Jurnal Ilmiah Pertanian

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Soil morphological characteristics in the active volcanic toposequence zone at Tangkuban Parahu Volcano, Indonesia

Karakteristik morfologi tanah di zona toposekuen vulkanik aktif di Gunung Tangkuban Parahu, Indonesia

Dani Lukman Hakim[1]*, Bjoern Machalett[2], Riyanto Adji[1], Rachmi Satwhikawara[1], Syamsu Alam[3]

[1]Department of Agribusiness, Faculty of Business, President University, Bekasi 17530, Indonesia
[2]Department of Landscape Architecture, Faculty of Landscape Architecture, Horticulture and Forestry, Erfurt University of Applied Sciences, Erfurt 99085, Germany
[3]Department of Soil Science, Faculty of Agriculture, Halu Oleo University, Kendari 93232, Indonesia

ARTICLE INFO

Article History
Received: Jun 14, 2024
Accepted: Jul 23, 2024
Available Online: Jul 28, 2024

Keywords:
volcanic soil formation,
morphological characteristics,
soil profile analysis,
Ratu crater topography,
agricultural soil management

Cite this:
J. Ilm. Pertan., 2024, 21 (2) 103-116
DOI:
https://doi.org/10.31849/jip.v21i2.20956

**Corresponding author*
E-mail: dani.lukman@president.ac.id

ABSTRACT
Soil formation in volcanic terrains presents a significant challenge due to the diverse physical and chemical properties imparted by volcanic activity, which are not yet fully understood. This study investigates the unique morphological characteristics of soil profiles within crater topography sequences at the Tangkuban Parahu Volcano, Indonesia. To address this gap, five representative sample profiles (I, II, III, IV, V) were analyzed. The Ratu Crater pathway topography was characterized by steep to very steep slopes. Detailed analysis identified three predominant soil layers, each with distinct features such as color, texture, porosity, and chemical composition, reflecting different stages of soil formation. At the highest elevation near the crater rim, Profile V was composed mainly of volcanic ash, with a loose structure, high porosity, and acidic pH, indicative of recent volcanic deposits. Profile III, at intermediate elevations, consisted of highly weathered soil with sandy loam textures and clear layer demarcations, suggesting prolonged soil development and consolidation. Profile I, at the lowest elevation, featured loamy sand with significant weathering and organic matter incorporation, indicating advanced soil development stages. The findings underscore the impact of volcanic activity on soil morphology, revealing distinct layers that correlate with various ages and developmental stages. Understanding these processes can inform agricultural practices.

ABSTRAK
Pembentukan tanah di daerah vulkanik menghadapi tantangan signifikan karena sifat fisik dan kimia yang beragam yang ditimbulkan oleh aktivitas vulkanik, yang belum sepenuhnya dipahami. Penelitian ini menyelidiki karakteristik morfologi unik dari profil tanah dalam urutan topografi kawah di Gunung Tangkuban Parahu, Indonesia. Untuk mengatasi permasalahan ini, lima profil sampel representatif (I, II, III, IV, V) dianalisis. Topografi jalur Kawah Ratu ditandai dengan kemiringan curam hingga sangat curam. Analisis mendetail mengidentifikasi tiga lapisan tanah utama, masing-masing dengan karakteristik unik seperti warna, tekstur, porositas, dan komposisi kimia, mencerminkan berbagai tahap pembentukan tanah. Pada topografi kawah paling atas dekat tepi kawah, komposisi Profil V terdiri dari abu vulkanik, dengan struktur yang lepas, porositas tinggi, dan pH yang masam, menunjukkan deposit vulkanik yang baru. Profil III, di ketinggian menengah, terdiri dari tanah yang sangat terkikis dengan tekstur lempung pasir dan demarkasi lapisan yang jelas, menunjukkan perkembangan dan konsolidasi tanah yang berkepanjangan. Profil I, di kawah terendah, memiliki pasir lempung dengan pelapukan signifikan dan akumulasi bahan organik, menunjukkan tahap perkembangan tanah yang lebih lanjut. Temuan ini menekankan dampak aktivitas vulkanik pada morfologi tanah, mengungkapkan horison tanah berkorelasi dengan berbagai usia dan tingkat perkembangan yang berbeda. Memahami proses-proses ini dapat memberikan informasi penting untuk praktik pertanian.

e-ISSN: 2502-5988
p-ISSN: 1829-8346

INTRODUCTION

Tangkuban Parahu, situated in West Java approximately 20 kilometers north of Bandung, is recognized as one of Indonesia's active volcanoes, with an elevation of 2,084 meters above sea level. Tangkuban Parahu is a volcanic structure located on the eastern perimeter of the Sunda caldera, displaying features consistent with a post-caldera formation (Hakim et al., 2020). During volcanic eruptions, the predominant types of rocks ejected are lava and sulfur, whereas, during periods of volcanic inactivity, the released minerals consist largely of sulfur vapor. The topographical features of the volcano exhibit a shield-like stratovolcano structure, and it is attributed to the Quaternary Volcano Zone, impacting the geomorphology of northern Bandung (Nurhasan et al., 2023; Angkasa et al., 2019; Barkah & Daud, 2021).

The region surrounding Tangkuban Parahu volcano is characterized by its fertility and serves as a prominent horticultural center, benefiting from the nutrient-rich soil resulting from volcanic eruptions. The presence of minerals in this environment facilitates a diverse range of flora, creating optimal conditions for cultivating agricultural produce, fruits, and ornamental plants. The correlation between volcanic activity and agricultural productivity showcases a symbiotic relationship, which contributes to the enhancement of regional biodiversity and economic growth.

The geological structure of the region has been investigated through a range of methods, including gravity, magnetotelluric, and seismic analysis, to comprehensively comprehend the subsurface characteristics and geothermal prospects (Nurhasan et al., 2023; Angkasa et al., 2019; Barkah & Daud, 2021). Several research studies have been undertaken on the Tangkuban Parahu volcano, focusing primarily on the geological conditions of the volcano and the soil genesis occurring in the surrounding external environment. However, a gap remains in understanding the mineral development within the confines of the crater, particularly in relation to agricultural productivity (Hakim et al., 2020).

The Tangkuban Parahu volcano has twelve craters, with the Ratu Crater being the largest. Research specifically focused on the Ratu Crater is scarce; however, examinations of geological formations, impact craters, and volcanic phenomena in disparate locales offer valuable perspectives and approaches that can be utilized to augment comprehension of the Ratu Crater within the broader framework of the Tangkuban Parahu volcano. A study on the geological configuration of the Ratu Crater has employed gravity surveys to characterize geological formations and ascertain the geothermal gradient and Bouguer anomaly (Nurhasan et al., 2023). The study examines the stratification and composition of soil layers, identifying key factors such as volcanic activity, ash deposition, and weathering processes that contribute to the unique soil profiles observed in the active volcanic toposequence zone.

The significance of volcanic craters lies in their crucial role in elucidating the mechanisms of volcanic activity and the resulting morphological alterations. The genesis of volcanic summit craters has been ascribed to various processes, including roof collapse into depressurized magma chambers or explosive excavation, highlighting the wide array of mechanisms involved in crater formation (Hanagan et al., 2020). The topographic sequences of a volcano crater are crucial for comprehending the dynamic processes and morphological transitions linked to volcanic activity. Numerical simulations have been employed to examine the influence of topography on the propagation and channelization of dense pyroclastic density currents, emphasizing the role of crater topography in shaping volcanic processes (Aravena & Roche, 2022).

The discipline of soil morphology involves examining and analyzing the physical attributes and configurations of soil profiles, encompassing the organization and attributes of soil horizons. The process includes the systematic examination and analysis of soil profiles to identify diagnostic horizons and classify soils according to their morphological characteristics (Mansyur et al., 2019). The composition of parental materials, influenced by topographical features, can impact soil microbial communities by affecting soil pH and nutrient availability (He et al., 2024). Additionally, the taxonomy system categorizes soils based on their morphological and physical characteristics, emphasizing the importance of soil morphology in the classification of soils. The physical, chemical, and biological characteristics of soil are intrinsically connected to its morphology, consequently influencing the mineral composition of forage (Guerra et al., 2019). Furthermore, the categorization of soil crusts based on their morphology has been postulated as a method of classification, underscoring the significance of morphological attributes in comprehending distinct soil varieties.

The gap in current research is the lack of a comprehensive understanding of the mineral development and soil formation processes within the crater, particularly the Ratu Crater, and how these processes impact agricultural productivity. This study aims to fill this gap by examining the stratification and composition of soil layers within the crater topography sequences at Tangkuban Parahu volcano, identifying key factors such as volcanic activity, ash deposition, and weathering processes that contribute to the unique soil profiles observed in the active volcanic toposequence zone.

MATERIALS & METHODS

This study consists of 3 main stages i.e. fieldwork, laboratory analysis, and desk work, and generally, the research scheme follows this workflow.

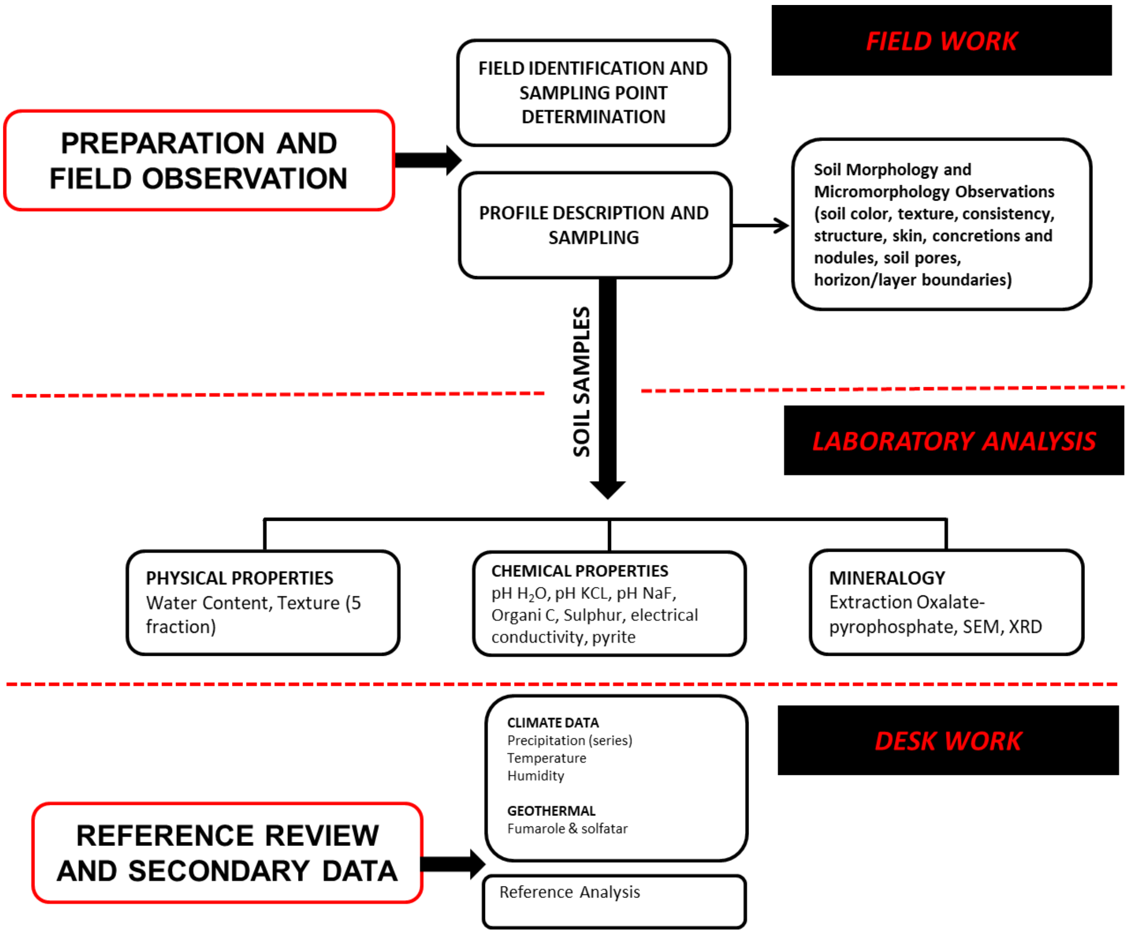


Figure 1. Scheme of research

Site setting

The present study involves an examination of a succession of volcanic ash deposits within the topographic sequences of Ratu Crater (Hakim et al., 2020). The transect traversed a wide environmental gradient, exhibiting variations in slope elevation. The process of relief measurement utilizing a clinometer entails the determination of the vertical angle formed between the observer, the designated target point, and the horizontal plane to calculate the disparity in elevation. By employing a clinometer to sight the target point and garnering the indicated angle, in conjunction with determining the horizontal distance to the point, the accurate calculation of relief is enabled through the application of trigonometric principles.

Sampling methods

Five sample profiles (I, II, III, IV, V) were selected as representatives based on the topographic sequences of the Ratu Crater pathway on Tangkuban Parahu volcano were characterized by a steep to very steep slope grades (Hakim et al., 2020). The focus of the observation and discussion is limited to the data obtained from these five specific profiles, representing different topographical features including toe, back, and summit. Analyses were conducted on samples taken from all profiles to assess their physical and morphological properties. Soil samples are collected using a soil auger and coring device to reach the desired depths, typically ranging from the surface to several feet below ground level. The samples are taken at multiple depths (e.g., 0-10 cm, 10-20 cm, and so on) to capture the vertical variability in soil properties. The samples predominantly consisted of volcanic ash parent material, originating from the eruption of the Tangkuban Parahu Volcano.

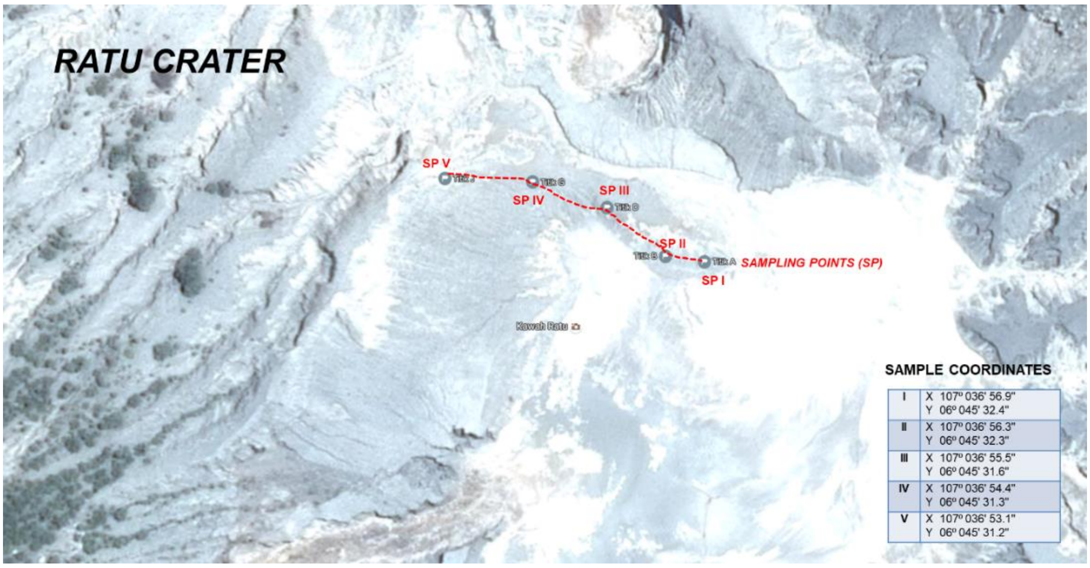


Figure 2. Sample distribution of Ratu Crater topography sequences (Hakim et al., 2020)

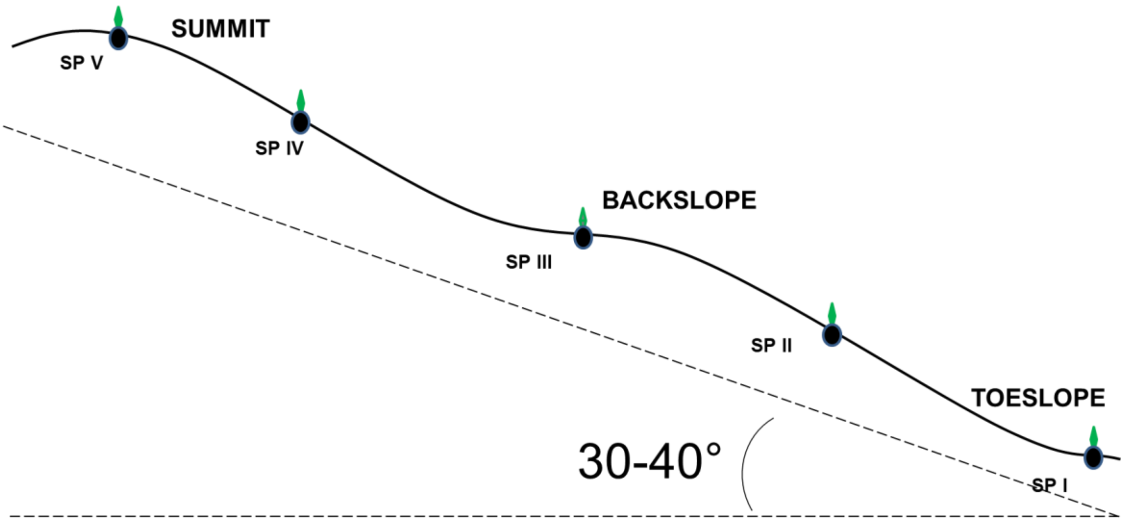


Figure 3. Cross-section illustration of sample points

Physical and morphological soil analysis

Dry water content

The method used for determining soil water content is the oven-drying method, whereby a soil sample is weighed, dried in an oven at a specific temperature (usually 105°C), and subsequently re-weighed to ascertain the moisture content. This approach offers a dependable means of quantifying the absolute dry water content by eliminating all moisture from the soil specimen (Liu et al., 2012).

Soil fraction

The soil fraction analysis employed the sequential extraction method, enabling the partitioning of elements in soil into distinct operationally defined fractions such as acid-extractable/exchangeable, reducible, oxidizable, and residual fractions. The samples underwent the process of air-drying and crushing to pass through a 2-mm sieve. The fractions of coarse sand (2. 0–02 mm), fine sand (0. 20–002 mm), silt (0. 020–0002 mm), and clay (0. 002 mm) were isolated through the use of a pipette and sieving techniques, following pretreatment with H_2O_2 to oxidize organic matter and dispersion facilitated by sodium hexametaphosphate (Hakim et al., 2020). This approach offers valuable perspectives on the dispersion and availability of elements within the soil, thus enhancing a thorough comprehension of soil structure and potential ecological ramifications. The current study examines the sequential extraction procedure for determining the distribution of silt and clay soil particles. A new quick method for separating silt and clay, which has proven to be reliable in analyzing the particle distribution in the silt-clay fraction with high accuracy, was employed (Ibrahim et al., 2023).

Soil color

The procedure for soil color observation utilizing the Munsell system involves the visual comparison of a soil sample to the color chips present in the Munsell soil color chart. The Munsell Soil Color Charts provide a range of color tiles that can be matched to the soil sample, facilitating accurate color determination (Hill et al , 2023). The Munsell Color Chart is generally acknowledged as the principal technique utilized for ascertaining soil color (Stiglitz et al., 2016). This methodology includes the assessment of soil color through the consideration of three primary attributes: hue, value, and chroma. The term "hue" pertains to the principal spectral color observed in the soil sample, encompassing hues of red, yellow, or brown. The value denotes the degree of lightness or darkness within a given color, wherein higher values correspond to lighter shades and lower values correspond to darker hues. The term "Chroma" denotes the level of intensity or saturation of a color, with elevated numerical values indicating the presence of more vibrant and vivid colors (Hakim et al., 2020). The implementation of a standardized approach for soil color descriptions serves to maintain uniformity across various studies and locations. This standardization facilitates improved comparison and interpretation of soil data within the fields of soil science and geology (Stiglitz et al., 2017). Additionally, the Munsell soil color chart provides a methodical approach for categorizing soil colors, facilitating researchers in accurately elucidating soil properties and categorizing soil types based on their color attributes (Stiglitz et al., 2017). The utilization of this method is essential for the documentation of soil characteristics in fieldwork and holds significant value in the development of predictive models for soil properties, including soil organic carbon content and soil moisture levels, by utilizing soil color as a key indicator (Stiglitz et al., 2017).

Soil structure

The observation of soil structure is an essential aspect of soil analysis and characterization, offering valuable insights into the organization of soil particles and aggregates. A variety of methods are employed for the assessment of soil structure, including visual inspections and advanced imaging technologies. Visual soil evaluation techniques, such as spade methods, provide an expedited assessment of soil structure characteristics with an emphasis on anthropogenic features. These methods serve to offer a cursory understanding of soil structure across extensive areas (Emmet-Booth et al., 2016).

Soil profile and genetic horizon

The process of soil layer and genetic horizon observation involves the systematic documentation of the various layers present within a soil profile, along with the identification and description of genetic horizons based on predetermined criteria. The procedure outlined by the Soil Survey Staff and the Food and Agriculture Organization (FAO) is aimed at standardizing the methodology for observing and describing soil layers and genetic horizons (Naumova et al., 2021). Furthermore, alongside visual observations, specialized tools and techniques can be employed to augment the precision and accuracy of soil layer and genetic horizon observations. Chemical fractionation techniques, such as the Tessier method, have been utilized to assess the elemental composition and mobility within distinct genetic horizons of forest soils (Jeske & Gworek, 2013). These analytical techniques offer valuable data on the distribution of elements across soil layers, contributing to a comprehensive understanding of soil properties.

RESULTS & DISCUSSIONS

Soil fraction

The texture analysis indicated that the sand and silt fractions are predominant in nearly all of the representative profiles. The concentration of the clay fraction is minimal. Certain profiles exhibit a clay content of less than 5%. Understanding the soil under discussion proves challenging due to the paramount influence of allophane, a mineral present in the clay fraction, on its properties. Consequently, it is arduous to envision how the soil would behave if the clay fraction were to account for less than 5% of its composition. The low clay content observed is consistent with field findings from the profile description, which indicated a texture category falling within the silt and sand fraction. The formation of pseudo-sand is attributed to the cohesive forces within the clay fraction, leading to an inaccurate representation of the soil particle size distribution.

The findings of the texture analysis may not precisely correspond to real conditions. Nevertheless, it was observed that the predominant fractions at the site were sand and silt, leading to the classification of the textures ranging from loam to sandy loam (Hakim et al., 2020). The distribution of soil fractions within each profile exhibited a consistent pattern with the sand fraction dominating, followed by the silt fraction, and finally the clay fraction. Additionally, the clay composition within each profile displayed a hierarchical sequence with the highest proportion recorded in Profile V, followed by Profiles III, I, II, and IV in decreasing order (Profile V>III>I>II>IV).

Table 1. Soil texture analysis on each sample profile

Profile	Sand	Silt (%)	Clay	Total Fraction
I	61.62	32.01	6.37	*sandy loam*
II	60.44	35.80	3.76	*sandy loam*
III	73.49	20.09	6.42	*loamy sand*
IV	81.54	15.09	3.37	*loamy sand*
V	42.96	45.10	11.94	*loam*

Source: Hakim et al., 2020.

Several research studies conducted on soils derived from volcanic ash have demonstrated that the dispersion of soil particles in these types of soils poses significant challenges. This difficulty in dispersion is a critical factor that affects the accuracy of determining particle distribution in volcanic ash-derived soils. According to Ken-ichi Maeda (1977), the limitations on the accuracy of texture analysis result from imperfect particle dispersion. The prevalence of non-crystalline (short-range order) minerals in volcanic ash soil is responsible for the frequently inconsistent composition of sand, silt, and clay. The principal factor contributing to the non-utilization of grain size classes in the classification of Andosols, which dominated by short-range order minerals (Hakim et al., 2020). Allophane, imogolite, and ferrihydrite are known for their strong and stable complexation abilities with various elements like boron and phosphate, influencing the availability and retention of these nutrients in the soil (Fauziah et al., 2022).

Soil color

The color of the soil indicates specific soil conditions and is closely associated with the soil's physical, chemical, and biological properties. The soil color observed in horizon A (L1) varies across the studied profiles, ranging from dark gray to very dark gray "2.5 YR 4/1" in Profile I, dark grayish brown "2.5 Y 4/2" in Profile II and Profile III, brownish yellow "2.5 YR 4/3" in Profile IV, and light yellowish brown "2.5 Y 6/4" in Profile V. The presence of a dark color in the A (L1) horizon of this soil suggests a high organic matter content. The outcomes of the soil chemical analysis conducted on the five profiles indicate that the observed values are within the range of very low criteria, specifically falling between 0.33% and 0.95%.

The color of soil holds significance in soil science for two primary reasons. Firstly, soil color directly serves as a distinctive feature that aids in the identification of different soil types. Secondly, soil color indirectly offers insights into other soil properties that may be challenging to observe accurately in the field. Various properties are associated with the color of the soil. These include organic matter content, parent material, soil mineralogy, drainage, aeration, soil temperature, and other factors.

Soil color is a critical factor in soil science due to its association with various soil properties that are difficult to directly observe in the field. It is associated with various soil physical properties including texture, bulk density, and porosity, all of which play a crucial role in controlling processes such as water movement, biogeochemical cycling, and the composition of plant communities (Hakim, 2023). Table 2 showcases various relations between color and other properties. Several types of iron and Al compounds related to color are presented in Table 3.

Table 2. Relationship between soil color and other properties

Soil Color	Other Properties
White	$CaCO_3$, gypsum, salt, parent material derivatives
White grey	Quartz, kaolin, carbonate, gypsum, salt, ferrous iron
Light grey	Low iron and organic matter, sandy soil with high quartz
Bluish/greenish grey	Gleization, poor-very poor drainage, saturated water, ferrous iron
grey	Dominant water saturation, poor drainage, ferrous iron
light brown-brown-dark brown	Varying content of organic matter and iron oxide, poor drainage
Yellow	Iron oxide hydrate, Al-oxide, high relative humidity, slightly convex slope, good drainage, young physiography
Red	Anhydrous iron oxide, low relative humidity, good drainage and aeration, relatively convex slope, basic-ultra basic parent material, old physiography
Dark red	Ultrabasic parent material, anhydrous iron oxide (hematite and magnetite), good drainage and aeration, granular structure, very low fertility
Dark-black	High organic matter, Mn compounds, magnetite, charcoal, granular structure, relatively fertile

Source: Hakim et al., 2020

Table 3. General mineral analysis of various iron-oxide compounds and their colors

Iron Compounds (Minerals)	Chemical Formula	Color
Hematite	Fe_2O_3	Red
Limonite	$Fe_2O_3xH_2O$	Reddish brown
Ferrous oxide	FeO	Bluish grey
Al oxide	Al_2O_3	Yellow

Source: Hakim et al., 2020

The color of volcanic ash soils plays a crucial role in providing valuable insights into their composition and properties. Studies have shown that volcanic ash soils generally display darker colors in comparison to soils of other types. Research has indicated that soils formed from volcanic ash display darker hues, are characterized by a finer, more granular texture, and exhibit decreased stickiness and plasticity in comparison to soils derived from volcanic tuff (Yatno & Zauyah, 2016). Moreover, volcanic ash soils are characterized by a dark gray color, which presents a distinctive visual appearance. The color of volcanic ash soils is influenced by a multitude of factors, including the concentration of organic matter, mineral composition, and various weathering processes. The organic carbon content significantly influences their color and properties, contributing to their high soil carbon storage capacity (Kramer & Chadwick, 2016). The mineralogical composition of volcanic ash, including the presence of iron-bearing minerals, can influence the color of soils by affecting their chemical properties and interactions with organic matter (Pizarro et al., 2017).

Soil structure

The process of soil structure formation is intricate and is influenced by various factors. The incorporation of organic matter is essential for the formation of soil aggregates, playing a pivotal role in this process. The process of organic matter accumulation, mediated by plant roots, fungal hyphae, and biological processes, results in the development of soil aggregates (Jha et al., 2023). The formation and stability of soil aggregates are influenced by various factors, including the presence of cemented substances, clay minerals, iron-aluminum oxides, and organic matter in the soil texture (Zhang et al., 2024).

The soil profile within the crater exhibits a lack of distinct structure, attributed to the incomplete development of its parent volcanic ash material, obscured by a thin lava flow acting as an adhesive for the overlying rock fragments. The soil particles exhibit a lack of aggregation into structural units, characterized by either loose or single-grained configurations with individual particles separated, analogous to grains of sand, and massive or compact formations where particles are aggregated without regular separation areas. Therefore, the level of structural development is determined to be 0 (zero), indicating the absence of any discernible structure. The nascent structure depicted embodies the transformation from parent material (C) to soil (A-B).

The structural development is greatly influenced by the cohesive forces present within the aggregate as well as the adhesion between aggregates. There is a positive correlation between the strength of cohesive forces and the weakness of adhesion forces with the development of a stronger structure. the stability of soil aggregates is a critical factor in the preservation of soil structure. Zhang et al., (2019) discussed the influence of soil physical structure and soil organic matter on the stability of soil aggregates and the subsequent impact on the formation and maintenance of soil structure. Moreover, Aggregate formation is very important in forming the desired soil structure, which affects water infiltration and erosion resistance (Sun et al., 2020).

Furthermore, soil aggregation is influenced by a confluence of abiotic, environmental, and biotic factors. A variety of abiotic and biotic factors influence the soil structure. Abiotic factors, such as clay content, mineralogy, and soil pH, as well as environmental factors like wetting and drying events, and biotic factors including plant root growth and soil fauna, all contribute significantly to the shaping of soil structure (Kaur et al., 2022). Microorganisms play a significant role in the formation of soil structure, whereby various forms of organic matter and soil texture influence the structure of prokaryotic communities and early-stage soil development (Yao et al., 2023).

Soil profile

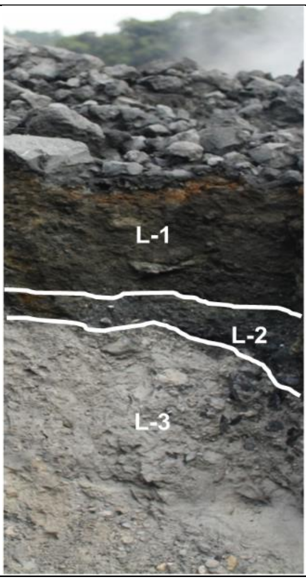
The process of soil profile formation entails the establishment of discernible strata or horizons within the soil, which is shaped by a multitude of factors. Meticulous morphological observations and classifications of soil horizons frequently delineate the soil profile formation process. Eremin & Renev, (2021), delineate the process of soil layer identification through the consideration of attributes including color, texture, structure, and composition. Furthermore, soil profile formation is influenced by several factors including soil type, land use, climate, and parent material. The presence of diverse microbial communities and functional structures in soil across varying depths indicates the significance of comprehending soil profile variations (Bai et al., 2017).

The characterization and classification of Andisols in the Kitakami mountain range, Northeastern Japan, emphasizing the expansion of the central concept of Andisols to include soils enriched with Al (Fe)-humus complexes. The presence of Al (Fe)-humus complexes contributes to the distinct properties of Andisols, influencing their development and soil horizon formation (McGrath et al., 2022). The formation of soil profiles in volcanic regions is a distinct process shaped by the properties of volcanic materials and the effects of volcanic eruptions. The main components of soil-forming Andisol are amorphous (short-range-order) minerals, such as allophane, imogolite, ferrihydrite, and Al/Fe-humus complexes (Fauziah et al., 2022).

Research has indicated that the deposition of volcanic ash results in decreased aggregate stability and limited soil infiltration due to hydrophobicity, thus presenting significant challenges for soil recovery in the aftermath of volcanic eruptions (Saputra et al., 2022). The formation of soil profiles on volcanic substrates is subject to the influence of various factors, including the composition of the volcanic materials, the type of volcanic eruption, and the duration of the volcanic event. These factors contribute to the creation of a wide range of soil characteristics and properties (Ahmad et al., 2020). The existence of volcanic hydrothermal alteration environments has been found to result in the development of distinctive soil types characterized by high cation exchange capacity (Iqbal et al., 2020.)

Cross-section and description of Profile I

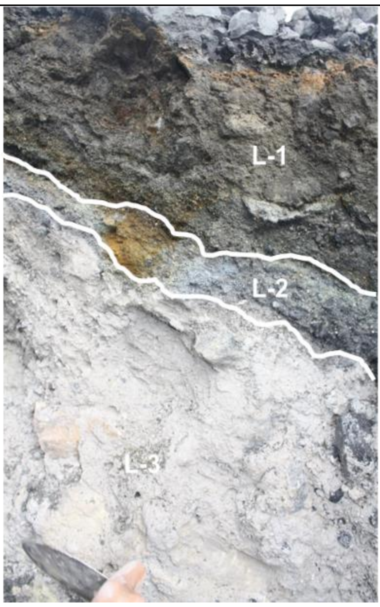
The first layer is characterized by a dark gray coloration and a sandy loam texture, exhibiting a loose structure with numerous macropores and limited presence of meso and micropores, accompanied by a diffuse boundaries layer and an absence of root systems, and possessing a pH level of 2.71. The second layer, which also exhibits a sandy loam composition, is distinguished by its dark gray coloration and displays a comparable structural makeup to the preceding layer. This includes an abundance of macropores and a scarcity of meso and micropores, with indistinct boundaries at the top and well-defined boundaries at the bottom, and is notably lacking in plant roots. The second layer exhibits a light gray loamy sand composition, characterized by a loose aggregation with numerous macro pores and limited meso and micropores. Additionally, this layer is distinguished by distinct upper boundaries and a lack of root penetration.



Depth (cm)	Layer	Description
0-34	L-1	very dark gray (2.5 Y 3/1), sandy loam, loose, many macropores, few meso and micropores, diffuse boundary layer, pH 2.71, no roots
34-46	L-2	dark gray (2.5 Y 4/1), sandy loam, loose, many macropores, few meso and micropores, diffuse layer boundaries at the upper boundary, and clear at the lower boundary, no roots
> 46	L-3	Light gray (2.5 Y 7/1) loamy sand, loose, many macropores, few meso and micropores, clear layer boundaries at the top boundary, no roots

Cross-section and description of Profile II

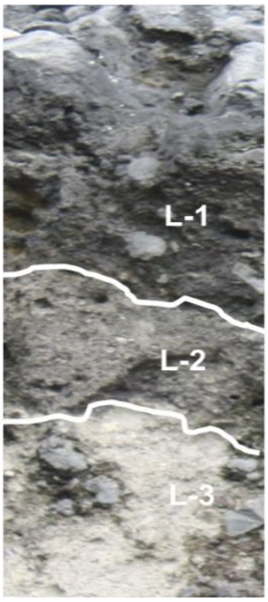
The first layer comprises a dark gray-brown sandy loam characterized by loose texture with abundant macro porosity, fewer meso and micropores, distinct boundaries, absence of roots, and a pH value of 3. 65. The second layer exhibits a slightly lighter hue, characterized as gray sandy loam, with a consistent texture featuring numerous macropores, limited meso and micropores, diffuse boundaries at the upper boundary, distinct boundaries at the lower boundary, and absence of vegetative roots. The third layer undergoes a transition to a loose, light gray loamy sand characterized by numerous macropores, few meso and micropores, distinct boundaries at its upper boundary, and an absence of root systems.



Depth (cm)	Layer	Description
0-21	L-1	dark gray-brown (2.5 Y 4/2), sandy loam, loose, many macropores, few meso and micropores, clear layer boundaries, pH 3.65, no roots
21-27	L-2	gray (2.5 Y 6/1), sandy loam, loose, many macropores, few meso and micropores, diffuse layer boundaries at the upper boundary, and clear at the lower boundary, no roots
> 27	L-3	light gray (5 Y 7/1) loamy sand, loose, many macropores, few meso and micropores, clear layer boundaries at the top boundary, no roots

Cross-section and description of Profile III

The top layer is characterized as being comprised of dark gray loamy sand that exhibits a loose granular structure featuring an abundance of macro pores and fewer meso and micropores. This layer also displays distinct boundaries, an absence of roots, and a measured pH of 3. 68 The second layer exhibits characteristics of a grayish-brown sandy loam composition, characterized by a loose texture and an abundance of macro pores, but limited meso and micropores. This layer is distinguished by diffuse boundaries at its upper extent and well-defined boundaries at its lower extent and is devoid of any visible roots. The third layer exhibits a transition to light gray loamy sand, retaining a loose texture characterized by numerous macro pores, a scarcity of meso and micropores, and distinct layer boundaries at the surface. Additionally, this layer is devoid of any root penetration.



Depth (cm)	Layer	Description
0-26	L-1	dark gray (2.5 Y 4/1), loamy sand, loose, many macropores, few meso and micropores, clear layer boundaries, pH 3.68, no roots
26-44	L-2	grayish brown (2.5 Y 5/2), sandy loam, loose, many macropores, few meso and micropores, diffuse layer boundaries at the upper boundary, and clear at the lower boundary, no roots
> 44	L-3	light gray (5 Y 7/1) loamy sand, loose, many macropores, few meso and micropores, clear layer boundaries at the top boundary, no roots

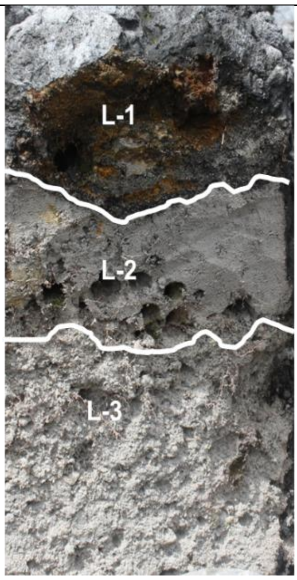
Cross-section and description of Profile IV

The first layer is delineated as brownish-yellow friable sand, distinguished by its loose consistency, ample macroscopic cavities, fewer mesoscopic and microscopic cavities, and well-defined perimeters. The solution exhibits a pH of 4. 80 and is devoid of any root structures. The second layer comprises light gray loamy sand, possessing a consistent loose texture characterized by an abundance of macro pores, a scarcity of meso and micropores, and distinct delineation at the upper boundary. Notably, no roots are present within this layer.

Depth (cm)	Layer	Description
0-38	L-1	Brownish-yellow (2.5 Y 4/3), loose sand, loose, many macro pores, few meso and micropores, clear layer boundaries, pH 4.80, no roots
> 38	L-3	light gray (5 Y 7/1) loamy sand, loose, many macropores, few meso and micropores, clear layer boundaries at the top boundary, no roots

Cross-section and description of profile V

The first layer exhibits a pale yellow-brown hue and is characterized by an open structure, abundant macroscopic voids, a lesser quantity of intermediate and small voids, distinct demarcations, and a pH value of 5. 51, and a moderate level of root penetration. The second layer, characterized by a gray sandy loam composition, displays a porous texture replete with macroscopic apertures while containing relatively few meso and micropores. This layer is distinguished by distinct demarcations at its upper extremity, and less defined boundaries at its lower limit, and exhibits minimal development of root networks. The third layer transitions to a light gray loamy sand, showcasing a relaxed framework characterized by an abundance of macro pores and a lower density of meso and micropores. The layer exhibits blended boundaries at its uppermost portion and is sparsely inhabited by roots.



Depth (cm)	Layer	Description
0-19	L-1	Light yellowish brown (2.5 Y 6/4), loose, loose, many macropores, few meso and micropores, clear layer boundaries, pH 5.51, medium rooting
19-36	L-2	gray (5 Y 6/1), sandy loam, loose, many macropores, few meso and micropores, clear layer boundaries at the upper boundary, and diffuse at the lower boundary, little rooting
> 36	L-3	light gray (5 Y 7/1) loamy sand, loose, many macro pores, few meso and micropores, mixed layer boundaries at the top, few roots

CONCLUSION

The comprehensive analysis conducted in this study identified three distinct soil layers, each exhibiting unique physical and chemical properties attributed to their respective formation mechanisms. The soil profiles demonstrate a clear gradient of soil development stages influenced by volcanic activity, ranging from loose, acidic volcanic ash at higher elevations to more weathered and organic matter-rich loamy sand at lower elevations. These findings highlight the significant impact of volcanic activity on soil morphology and enhance our understanding of environmental and ecological processes within volcanic landscapes. This study underscores the importance of recognizing and preserving the unique soil properties found in volcanic terrains, which have substantial implications for soil conservation, agricultural practices, and preservation initiatives in similar regions worldwide. The insights gained from this research contribute to our understanding of volcanic soil formation processes and emphasize the critical role these distinctive ecological systems play in guiding sustainable land-use practices. By comprehending the composition and characteristics of volcanic soils, farmers can develop more effective and sustainable agricultural strategies, such as selecting appropriate crops and implementing optimal soil management techniques, to enhance long-term soil productivity and health.

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