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Subsoil mineralogy as environmental factors in controlling topsoil material in the Menoreh-Sumbing volcanic structural transitional landscape, Central Java

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Abstract: Subsoil mineralogy significantly influences in shaping topsoil properties and affecting agricultural land management, particularly in volcanic-structural landscapes. This study examines the control of subsoil characteristics on topsoil development in the Menoreh–Sumbing transitional landscape. Light detection and ranging (LiDAR) and aerial imagery were used to analyse surface topography and agricultural land use patterns. Field surveys and laboratory tests assessed the physico-chemical properties of 294 topsoil samples, while scanning electron microscopy (SEM), scanning electron microscopy-energy dispersive X-ray analysis (SEM-EDX), and X-ray diffraction (XRD) analyses characterised the subsoil's mineral composition. Results indicate that >85% of the topsoil samples have clay textures, with structure types such as columnar and blocky, indicative of compaction and reduced water permeability. Most samples showed moderate to poor ratings in physical and chemical parameters, such as porosity, infiltration, and bulk density. Subsoil analysis revealed dominance of secondary weathering minerals, particularly kaolinite, and quartz, indicating advanced pedogenic processes under intense leaching. These mineralogical properties contribute to hard, compact, and dry surface conditions, as confirmed through farmer interviews. Farmer interviews verified these findings, with many reporting sticky, dry, and hard soil conditions that impede cultivation. Adaptive strategies ranged from manual hoeing and manure application to complex systems involving mechanical tools, chemical fertilisers, and organic amendments. This study highlights that subsoil in the study area actively influences topsoil development and land use practices. The findings emphasise the need for site-specific interventions that address subsoil constraints to enhance agricultural productivity and environmental sustainability.

Keywords: farmer adaptation strategies, land resource management, pedogenic processes, subsoil material, topsoil characteristic

INTRODUCTION

The Earth's endogenetic processes set the type of soil parent material, rate of weathering, and the geochemical environment in which subsoils form. Their influence is particularly evident in volcanic and tectonically active regions, where soils often show variable mineral content (Sashurin *et al.*, 2017; Zheng, 2019). In volcanic environments, soil formation is effectively explained by the five factors of soil formation conceptual model, originally proposed by (Jenny, 1941), which highlights the interactions among parent material, climate, topography, biological activity (organisms), and time. This framework is particularly applicable to volcanic settings, where young parent materials such as tephra, ash, and lava undergo rapid transformation due to intense weathering processes driven by high rainfall and steep topography. Additionally, the Soil-Landscape Model (Birkeland, 1984) underscores the influence of geomorphic processes on pedogenesis, particularly in dynamic volcanic terrains where soil development is closely linked to slope position, drainage conditions, and geomorphic age.

The endogenetic processes can alter the physical and chemical properties of subsoil, impacting its structure, composition, and functionality (Zhang *et al.*, 2023). Subsoil characteristics are a key factor in forming the physical and chemical properties of the topsoil. Key subsoil features such as texture, structure, organic matter content, and chemical composition can directly or indirectly influence topsoil structure, nutrient availability, water retention, and microbial activity (Richter and Markewitz, 1995; Brady and Weil, 2008). Various physical properties of topsoil, which are crucial for agricultural productivity, and environmental sustainability strongly affected by subsoil (Xia, Rufty and Shi, 2020). Through various mechanisms, the chemical composition of topsoil also significantly determines by subsoil (Cotrufo *et al.*, 2022).

Subsoil conditions often define the limits of agricultural productivity, especially in marginal or stressed environments. Compacted or chemically constrained subsoil, such as those with high acidity, or poor structure can limit root penetration and reduce crop performance (White and Kirkegaard, 2010; Bengough *et al.*, 2011; Sparks, Singh and Siebecker, 2022). Although less fertile than topsoil, subsoil can supply essential nutrients like potassium and calcium, especially for deep-rooting crops (Kautz, 2015).

Subsoil mineralogy, as a primary environmental factor, governs the availability of weatherable minerals and the structural characteristics of soil horizons. The transformation of volcanic ash into secondary clay minerals, often driven by endogenetic processes, leads to the development of fine-textured soils with distinctive chemical and physical limitations (Shen *et al.*, 2021; Zhao, Xu and Hao, 2023). These clay-rich subsoils typically exhibit high plasticity, low permeability, and acidity, which in turn influence root development, water dynamics, and nutrient cycling in the topsoil (Soong *et al.*, 2020; Fukumasu *et al.*, 2022).

Although the topsoil is commonly considered the most fertile layer due to higher organic matter content and microbial activity, its formation and functional capacity are not independent of subsoil conditions. Subsoil properties such as mineral composition significantly influence topsoil aggregation, nutrient retention, and crop productivity (Huang *et al.*, 2023; Zhang *et al.*, 2023).

This study objectives to investigate how subsoil mineralogical composition, influenced by regional geologic processes, regulates the physical and chemical properties of topsoil in the Menoreh–Sumbing volcanic structural transitional landscape. By integrating SEM-EDX and XRD mineral analyses with topsoil characterisation and farmer insights, we seek to provide a comprehensive understanding of soil formation processes and their implications for sustainable land management in a geomorphologically dynamic region.

MATERIALS AND METHODS

GEOLOGY-GEOMORPHOLOGICAL SETTING OF THE STUDY AREA

The research was conducted on a section of volcanic-structural transitional landscape, covering 8.15 km^2 of the boundaries of the Kodil Watershed, Central Java, Indonesia. The study area lies between coordinates −7.5839, 110.0590 and −7.5397, 110.0742. Administratively, the study sites are in Kalijambe Village (Purworejo Regency), Margoyoso Village, Wonogiri Village, and Kwaderan Village (Magelang Regency). The site is located along the foot slopes of the volcano and is characterised by a radial centrifugal drainage system, and forms part of a unified volcanic landscape. The key research location sits between the Quaternary-Neogene volcanic transition zone (Noviyanto, Sartohadi and Purwanto, 2020; Purwaningsih *et al.*, 2025). Based on international FAO-WRB, the soil type in the research location primarily corresponds to Acrisols, and Alisols (IUSS Working Group WRB, 2015). According to Indonesia geological maps (sheets 1407-5 and 1408-2) the region is underlain by the Bemmelen Formation (Tmok). The Bemmelen Formation is in the southern region of Java, specifically within a volcanic island arc formed by the subduction of tectonic plates. The southern zone is predominantly composed of ancient volcanic sedimentary deposits that have been subjected to multiple tectonic processes (Hall and Smyth, 2008). An analysis was conducted using spatial arrangement and superposition theory to understand how this geological setting influences surface parameters (Fig. 1).

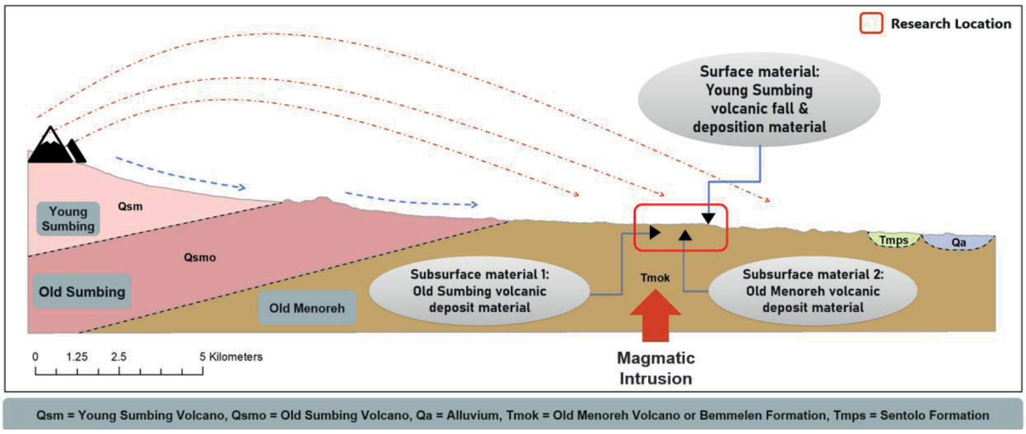


Fig. 1. Environmental cross-sectional profile of the research location illustrating the complexity of the Bemmelen Formation (Tmok) surface; source: Indonesia geological map (sheets 1407-5 and 1408-2), modified

The volcanic history of the Sumbing and Menoreh regions shows a stratigraphic sequence where younger Quaternary volcanic deposits from the Young Sumbing Volcano (Qsm) overlie older deposits from the Old Sumbing Volcano (Qsmo), which are more susceptible to weathering, erosion and landslide (Marfai *et al.*, 2008). These processes have produced colluvial and alluvial materials that influence slope stability and surface dynamics. The adjacent Old Menoreh Volcano or Bemmelen Formation (Tmok), from the Neogene period, are dominated by breccias and andesite formations. Tectonic uplift and deformation have shaped the morphology and geological structures, acting as both barriers and pathways for later volcanic flows. These interactions highlight a close relationship between volcanic activity, tectonic processes, and landscape evolution over time.

The Tmok complexity is formed by transported deposits of Qsmo material, overlaid by fallout deposits of Qsm, and further influenced by past magmatic intrusion processes through hydrogeothermal alteration. These stratigraphic and geomorphological interactions contribute to the spatial variability of soils and landscape morphology.

According to Bemmelen's theory, the study area is inferred to have undergone magmatic intrusion (Bemmelen van, 1949). This process initiated hydrothermal alteration in the Neogen breccia rocks, resulting in intensely weathered material rich in clay minerals. These altered materials, when saturated with water, exhibit low shear strength and high plasticity, making them particularly susceptible to erosion and landslide (Wida, Maas and Sartohadi, 2019). Erosion and landslide are dynamic processes that shape land surface morphology through the removal and redistribution of soil and rock materials (Geertsema, Highland and Vaugeouis, 2009). Their interactions create diverse landscapes.

Surface geomorphological processes and their interaction with cultivation practices were identified using light detection and ranging (LiDAR) data and high-resolution aerial imagery. A Digital Terrain Model (DTM) derived from LiDAR was analysed using the geomorphons classification tool, which automatically identifies landform types based on local terrain geometry (Jasiewicz and Stepinski, 2013). This method classifies each raster cell into one of ten standard landform elements: peak, ridge, shoulder, spur (lateral ridge), slope, hollow, foot slope, valley, depression, and flat. Each geomorphon category represents a specific geomorphic feature, enabling fine-scale landform delineation and comprehensive landscape interpretation. Agricultural cover interpretation was performed using supervised classification in ArcGIS Pro, employing the Maximum Likelihood classifier. These classification supports spatial analysis of the relationship between topography and land use, particularly in agricultural areas.

TOPSOIL PHYSICO-CHEMICAL PROPERTIES, AND SUBSOIL MINERALOGY

Topsoil samples in this study were obtained from both secondary sources and primary field collections. In total, 294 locations have soil texture data, with 89 samples have soil structure data, 159 have bulk density measurements, 117 have porosity data, 80 have permeability data, 41 have infiltration measurements, 146 have pH data, 180 have organic matter content, and 50 have C-organic data. Mineralogical analysis of subsoil (parent material) was conducted at four selected soil profile locations.

Several methods were applied to assess the physical and chemical properties of the soil in both the topsoil and subsoil mineral content. Soil texture was determined using the hydrometer method, while soil structure was assessed through direct visual observation of the soil profile to identify aggregate shape and size. Bulk density was measured by comparing the oven-dry weight of the soil to the volume of a known cylindrical sample. Porosity was calculated based on the ratio between bulk density and particle density. Permeability and infiltration rates were measured in the field using single-ring and double-ring infiltrometer methods.

Chemical properties, including soil pH, were measured in the field using a calibrated portable pH meter with a glass electrode probe inserted into a 1.0:2.5 soil-to-water suspension. Organic matter and C-organic content were quantified using the Walkley–Black wet oxidation method. To further examine mineral morphology and elemental composition, scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) were employed. Mineral composition was identified using X-ray diffraction (XRD) analysis. These techniques are particularly well-suited for analysing volcanic soils, which often undergo complex mineral transformations resulting from hydrothermal alteration, intense leaching, and rapid physical weathering. By integrating morphological, chemical, and crystallographic data, SEM-EDX and XRD analyses offer comprehensive mineralogical fingerprints that enhance environmental interpretation and inform practical land management strategies.

The classification of topsoil physicochemical parameters is used to evaluate soil quality and identify necessary improvements to support optimal agricultural productivity. Each parameter is grouped into five classes, ranging from very low (class 1) to very high (class 5). This classification system provides a practical reference for assessing land suitability and determining appropriate soil management interventions (Tab. 1).

FARMER PERCEPTION TOWARD LAND SURFACE CHARACTERISTIC

Structured in-depth interviews were conducted with 47 farmers residing in or owning land within the key research areas, focusing on those actively engaged in agriculture. Respondent selection aligned with the spatial distribution of physical land data sampling points. The interviews, combined with physical data analysis and direct field observations, informed a tabular-descriptive analysis. Questions explored various aspects of land management, including land type, cultivation intensity, soil fertility perceptions, fertiliser use, tools employed, erosion and landslide experiences, and adaptation strategies. This approach aimed to capture how farmers respond to local land limitations using traditional knowledge and context-specific practices.

RESULTS AND DISCUSSION

SURFACE MORPHOLOGY AND AGRICULTURAL LAND USE PATTERN

Landform type and slope position are critical in determining land use and land cover patterns. Agricultural activities are concentrated in lowland areas with gentle slopes (<5°), which offer better

Table 1. Classification of parameters used to measure the physical-chemical properties of topsoil[1)]

Class level	*BD* (g·cm^{-3})	Porosity (%)	Permeability (cm·h^{-1})	Infiltration (cm·h^{-1})	pH	Organic matter (g·kg^{-1})	C-organic (g·kg^{-1})
1	<1.00 (very low)	<30 (very bad)	<0.1 (very slow)	<5 (very slow)	<4.5 (very acidic)	<2.00 (very low)	<1.00 (very low)
2	1.00–1.20 (low)	30–40 (bad)	0.1–2.0 (slow)	5–20 (slow)	4.5–6.5 (acidic)	2.00–3.50 (low)	1.00–2.00 (low)
3	1.20–1.40 (medium)	40–50 (medium)	2.0–6.5 (medium)	20–63 (medium)	6.6–7.5 (neutral)	3.60–5.00 (medium)	2.01–3.00 (medium)
4	1.40–1.60 (high)	50–80 (porous)	6.5–12.5 (fast)	63–127 (fast)	7.6–8.5 (alkaline)	5.00–8.50 (high)	3.01–5.00 (high)
5	>1.60 (very high)	>80 (very porous)	>12.5 (very fast)	>127 (very fast)	>8.5 (very alkaline)	>8.50 (very high)	>5.00 (very high)

[1)] Classification acc. to Indonesian Agency for Agricultural Research and Development (Ind.: Badan Penelitian dan Pengembangan Pertanian).
Explanation: *BD* = bulk density.
Source: own elaboration.

accessibility and suitability for cultivation. Mixed gardens are largely located on slopes (225.09 ha) and spurs (59.63 ha), indicating a preference for moderately inclined terrain. Irrigated and rainfed paddy fields are mostly found in hollows (7.98 ha and 4.15 ha), where water naturally accumulates. Dry field agriculture is more flexible, occurring on slopes (39.82 ha) and hollows (9.50 ha), and present on ridges along with some irrigated fields. Flat areas show minimal use, likely due to their limited presence or lower agricultural suitability in this volcanic landscape (Michon and Mary, 1994; Duffy *et al*., 2021).

TOPSOIL PHYSICO-CHEMICAL CHARACTERISTICS AND MINERALOGY OF THE SUBSOIL

Laboratory analysis of 294 topsoil samples exposed that 85% had a clay content exceeding 50%, classifying them as clay-textured soils (Fig. 2a). While conventional soil formation theory suggests that clay content in hilly regions typically remains below 50% due to limited weathering process (Birkeland, 1984; Schaetzl and Anderson, 2015), the high clay percentage in this study is attributed to past hydro-geothermal alteration rather than typical rock weathering (Velde and Meunier, 2008). This alteration process transformed the original rock minerals entirely into clay, resulting in fine-grained materials that are now exposed as surface soil (Wilson, 2004).

The analysis shows that columnar medium to large structure is the most common, especially in clay-textured soils (29 samples), indicating a strong link between fine textures and columnar forms. Blocky angular fine (11 samples) and blocky angular medium (5 samples) structures also frequently occur in clay soils, reinforcing the association between high clay content and compact structures. In contrast, crumb and granular structures appear across a wider range of textures, suggesting greater variability. These patterns highlight how soil texture influences structural development, with finer soils supporting cohesive, compact structures, while coarser soils tend to form more friable and loosely arranged structures (Woldeyohannis, Hiremath and Tola, 2024).

Most topsoil samples fall into classes 2 and 3, indicating moderate to poor physico-chemical conditions. Bulk density is largely in class 2 (61 samples) and class 3 (44 samples), reflecting low to moderate compaction (Fig. 2c). Porosity is mostly in class 3 (56 samples), suggesting moderate pore space. Permeability and infiltration are also mainly in classes 2 and 3, indicating limited to moderate water absorption. Chemically, soil pH is concentrated in class 2 (145 samples), indicating acidity. Organic matter and C-organic content are highest in classes 3 and 2, showing generally low to moderate fertility levels.

The four soil profile sampling sites, presented both graphically (Fig. 3) and in tabular form (Tab. 2), illustrate variations in pedogenic processes across different landscape positions. Each profile comprises three distinct horizons: Ap (topsoil), Bt (argillic horizon), and C (subsoil). The Bt horizon, located beneath the surface layer, is characterised by clay illuviation from the overlying horizon because of water translocation (IUSS Working Group WRB, 2015). Overall, soil textures range from clay-to-clay loam, with surface structures dominated by blocky forms and columnar aggregates in the lower horizons. Topsoil properties such as porosity and infiltration are generally moderate to low, while permeability varies from slow to rapid depending on the degree of structural development and aggregation. The soils are typically acidic, with low to very low levels of organic matter and organic carbon, indicating limited inherent fertility. These characteristics suggest that soil formation in the study area is strongly influenced by solum depth, internal structural development, and the extent of parent material weathering.

The analyses of the C horizon (sub-stratum) using SEM, SEM-EDX, and XRD were conducted on four representative subsoil to identify the mineral composition of the soil's parent material. These methods confirmed the presence of halloysite and kaolinite minerals commonly found in volcanic ash-derived soils supporting previous research on the Mount Sumbing region. Halloysite, an aluminosilicate clay mineral with a tubular structure, was clearly observed in samples A (G.14) and B (G.23) under 50,000× zoom. In contrast, kaolinite, which features a layered, sheet-like morphology, was identified in samples G.20 and G.33. These findings provide detailed mineralogical evidence of weathering processes in volcanic parent materials.

Based on SEM-EDX analysis of sample A (G.14) shown in Figure 5, the subsoil is primarily composed of five elements: oxygen (58.356%), aluminium (13.601%), carbon (13.883%), silicon (10.754%), and iron (3.407%). Oxygen is the most abundant, while aluminium and silicon are also present in significant amounts. Although iron appears in lower concentra-

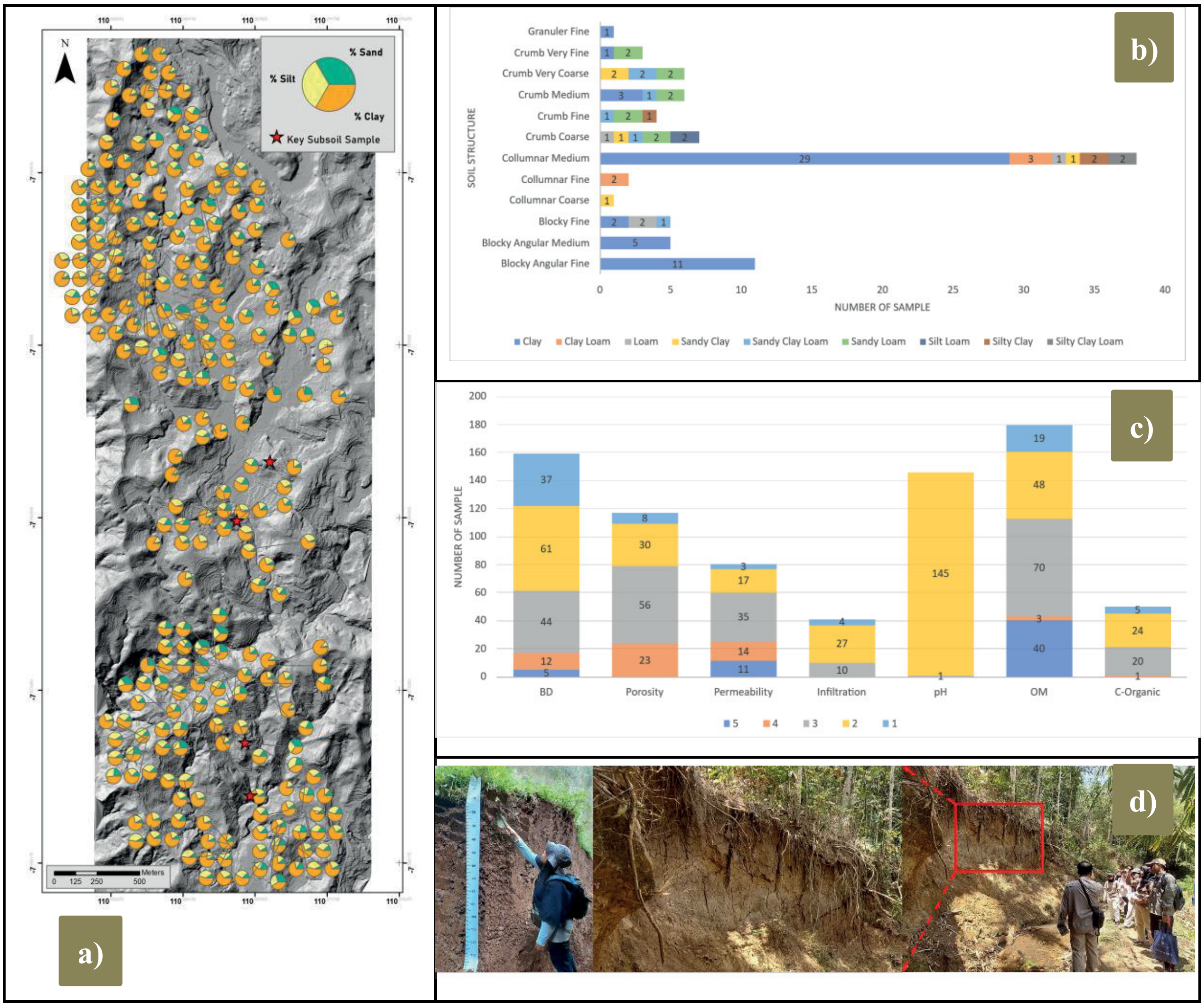


Fig. 2. Physico-chemical soil findings measurements: a) the distributions of sand, silt, and clay proportions across the study site, b) distribution of structure types and sizes associated with each soil texture class, c) frequency of measured physico-chemical soil parameters categorised by parameter class in the topsoil layer, d) field documentation of soil profile observation and sampling procedures; source: own study

Fig. 3. Topsoil (Ap) and subsoil (C) horizon in four selected soil profiles (detail descriptions of morphological, physical, and chemical properties in Tab. 2); source: own study

Table 2. Detail descriptions of representative soil profiles from different sampling positions

Horizon	Description	Profile G.14	Profile G.23	Profile G.20	Profile G.33
Ap	solum	0–15 cm	0–40/70 cm	0–10 cm	0–35 cm
	colour	7.5 YR 2.5/1	7.5 YR 3/3	10 YR 3/6	5 YR 3/4
	texture	clay	clay loam	clay	clay
	structure	blocky fine	blocky fine	crumb medium	blocky medium
	bulk density	very low	low	medium	low
	porosity	medium	bad	medium	medium
	permeability	slow	slow	fast	medium
	infiltration	slow	slow	medium	slow
	pH	acidic	acidic	acidic	acidic
	organic matter	medium	low	medium	very low
	C-organic	very low	low	medium	very low
Bt	solum	15–80 cm	80–120 cm	10–70 cm	35–85 cm
	colour	7.5 YR 3/4	7.5 YR 2.5/3	7.5 YR 3/3	7.5 YR 3/3
	texture	silty clay	clay loam	clay loam	clay
	structure	columnar medium	blocky medium	blocky fine	columnar medium
C	solum	>80 cm	>120 cm	>70 cm	>85 cm
	colour	7.5 YR 2.5/2	7.5 YR 3/4	7.5 YR 5/6	10 YR 5/6
	texture	silty clay	clay loam	silty clay	clay
	structure	blocky coarse	blocky coarse	blocky coarse	columnar coarse

Explanations: horizons as in Fig. 3.
Source: own study.

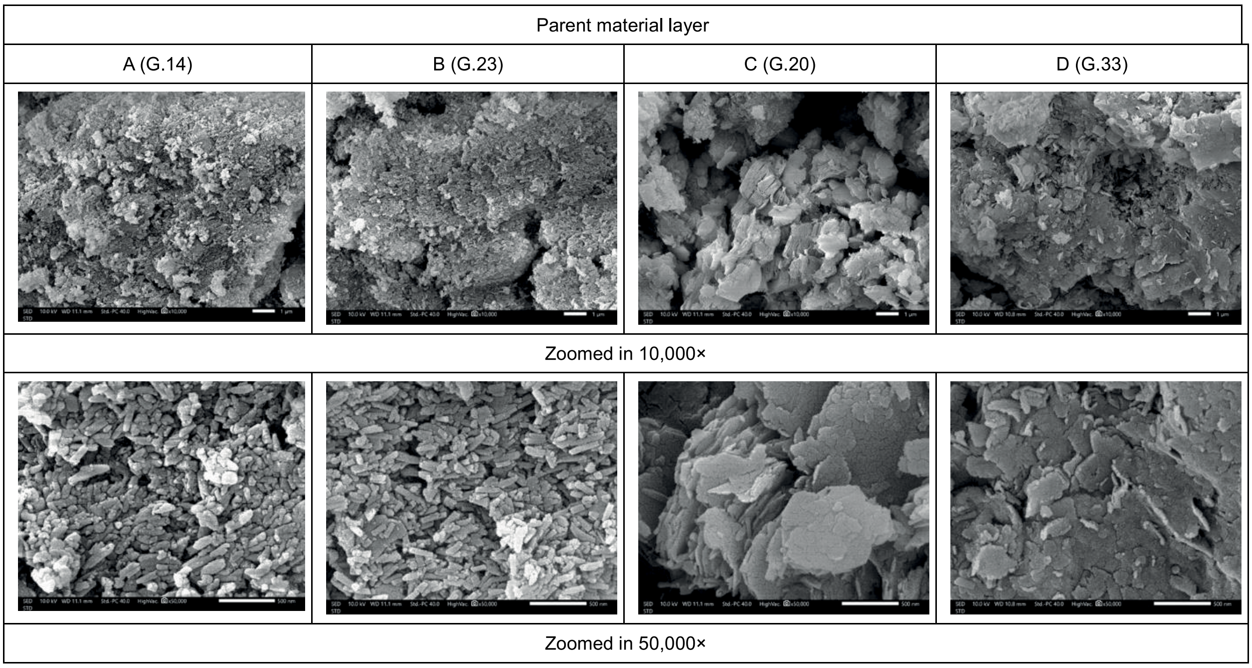
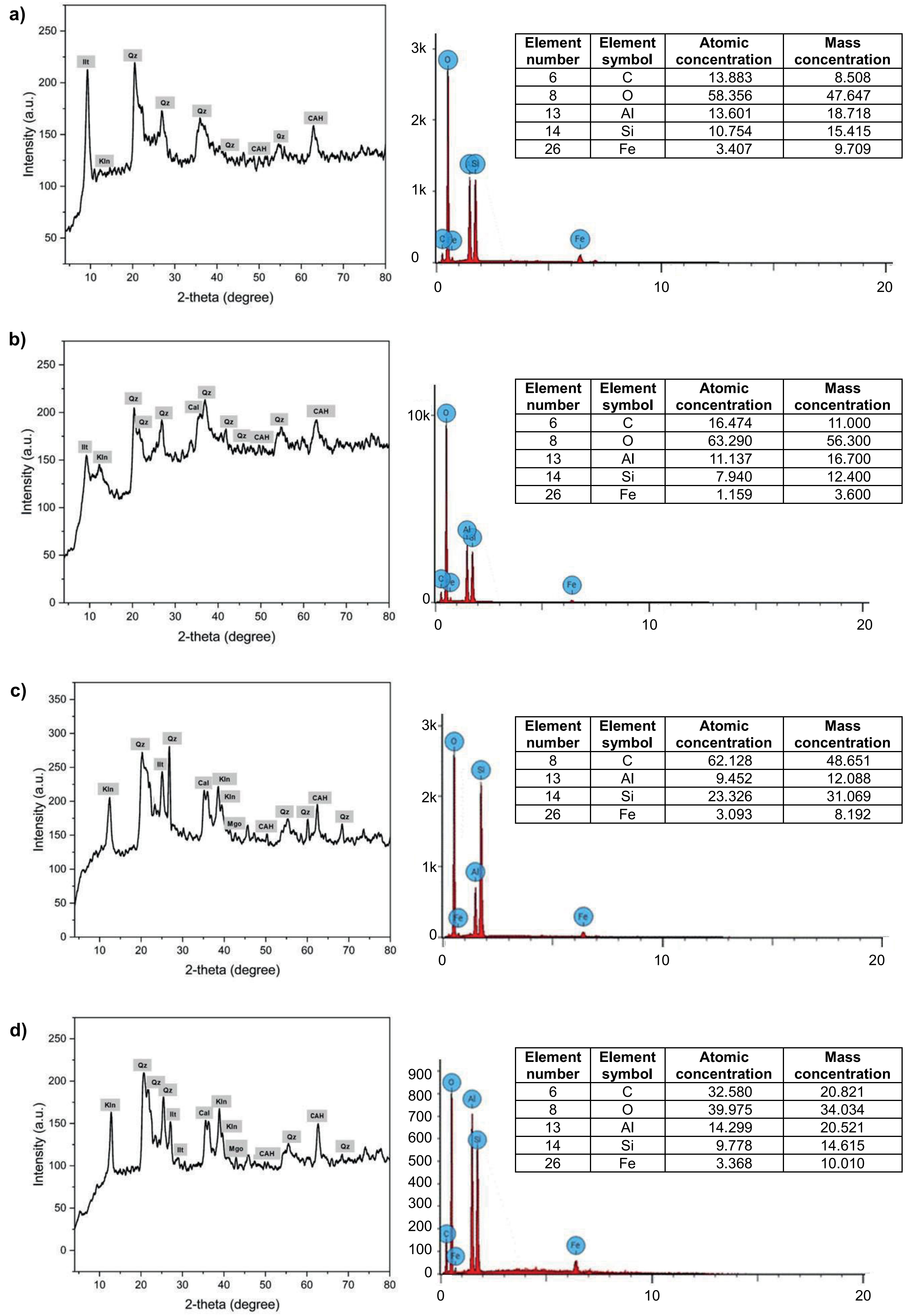


Fig. 4. Test results of scanning electron microscopy (SEM) images on the parent material layers; at 50,000× zoom, the morphological appearance of the minerals shows that samples A and B display a tabular form, whereas samples C and D present a platy structure; G.14, G.23, G.20, and G.33 as in Fig. 3 and Tab. 2; source: own study

tion, it remains a relevant component. Complementary XRD analysis confirms the mineralogical composition, with quartz (Qz) as the dominant mineral, indicated by strong diffraction peaks. The sample also contains kaolinite (Kln) and illite (Ilt), both 2:1 clay mineral, as well as calcium aluminium hydrate (CAH).

The results of the SEM-EDX analysis on subsoil sample B (G.23) indicate that the dominant elemental composition, based



a)

Element number	Element symbol	Atomic concentration	Mass concentration
6	C	13.883	8.508
8	O	58.356	47.647
13	Al	13.601	18.718
14	Si	10.754	15.415
26	Fe	3.407	9.709

b)

Element number	Element symbol	Atomic concentration	Mass concentration
6	C	16.474	11.000
8	O	63.290	56.300
13	Al	11.137	16.700
14	Si	7.940	12.400
26	Fe	1.159	3.600

c)

Element number	Element symbol	Atomic concentration	Mass concentration
8	C	62.128	48.651
13	Al	9.452	12.088
14	Si	23.326	31.069
26	Fe	3.093	8.192

d)

Element number	Element symbol	Atomic concentration	Mass concentration
6	C	32.580	20.821
8	O	39.975	34.034
13	Al	14.299	20.521
14	Si	9.778	14.615
26	Fe	3.368	10.010

Fig. 5. Test result of scanning electron microscopy-energy dispersive X-ray analysis (SEM-EDX) and X-ray diffraction (XRD) across the four subsoil sampling sites demonstrating spatial variability in mineralogy that reflects differences in weathering intensity and parent material composition: a) G.14, b) G.23, c) G.20, d) G.33; G.14, G.23, G.20, and G.33 as in Fig. 3 and Tab. 2; minerals content: Qz = quartz, Kln = kaolinite, Ilt = illite, Cal = calcite, Mgo = magnesium oxide, CAH = calcium aluminium hydrate; source: own study

on atomic concentrations, consists of oxygen (63.29%), carbon (16.47%), aluminium (11.14%), silicon (7.94%), and iron (1.16%). Carbon is present in a relatively high concentration (16.47%), while iron, though found in a lower proportion (1.16%), remains a significant component. The results of the XRD analysis reveal the presence of several minerals. Quartz (Qz) is the dominant phase, as evidenced by the intensity of its diffraction peaks. Kaolinite (Kln) and illite (Iln), representing 1:1 and 2:1 clay mineral respectively, are also identified. Additionally, calcite ($CaCO_3$) appears as a minor peak, and calcium aluminium hydrate (CAH) is detected in several diffraction patterns. The SEM-EDX analysis of subsoil sample C (G.20) shows that the dominant elements are oxygen (64.13%), silicon (23.33%), aluminium (9.45%), and iron (3.09%). The high silicon and aluminium content correspond with the presence of silicate and clay minerals. Results of XRD confirm quartz (Qz) as the dominant mineral phase, aligned with the elevated silicon levels. Kaolinite (Kln) and illite (Ilt), representing 1:1 and 2:1 clay mineral respectively, are also identified, consistent with the aluminium content. Calcite (Cal) is detected, indicating carbonate presence, which may not be fully captured by EDX. Minor peaks also indicate magnesium oxide (Mgo) and calcium aluminium hydrate (CAH).

The EDX analysis of subsoil sample D (G.33) shows that the soil is primarily composed of oxygen (39.98%) and carbon (32.58%), with notable amounts of aluminium (14.30%) and silicon (9.78%), and a smaller concentration of iron (3.37%). The XRD analysis confirms quartz (Qz) as the dominant mineral, indicated by strong intensity peaks that reflect a high free silica content. Kaolinite (Kln) and illite (Ilt), both secondary clay minerals formed from silicate weathering, are also identified. Additionally, minor peaks of calcite (Cal), magnesium oxide (Mgo), and calcium aluminium hydrate (CAH) are present, consistent with the mineral profile observed in sample G.20.

Subsoil mineralogy, derived from complex geological and geomorphological processes, influence topsoil properties and agricultural land potential in the Menoreh–Sumbing volcanic structural transitional landscape. The integration of geomorphons-based landform classification with agricultural land use provides additional insight into how landscape position modulates the expression of subsoil influence (Richter and Markewitz, 1995). Slope and spur positions, which dominate mixed gardens and dryland fields, more suitable for certain crop commodities that do not require extensive water (Vance and Milroy, 2022). In such areas, the topsoil may either thin out (<20 cm) or accumulate depending on slope dynamics, exposing more of the underlying altered material. Meanwhile, hollows and foot slopes that accumulate finer sediments are more likely to support paddy fields due to higher moisture retention and gentler tillage conditions (Liu *et al*., 2011; Mujiyo *et al*., 2024).

Climatic data indicate that the study area lies within a humid tropical climate zone, characterised by a rainfall regime dominated by wet months (≥100 mm) from October to May and dry months (≤60 mm) from June to September (Sartohadi, Rahma and Nugraha, 2024). This pattern reflects an intense rainy season at the beginning and end of the year, with a short but distinct dry season in mid-year. Air temperatures remain consistently high and stable throughout the year, promoting vigorous chemical weathering processes. The combination of high rainfall and warm temperatures accelerates the transformation of primary minerals into secondary minerals and enhances the leaching of base cations and essential nutrients.

The dominance of kaolinite and halloysite in the C horizon plays a direct role in structuring the physical characteristics of overlying topsoil. Clay-rich mineralogy contributes to high clay content (>50%) in 85% of topsoil samples, which explains the prevalence of compact structures such as columnar and blocky types (Bronick, 2005; Ryan *et al*., 2016). These structures are often associated with limited permeability and lower aggregate stability, resulting in moderate to poor ratings in topsoil bulk density, porosity, infiltration, and permeability (Hillel, 2003; Ryan *et al*., 2016; Ousaha, Afzal and Shao, 2025). This trend reflects how subsoil mineral composition determines the physical environment for root development and water movement, aligning with findings regarding mechanical resistance and subsoil constraints (Bengough *et al*., 2011).

The physical and chemical properties of the soils in the study area are governed by the interaction of three dominant minerals kaolinite, halloysite, and quartz which collectively form dense microaggregates with low total porosity. Kaolinite, a 1:1 layer silicate with low cation exchange capacity (*CEC*) and limited surface area, exhibits strong cohesiveness and plasticity when wet but hardens upon drying, resulting in slow infiltration, surface sealing, and a compacted top layer, as frequently reported by farmers. Halloysite, also a 1:1 mineral with tubular morphology and relatively higher *CEC*, displays high reactivity in early weathering stages; however, its weak structure renders soils prone to compaction and erosion when disturbed (Joussein *et al*., 2005). Both kaolinite and halloysite have low surface charges, which promote particle aggregation but, under acidic and organic-poor conditions, facilitate compaction, disrupt macropore continuity, and limit water movement. The absence of polyvalent cations further inhibits flocculation, accelerating clay particle dispersion and crust formation during rainfall, thereby increasing runoff and erosion risk on sloping land. Quartz, though chemically inert and non-contributory to fertility, enhances localised aeration and drainage but may also introduce weak zones that promote lateral water flow. These mineralogical interactions, operating at the microscale, control the soil's macroscopic structural, hydrological, and stability characteristics in volcanic landscapes (Terraza Pira *et al*., 2023; Muslim, Iqbal and Satriyo, 2024).

Chemical interactions between subsoil and topsoil are also evident. The acidic pH values observed in most of samples (class 2) are likely influenced by weathered aluminosilicates and limited buffering capacity from base-rich minerals. The presence of aluminium (Al) and silicon (Si) elements suggests the formation of clay minerals such as kaolinite, halloysite, or other aluminium silicates, which typically develop during the weathering of volcanic rocks (Deng *et al*., 2025). This evidence strengthens the finding of (Bemmelen van, 1949) about hydrothermal alteration triggered by magmatic intrusion. Formation of kaolinite under the process of weathering need very long period. In addition to their association with clay minerals, aluminium and silicon also constitute the primary components of quartz. Although present in relatively low concentrations, iron (Fe) is an important factor in in determining soil colour (reddish colour) and reactivity, and it has the potential to form iron oxide minerals such as hematite or goethite.

The dominance of quartz minerals observed in the XRD analysis indicates a high concentration of free silica, suggesting that quartz is a primary mineral with strong resistance to weathering (Weil and Brady, 2016). This finding is consistent with the elevated silicon (Si) content revealed by the SEM-EDX analysis. Though quartz is dominant across all samples, the presence of calcium aluminium hydrates and traces of calcite in some profiles (e.g., G.20 and G.23) indicate spatially heterogeneous chemical conditions in the parent material. This may partially explain the variation in topsoil fertility as perceived by farmers from moderately fertile in loose, red-textured soils to poor in compact, sticky clays.

The measured conditions of acidic pH, low to moderate organic matter content, high clay content, and a compacted structure suggest potential negative impacts on soil biodiversity and functional capacity (Fierer and Jackson, 2006; Lagomarsino, Grego and Kandeler, 2012; Jiang *et al.*, 2024). This is likely the case in which microbial richness is reduced, given the well-established relationship between soil texture and structure, chemical properties, and microbial community composition.

The integration of SEM-EDX and XRD data indicates that the subsoil at the research site consists of secondary weathering minerals such as kaolinite, halloysite, and illite, along with free quartz, which is highly resistant to weathering. Additionally, the presence of calcium- and aluminium-based hydrate compounds is observed. These mineralogical characteristics reflect an intense leaching process typical of volcanic rocks in humid tropical environments and suggest the potential development of argillic horizons or the accumulation of secondary clay minerals in the subsoil (Shoji, Nanzyo and Dahlgren (eds.), 1993; Bigham, 1995; Eswaran, 2000; Buol *et al.*, 2011).

Subsoil properties identified through SEM, SEM-EDX, and XRD analyses particularly the dominance of halloysite, kaolinite, illite, and elevated concentrations of silica and aluminium have significant implications for environmental sustainability. These clay-rich mineral compositions are commonly associated with poor water permeability and low pH, conditions that restrict root penetration and reduce agricultural productivity. Moreover, they contribute to increased surface runoff and erosion during periods of heavy rainfall.

FARMERS' PERCEPTIONS OF AGRICULTURAL LAND MANAGEMENT AT THE STUDY LOCATION

Farmers' perceptions of topsoil characteristics offer important insights for land management strategies (Tab. 3). Some respondent described their soil as loose and sandy (e.g., respondents 1, 24, 25, 46, 47), while others noted it was also water-retentive, indicating good cultivation potential (17, 19–23, 30, 31). In contrast, many farmers reported clayey, sticky, and dry soils, with some adding hardness as a constraint (2–6, 32–45). Red-coloured soil was viewed by some (26–29) as fertile, while others (8–16) associated it with poor fertility and low water retention. A few respondents (5, 7, 18) were unsure about their topsoil characteristics.

Most farmers reported that their topsoil was relatively easy to cultivate, with 20 respondents (e.g., 2, 4, 6, 7, 13, 14, 15) giving positive assessments (Tab. 4). This was often attributed to sandy and loose texture (respondents 30, 46), while others noted that only the top layer was easy to work (respondents 19–22). In contrast, several farmers experienced difficulties, with some describing the soil as generally hard to manage (respondents 12, 24–26), and others specifically citing sticky and hard-to-hoe conditions (respondents 1, 3, 5, 8–11, 16, 42, 44). These responses reflect diverse topsoil conditions affecting cultivation practices.

Farmers' perceptions particularly among those who experience difficulties in tilling the soil correspond with empirical findings indicating clay dominance and pronounced compaction.

Table 3. Farmers' views on the characteristics of agricultural topsoil

Physical characteristics of topsoil	Respondent
Loose and sandy soil	1, 24, 25, 46, 47
The soil is loose and sandy, with good water-holding capacity	17, 19, 20, 21, 22, 23, 30, 31
The soil is clayey, sticky when wet, and hard when dry	2, 3, 4, 6
Clay, sticky, dry and hard	32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45
The soil is clayey, sticky when wet, and hard and compact when dry	26, 27, 28, 29
The soil is clayey in texture, with a reddish colour, sticky when wet, and hard when dry	8, 9, 10, 11, 12, 13, 14, 15, 16
No statement	5, 7, 18

Source: own study.

Table 4. Farmer's views on level of topsoil management

<table>
<tr><th>Positive</th><th>Respondent</th><th>Negative</th><th>Respondent</th></tr>
<tr><td>Easy to manage</td><td>2, 4, 6, 7, 13, 14, 15, 17, 18, 23, 27, 32, 33, 35, 39, 45, 47</td><td rowspan="2">hard to manage</td><td rowspan="2">12, 24, 25, 26, 28, 29, 31, 34, 36, 37, 38, 40, 41, 43</td></tr>
<tr><td>The surface soil is easy to cultivate due to its sandy and loose texture</td><td>30, 46</td></tr>
<tr><td>Easy to cultivate, but only in the surface layer</td><td>19, 20, 21, 22</td><td>difficult to hoe due to its sticky consistency</td><td>1, 3, 5, 8, 9, 10, 11, 16, 42, 44</td></tr>
</table>

Source: own study.

More than 85% of the topsoil samples contain over 50% clay and display blocky or columnar structures. These texture and structural characteristics, associated with high bulk density, low porosity, and limited permeability, particularly in plots subjected to continuous tillage or rainfall, are consistent with farmers' descriptions of the soil as "sticky when wet and dry and hard when tilled". Such observations reflect the hydromechanical behaviour of kaolinite- and halloysite-rich soils, which exhibit high plasticity when moist and become rigid upon drying.

Farmers adopt a range of strategies to overcome soil processing difficulties, from basic to highly integrated approaches (Tab. 5). At level 1, simple tools like hoes and manure are used (e.g., respondents 2, 5, 12). Levels 2 and 3 combine manure with chemical and liquid organic fertilisers. Mechanical tools, such as hand tractors, are introduced at levels 4 and 5. More advanced strategies (levels 6–7) involve combining machinery with chemical inputs in a single cycle. The most integrated approaches (levels 8–10) include multiple tools, fertiliser types, straw incorporation (respondents 15, 16), and manual weeding (respondents 8–11). However, qualitative observations from farmer interviews indicate an increasing reliance on chemical fertilisers to ensure stable crop yields. Farmers commonly express the belief that without the application of chemical fertilisers, their harvests would be significantly reduced.

Farmer interviews reveal a nuanced understanding of these soil properties, with many respondents associating soil workability and productivity with topsoil texture and structure. The fact that farmers identify difficulties in hoeing, compaction, and poor water retention mirrors the analytical results. Furthermore, their adaptive strategies ranging from the use of manure and hoes to more integrated practices involving mechanical tools and organic amendments demonstrate local responses to underlying subsoil constraints. Manual hoeing temporarily disrupts dense, compacted microaggregates, mitigating the inherently poor loosening capacity of soils characterised by the low shrink–swell potential of these clay minerals. The application of manure and incorporation of crop residues enhance soil structure and fertility by promoting aggregation, increasing cation exchange capacity, and stimulating microbial activity, particularly in acidic soils with low organic matter content.

Effective land management practices in volcanic soil regions such as organic matter amendment, agroforestry, terracing, cover cropping, and targeted fertilisation are essential for addressing soil compaction, limited water permeability, and nutrient deficiencies. Given the dominance of kaolinite, halloysite, and quartz which collectively contribute to soil acidity, compaction, and poor nutrient retention management practices must be specifically tailored to this mineralogical composition. To address acidity and mitigate aluminium toxicity, the application of dolomitic or calcitic lime, calibrated to the soil's pH buffering capacity, is recommended. Incorporating organic materials such as manure, composted rice hulls, or green manures enhances aggregation and porosity, reduces surface hardening, and alleviates subsurface compaction when combined with minimal or occasional deep tillage (Šarauskis *et al.*, 2024). The use of cover crops further improves soil structure through biological processes. To enhance nutrient retention, organic amendments should be integrated with biochar or slow-release fertilisers (Nugraha, Sartohadi and Nurudin, 2022; Khan *et al.*, 2024), alongside mycorrhizal inoculants, or rock phosphate to improve phosphorus availability. These interventions reinforce the role of subsoil mineral and structural conditions in shaping land management practices on subsoil-topsoil interactions (Cotrufo *et al.*, 2022).

This study presents that the subsoil in the Menoreh–Sumbing transitional landscape is not merely a passive layer but a dynamic environmental factor that constrains or facilitates surface soil development, topsoil fertility, and cultivation practices. Understanding these vertical linkages is essential not only for interpreting soil formation processes but also for designing more targeted land management and rehabilitation strategies in structurally complex volcanic landscapes. Given the spatial variability of subsoil characteristics, land management and development strategies should be tailored to micro-site conditions.

Table 5. Strategies to resolve difficulties in land cultivation, ranked from simplest (1) to most comprehensive (10)

Level	Land cultivation strategies	Respondent
1	cultivated using a hoe, fertilised with manure	2, 5, 12, 26, 27, 28, 29, 30, 31
2	cultivated using a hoe, fertilised with manure and chemical fertilisers	3, 4, 18, 19
3	cultivated using a hoe, fertilised with manure and liquid organic fertiliser	17
4	cultivated using a hand tractor, fertilised with manure and chemical fertilisers	20, 21, 22, 23, 24, 25
5	cultivated using a machine tractor, fertilised with chemical fertilisers	6
6	cultivated using a machine tractor, fertilised with manure and chemical fertilisers	14
7	cultivated using hand tractors, hoes, fertilised with manure and chemical fertilisers	1, 7, 11
8	cultivated using a hoe, fertilised with manure, chemical fertiliser, and liquid organic fertiliser	32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 47
9	cultivated using hand tractors, hoes, fertilised with manure, chemical fertilisers and the rice straw turning method	15, 16
10	cultivated using hand tractors, hoes, fertilised with manure, chemical fertilisers and weed decomposition methods	8, 9, 10, 11

Source: own study.

Mineralogy-based interventions such as liming, organic matter application, and improved tillage are technically essential for addressing the limitations of kaolinite-, halloysite-, and quartz-rich soils. However, their adoption is constrained by high costs, limited input availability, and labour shortages. Smallholder farmers often lack both the financial capital and workforce required to implement these measures, while practices such as subsoiling remain impractical without access to appropriate mechanisation. More affordable and traditional locally relevant strategies (Nugroho, Sallata and Allo, 2023; Izadi and Aghamir, 2024), including soil cover, legume rotations, and integrated nutrient management, show potential but are hindered by limited extension support and the absence of immediate, visible yield benefits. For such interventions to be effective, they must be adapted to the socio-economic realities and capacities of the local farming community.

While current observations suggest ongoing soil degradation in the absence of management interventions, there remains potential for stabilisation or even improvement through the adoption of adaptive, site-specific conservation strategies by farmers. In the absence of an integrated support system that aligns technological, institutional, and ecological components, the region faces the risk of entering an unsustainable cycle of agricultural intensification. Future research should explicitly monitor these trends to inform evidence-based policies and land management practices in volcanic-structural agricultural landscapes.

CONCLUSIONS

This study confirms that subsoil mineralogy influenced by geological history and hydrothermal alteration of volcanic materials, vitals in shaping soil properties in the Menoreh–Sumbing transitional landscape. The dominance of kaolinite group reflects intense weathering, resulting in clay-rich upper layers with poor structure and acidic conditions. These characteristics limit water infiltration, root growth, and nutrient availability, posing challenges for cultivation. Farmers' observations and adaptive practices highlight how these subsurface conditions are experienced and managed in the field. Sustainable land management in this region must consider both subsoil characteristics and the underlying geological processes shaping them. These findings can be adapted in other similar landscape. The diagnostic emphasis on subsoil mineralogy, particularly the identification of alteration-induced clay minerals can serve as an early warning indicator for soil degradation and reduced land productivity. Moreover, the approach of integrating mineralogical, topographical, and climatic parameters provides a replicable model for delineating micro zones of conservation and cultivation priority.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interest.

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