrient reserves attributed to the presence of fresh magnetite iron minerals. This is advantageous for the growth and development of root plants. The study area, despite intensive management for tea cultivation, exhibits a high nutrient reserve due to its significant content of easily weathered minerals. The presence of easily weathered minerals indicates the potential for nutrient reserves in volcanic soils accessible to plants.

This study identifies- easily weathered minerals found in volcanic soils, specifically the pyroxene group (augite and hypersthene) and feldspar (andesine, labradorite, biotite, sanidine). Augite ((Ca,Na)(Mg,Al,Fe)(Si,Al)₂O₆) was present in all profiles, exhibiting the highest concentration in profiles P3 and P4. Augite is classified within the ferromagnesium mineral group, serving as a principal reservoir for Fe and Mg (Churchman & Lowe, 2012). Furthermore, augite serves as source of additional nutrients, including calcium and sodium. In addition to augite, hypersthene ((Mg,Fe²⁺)SiO₃) serves as a significant nutrient reserve for Fe and Mg (Huang & Wang, 2005). Hypersthene, similar to augite, is present in all profiles, with the highest abundance observed in profiles P3 and P4. Research conducted by (Muslim et al., 2024) indicates that volcanic soil on Mount Gede-Pangrango in West Java is dominated by augite and hypersthene. With high levels of augite and hypersthene, P3 has the highest primarily composed of augite and hypersthene. P3 exhibits elevated levels of aufite and hypersthebe, resulting in the highest exchangeable Ca and Mg content. In contrast, although profile P4 possesses substantial Mg nutrient reserves, it exhibits the lowest exchangeable Mg Contents (Figure 5). The incorporation of organic matter facilitates weathering processes, leading to the release of available nutrients into the soil solution.

Volcanic soils are notably characterized by their elevated P retention in comparison to other soil types. Nutrient inputs during cultivation can modify this characteristic. In general, the phosphorus retention value exceeds 90% across all soil profile and sample composites. However, at P3 at the depths greater than 48 cm, the P retention values are 78%, 79 % and 87 %. The retention of P exhibits a positively correlation with Al_o, supported by a 78% confidence interval (Wibisono et al., 2016). This supports the findings of Prasetyo et al. (2009), which indicate that elevated levels of Al_o, Si_o, and Fe_o are associated with increased P retention in Andisols. High P retention, as indicated in Table 4b, is a primary issue in Andisols. Several measures can be implemented to enhance P availability in these soils. Significant quantities of fresh soil organic carbon enhance and sustain biological activity while facilitating organic P mineralization, thereby increasing P

availability in Andisols (Takeda et al., 2009). The application fresh organic fertilizer is an effective method for enhancing phosphorus availability for plants. The research indicates that NPK fertilization may serve effective management strategy for enhancing soil organic carbon sequestration through increased microbial carbon use efficiency in Andosols. Additionally, improved, soil Carbon and Phosphorus availability mitigated microbial P limitation (Lyu et al., 2025).

Based on the observed physical and chemical properties, we classified the soils using Soil Taxonomy to enhance the interpretation of soil characteristics and enable comparison among profiles. According to Soil Taxonomy, all soil profiles were classified as Andisols (Hapludands). The chemical analysis, indicated that all profiles demonstrated andic properties surpassing 60% within 60 cm from the surface. The criteria for andic properties comprise included P retention exceeding >85% and $Al_0 + \frac{1}{2}Fe_0 > 2\%$ (Soil Survey Staff, 2022). Furthermore, bulk density below $< 1 \text{ g cm}^{-3}$ and NaF pH exceeding >10 across all profiles suggest the predominant features of Andisols, which are linked to non-crystalline minerals. Profiles P1, P2, and P3 were classified into the subgroup Acrudoxic, into the subgroup Alic Hapludands, as they exhibited Al^{3+} saturation exceeding $> 2 \text{ cmol kg}^{-1}$ with a thickness greater than of $> 10 \text{ cm}$. Soil profile P4 was classified in the subgroup as Acrudoxic, indicating a indicates that the soil has very low effective CEC of less than $< 2 \text{ cmol kg}^{-1}$, The total amount of bases extracted from the fine soil fraction using NH_4OAc and Al^{3+} extracted with 1 N KCl of $< 2 \text{ cmol kg}^{-1}$.

Strategies to reduce erosion and avert soil degradation involve the planting of shade trees in open-field regions. Incorporating shade trees into tea cultivation provides multiple advantages. Shade trees that provide both protection and nitrogen fixation include *Crotalaria usaramoensis*, *C. anagregoides*, and *Tephrosia sp.* Once the plants exceed 1 meter in height, they should be pruned by 50 centimeters to prevent root interference with the tea plants. Shade trees undergo pruning every 4 to 6 months during the two rainy seasons, and with the resulting pruning utilize as mulch for the tea plants. This mulch serves to safeguard protect the soil against erosion. Relying solely on mulching is frequently inadequate; therefore, mulch derived from Guatemala grass, various grasses, and straw is essential. During the pruning of tea plants, the residual pruning are covering the plants. This offers multiple advantages, including shielding the soil from direct sunlight, reducing evaporation, thereby regulating surface temperatures, and mitigating erosion. Additionally, the residual pruning decompose serving, as a source of organic matter and nutrients in the soil (Effendi et al., 2010). In addition, research conducted by Le et al. (2023) indicated that agroecological management practices, such as the use of organic manure, organic

mulching, and integrated pest and disease management, led higher net income for tea farmers in comparison to conventional management practices. The application of mulch derived from pruning residues is crucial, particularly in P2, which has the highest erosion levels and is characterized by the thinnest epipedon layer.

The preceding discussion reveals that all profiles exhibit deep soil layers, low base saturation values, elevated acidity levels, and high organic carbon content in the topsoil, with lower levels in the subsoil, aligning with the observed soil depth and low carbon-to-nitrogen ratio. Profiles P1 and P4 exhibit robust, tea plant vigor and possess deep root systems. P4 demonstrated a lower bulk density and greater porosity compared to P1. Nonetheless, P1 exhibited a greater proportion of available water. Both profiles demonstrate acidic soil pH and low base saturation levels. Site P1 exhibits a clay loam texture, leading to a greater CEC compared to P4. P4 exhibits a sandy loam texture and possesses elevated levels of organic carbon and nitrogen compared to P1. Each site has unique attributes that facilitate optimal tea growth.

In profile P2, characterized by enhanced plant vigor, the observed physical properties include low bulk density and high porosity. The organic carbon value is low, characterized by minimal organic matter content, and the upper solum is the thinnest relative to the other three profiles. The pruned tea canopy enhances soil surface exposure. This influences the decomposition of organic matter and enhances the weathering of minerals in the vicinity of profile P2. These conditions are also assessed as a nutrient source for tea plants, as indicated by the high and diverse mineral content. Profile P3 demonstrates poor tea plant vigor, exhibiting conditions that closely resemble those of the other three profiles. The findings suggest that the soil properties at the study site continue to facilitate tea plant growth, health conditions of the plants. The soil characterized that underpin our findings indicates substantial mineral nutrient reserves with variability and a low C/N ratio.

The findings demonstrate deterioration in soil quality in tea plantations adjacent to the study area, likely attributable to land management practices that overlooking the intrinsic soil and site-specific attributes. Haffif (2020), identifies topsoil thinning due to erosion as an indicator of plantation degradation, at the site. A deterioration of soil chemical properties has been observed, notably reduction in organic matter content, which subsequently affects other chemical attributes. Soil functionality remains adequate, bolstered by significant nutrient reserves in primary minerals. Land management strategies that account for the distinct characteristic of volcanic soils is crucial to mitigating degradation and ensuring sustained agricultural productivity over the long term.

Table 8. Pearson's correlation of soil properties and yield.

Soil Profile	Block Plantations	Solum (cm)	BS (%)	CEC (Cmol.kg ⁻¹)	C-org.		Yield ton/block	Pearson's correlation			
					(%)	N		BS	CEC	C-org.	N
Profile P1	C-12	0-18	3,8	32,39	3,43	0,27	990,46	-0,056	0,091	0,256	0,227
Profile P2	C-10	0-14	12,00	22,18	5,72	0,84	384,17				
Profile P3	C-9	0-18	13,00	25,00	6,69	1,16	1241,68				
Profile P4	C-4	0-16	11,00	19,41	6,99	0,98	1181,43				

4.1. Relationship Topsoil Characteristics with Tea Plant Productivity

The Pearson coefficient correlation between base saturation and yield is -0.056 (Table 8), suggesting an extremely weak and practically negligible association. A value near zero indicates that variation in base saturation does not significantly affect tea production. The CEC shows a correlation of 0.091 (Table 8), indicating a very weak association. This indicates that the soil's capacity for cation retention and exchange is not a key factor influencing yield variation in the study area: rather, external factors such as microclimate, plant age, pruning intensity, or field management are likely to be more significant in determining productivity.

Soil organic carbon and nitrogen exhibit higher correlations with yield, recorded at 0.256 and 0.227 , respectively. These values indicate weak relationships; however, they suggest a modest correlation between higher organic matter and nitrogen levels and increased production. This pattern corresponds with the functional roles of organic matter in enhancing soil structure, water retention, and nutrient availability, alongside the significance of nitrogen in promoting shoot growth in tea plants. Despite the low correlations, the impact of these soil properties on yield is minimal, indicating that productivity is primarily determined by agronomic practices and environmental conditions rather than the chemical soil characteristics assessed in this study.

4.2. Limitations of Research and Plant Vigor

This research focuses exclusively on the physiological analysis of plant tissue. We sought to acquire soil properties and establish correlation with plant vigor. This study examined soil characteristics across various layers of a selected soil profile, correlating them with the vigor of tea plants and their respective locations. The vigor of the tea plant in this study was assessed based on the physiological characteristic of the leaves at the apex, specifically their color and physical shape. Healthy tea plants exhibit leaves that range from light to dark green, characterized by a symmetrical, smooth, and uniform shape, devoid of any damage. Tea plants exhibiting poor health display a combination of dark and light green leaves, accompanied by yellowish and brownish patches resulting from pest and disease infestations, as well as wavy or curled leaf structures. Rejuvenated tea plants, resulting from pruning or rejuvenation, exhibit a light green coloration with predominantly bud-shaped leaves.

5. CONCLUSION

Cultivation of tea on Andosols has resulted in notable chemical degradation, characterized by acidification, depletion of organic matter, diminished CEC, and a decline in of andic properties. No significant relationship was found between the health of tea plants and soil fertility properties. Consequently, it is posited that the health of tea plants at the study site is predominantly affected by external factors, including crop management practices and elevator temperatures linked to diminished canopy cover. This requires confirmation through future research involving tea

plant tissue analysis. The observed changes indicate advanced weathering and diminished soil resilience in monoculture systems. Restorative management practices, including the addition of organic matter and balanced fertilization, are essential or preserving soil quality and ensuring sustained tea productivity.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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