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Potential of Trace Elements in Volcanic Highlands: Geogenic Sources and Their Implications for Productivity

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Abstract

This study investigates the mineralogical composition and trace element potential of volcanic highland soils in Kejajar District, Wonosobo, Central Java, an area that has experienced long-term horticultural intensification. Volcanic Andisols in this region are known for high fertility but also carry risks of trace element accumulation due to complex mineralogy and intensive land use. Bulk powder X-ray diffraction identified feldspar, epidote, apatite, pyrite, and clay minerals, which may release essential (Zn, Cu, Fe, Mn) and toxic (Cd, Pb, As) elements through natural weathering and agricultural activities. Results show that horticultural soils on 9–15% slopes exhibited the highest HCl 25%-extractable P (224.70 mg/100 g). At the same time, shrubland soils also displayed high values (179.74 mg/100 g), indicating contributions from both fertilizer and geogenic sources. Although horticultural soils had higher chemical fertility, the shrubland maintained better physical (bulk density, 0.78 g/cm³) and biological quality (soil respiration, 36.48 mg C/kg/day). Productivity trends further highlight risks: cabbage yields declined by 41% (2020–2023), and potato production dropped by 11% (2017–2021). These findings demonstrate the dual role of geogenic and anthropogenic inputs in shaping soil quality and productivity. Sustainable management requires integrated strategies, including trace element monitoring, pH regulation, organic matter enhancement, and the use of low-contaminant fertilizers, to ensure long-term agroecosystem resilience in volcanic highlands.

1. Introduction

The Wonosobo volcanic plateau in Central Java has long been recognized as one of the primary horticultural centers in Indonesia, particularly for high-value commodities such as potatoes, cabbage, leeks, carrots, and various types of leafy vegetables. Its favorable agroclimatic conditions, characterized by cool temperatures, high rainfall, and fertile volcanic soils, make this area ideal for intensive horticultural agriculture cultivation throughout the year. However, the pressure of land intensification over the past few decades has raised concerns regarding soil quality degradation, including the potential accumulation of harmful trace elements (Zeng et al., 2022; Liu et al., 2023).

Volcanic soils, especially Andisols, typically have a high content of organic matter and cation exchange capacity (CEC), which strongly supports agricultural productivity. However, their complex mineralogical composition, including minerals such as pyrite, feldspar, epidote, and apatite in volcanic parent rocks (e.g., andesite and basalt), has the potential to release heavy metal elements, such as lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (As) into the soil through geochemical weathering processes (Fan et al., 2016; Cao et al., 2021). Recent studies suggest that volcanic rock weathering can be a significant source of geogenic contamination in highland farmland (Hu et al., 2020; Yang et al., 2021).

In addition, anthropogenic inputs from modern agricultural practices, such as the application of phosphate fertilizers, pesticides, and organic wastes, also contribute significantly to increased concentrations of heavy metals, particularly Cd and Pb, in soils (Zhao et al., 2020; Zeng et al., 2022). A recent local study in the Wonosobo agricultural area further found that Cd is the dominant element in soil pollution, as indicated by the geo-accumulation index (Igeo), and poses a potential risk to human health, especially children (Rahayu et al., 2023).

In steep hilly landscapes, such as in Wonosobo, the mobility of heavy metal elements is exacerbated by erosion processes and the exposure of subsoil layers enriched in reactive minerals. This poses significant ecological and agronomic risks, including disturbances to soil microorganisms, inhibition of nutrient uptake by plants, and potential toxicity to consumers of agricultural products (Liu et al., 2023; Rahayu et al., 2023). Accordingly, a deeper understanding of the sources, distribution, and dynamics of trace elements in volcanic farmland is essential to support sustainable and environmentally friendly land management.

Although numerous studies have examined heavy metal contamination in farmland, most have focused on anthropogenic inputs such as fertilizers, pesticides, and waste application. However, these studies often overlooked the role of volcanic mineralogical composition, which strongly influences the release and mobility of trace elements. In tropical volcanic highlands, such as Wonosobo, primary and secondary minerals (e.g., apatite, pyrite, feldspar, and epidote) can serve as geogenic sources of both essential and toxic elements. Previous research did not fully capture how these mineralogical controls interact with intensive land use and steep slopes to drive trace element dynamics. This research seeks to fill that gap by explicitly linking soil mineralogy with trace element availability and its implications for soil productivity and agroecosystem sustainability in volcanic highlands. This research aims to fill the gap by characterizing soil properties and the mineralogical composition of highland soils based on geological units and types of land use. After that, to assessed the potential geogenic contribution to heavy metal accumulation. The ultimate objective is to determine its implications for soil productivity and environmental quality in the context of land-use intensification and volcanic slope dynamics.

2. Research Methods

2.1. Research Location

This research was conducted in Kejajar Village, Wonosobo Regency, Central Java, situated at elevations ranging from 1,700 to 2,250 meters above sea level. The area is part of a volcanic plateau with varied topography, including steep slopes (>40%) in natural shrub areas and moderate slopes (9–26%) in horticultural farmland.

Climatically, the study area falls within the tropical highland climate zone, characterized by daily temperatures ranging from 24 to 30°C during the day and from 17 to 20°C at night, which occasionally drops to 15–20°C during the dry season (July–August). The annual rainfall average is about 3,400 mm, with peak precipitation in January and extreme dry conditions in July. Rainfall occurs on approximately 196 days a year. Geologically, the study area is located on three main volcanic formations, namely: (1) the Jembangan Volcanic Formation (Qj), which consists of andesite lava and clastic volcanic materials containing hornblende, augite, and basalt minerals; (2) the Sundoro Volcanic Formation (Qsu), which is composed of augite-olivine, pyroclastics, and basaltic lavas; and (3) the Dieng Volcanic Formation (Qd), which is dominated by quartz-andesite lava with an increased silica content at depth.

Based on land use data from 2014 to 2023, the extent of horticultural land increased from 27.3% (192.45 ha) to 30.0% (211.23 ha). This increase led to a decrease in shrubland area from 61.9% (435.66 ha) to 59.7% (420.52 ha), indicating a significant land conversion driven by agricultural intensification in the volcanic highland areas.

2.2. Research Design

This study employed an exploratory design that integrated field observations and laboratory analyses to identify the mineral composition and potential geogenic sources of trace elements in volcanic highland agricultural soils in Kejajar Village, Wonosobo Regency, Central Java. Soil samples were collected from four locations (Figure 1) representing two primary types of land use, namely horticultural fields and shrubland, as well as variations in slope gradients. The sampling locations were selected based on three dominant geological units—Dieng Volcano, Sundoro Volcano, and Jembangan Volcano—taking into account both slope variation (9% to >40%) and recent trends in and-use change.

Soil sampling was conducted at four different locations with a total of 24 sampling points. At each location, six soil samples were collected randomly and subsequently composited into a single representative sample per site. Site 1 represented horticultural land with a slope of 26–40%, Sites 2 and 3 represented horticultural land with slopes of 9–15%, and Site 4 represented natural shrubland with a slope of more than 40%.

Horticultural land in Kejajar District reflects an intensive cultivation system that has been maintained for more than three decades. These areas are predominantly planted with high-value vegetable crops, such as potatoes, cabbage, leeks, and carrots, featuring a relatively short rotational planting pattern. Agricultural intensification is characterized by a high frequency of tillage, intensive use of chemical fertilizers, and the practice of liming using dolomite to neutralize soil acidity. Some farmers periodically apply dolomite as a strategy to maintain land productivity, considering that the Andisols in this area tend to be acidic. These practices contribute to maintaining high chemical fertility in the soil; however, they also have the potential to degrade the physical and biological quality of the soil over the long term.

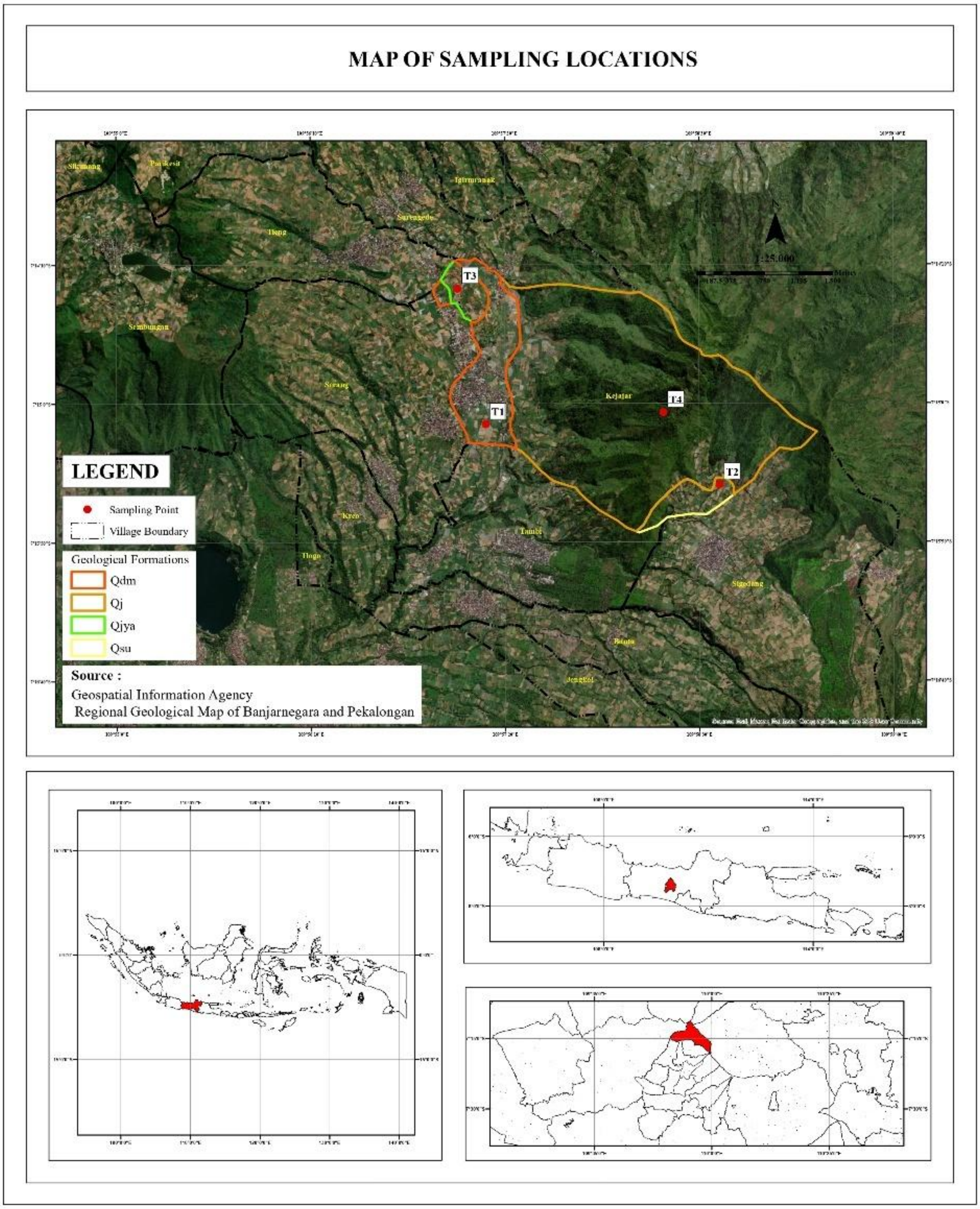

Figure 1. Sampling location based on geological formations and land use in Kejajar, Wonosobo

On the other hand, shrublands within similar geological and topographic settings are still relatively natural and are not subject to intensive management. The vegetation is dominated by grasses and shrubs, with the dynamics of organic matter input primarily driven by natural litter. The limited anthropogenic disturbance allows shrubland soils to retain higher reserves of organic matter, with more stable biological activity and physical properties than those of horticultural land. Thus, the existence of shrubland can serve as a natural benchmark for evaluating the impact of horticultural intensification on soil quality in the Kejajar volcanic mountainous area.

Soil samples were collected from depths of 0–40 cm using a soil auger. All samples were dried, ground, and homogenized before laboratory analysis. The analyses included soil mineralogy using the X-ray Diffraction (XRD) method, soil chemical properties which include soil pH-H_2O (1:2.5) and pH NaF (1:50) measured using a pH meter, cation exchange capacity (CEC) determined with Ammonium acetate (NH_4OAc), and P_2O_5 content measured by HCl extraction (25% HCl), total N Kjedhal method (destruction and distillation), soil physical properties represented by bulk density measured using ring method, and soil biological properties including organic C content analyzed with muffle furnace, and soil respiration measured by incubation method as published by Balittan (2009).

XRD analysis was performed at the Laboratory of Mineral and Hydrocarbon Fluid Analysis, Faculty of Mineral Technology, National Development University (UPN) "Veteran" Yogyakarta, using the bulk powder preparation method (USGS; Simpson & Tillick, 1999). The brand and model of instrument used was Malvern Panalytical Empyrean Series 3 floor-standing X-ray diffractometer (powder XRD) equipped with sample preparation facilities. Bulk powder analysis is primarily employed to determine the presence of primary minerals in rocks or to detect specific compounds in solid samples. Although clay minerals may also appear in this analysis due to the random orientation of particles. Before analysis, the soil samples were dried in an oven, ground using an agate mortar, sieved through an ASTM No. 230 mesh (0.062 mm), and mounted on a glass stand for XRD measurement (Nurcholis et al., 2018).

2.3. Data Analysis

This study uses descriptive quantitative data analysis to examine the relationship between soil mineralogical composition and the potential accumulation of trace elements in volcanic highland agricultural systems. The analysis was performed by comparing four sampling locations, selected based on a combination of land use (horticulture vs. shrubland), slope classes (9–15%, 26–40%, >40%), and geological units (Dieng, Sundoro, and Jembangan volcanoes). The results were interpreted to evaluate the geogenic contribution to heavy metal risk and its implications for soil health and agricultural productivity.

3. Results and Discussion

3.1. Soil Characteristics in Horticultural and Shrubland Areas based on Geological Formations

Table 1 presents the key physical, chemical, and biological properties of the soils from the four sampling sites representing the two dominant types of land use—horticulture and shrubland—across different slope classes. These parameters offer insight into how land use and topography influence soil fertility and functionality in volcanic highland systems.

Soil pH (H_2O) ranged from moderately acidic to slightly acidic across all locations (5.53–6.74). The highest pH value (6.74) was observed in horticultural land with slopes of 26–40%, suggesting that the acidification process was relatively limited despite intensive cultivation, likely due to periodic liming practices. In contrast, the lowest pH (5.53) was recorded in shrubland with steep slopes (>40%), which may have been influenced by volcanic materials from previous eruptions. This condition aligns with the geomorphological characteristics of the Dieng Plateau, a post-volcanic region characterized by the manifestation of solfatara activity, which emits sulfur-rich gases such as SO_2 and H_2S (Hochstein et al., 2015; Wibowo & Budi, 2014). When these gases react in the atmosphere and return to the Earth's surface with precipitation, they can form acid rain that contributes to soil acidification (Ulrich et al., 2019). This process accelerates the leaching of alkaline cations (Ca^{2+}, Mg^{2+}, K^+) while increasing the mobility of toxic metals, such as Al^{3+}, thereby accelerating soil pH degradation, especially in steeply sloping areas that are highly prone to erosion (Rengel, 2011).

Cation Exchange Capacity (CEC) was relatively high across all sites (23.58–30.97 cmol/kg), indicating strong nutrient storage capacity, a typical feature of Andisols rich in amorphous clay minerals (allophane, imogolite) and organic matter (Shoji et al., 1993; Dahlgren et al., 2004). Shrubland exhibited the highest CEC value, attributed to the better conservation of organic matter under minimal land disturbance, which promotes the greater accumulation of soil organic carbon and enhances soil cation exchange processes (Nanzyo, 2002; Parfitt, 2009).

The soil organic carbon content (Organic C) was relatively high and consistent across the study site, ranging from 7.11% to 8.86%. These values confirm the inherent fertility of volcanic soils in this region, which are generally rich in organic matter due to the continuous input of biomass from plant residues and vegetation litter in highland ecosystems (Six et al., 2002; Sanchez, 2019). Sites with natural shrub cover showed the highest organic C content (8.86%) and the lowest bulk density (BD) at 0.78 g/cm³. This combination shows a loose and porous soil structure that promotes optimal aeration, root growth, and soil microbial activity (Lal, 2004; Carter & Gregorich, 2008).

This condition is consistent with the highest soil respiration rate observed in natural shrubland areas, measured at 36.48 mg C/kg/day. The high rate of soil respiration indicates a highly active microbial community and an intensive decomposition process of organic matter (Raich & Tufekcioglu, 2000; Kuzyakov, 2006). In contrast, one horticultural site on a 9–15% slope recorded a much lower respiration rate (12.34 mg C/kg/day). This may be due to soil compaction from intensive tillage, which reduces porosity and oxygen availability, as well as soil microbial biomass (Batey, 2009; Hamza & Anderson, 2005).

Soil moisture ranged from 26.48% to 35.09%, with the shrubland again showing the highest value, likely due to its greater canopy cover and lower evaporation rates. Total nitrogen content was generally adequate (0.28–0.59%), with the highest concentration found in horticultural soils on moderate slopes (0.59%), likely due to fertilization. Despite the lack of external inputs, the shrubland maintained relatively high nitrogen levels (0.51%), indicating efficient recycling of organic matter.

The highest availability of phosphorus (P) was recorded in horticultural land with a 9–15% slope (224.70 mg/100 g). This is most likely due to the application of fertilizer, especially superphosphate or SP-36. However, the relatively high values observed in shrubland (179.74 mg/100 g) indicate that fertilizer alone does not explain the trend. Additional sources, such as phosphate released from geogenic minerals (e.g., apatite) and organic matter mineralization, also contribute to the accumulation of available P in these soils (Hu et al., 2020; Zeng et al., 2022; Liu et al., 2023). Conversely, the lowest P availability (173.50 mg/100 g) was also found in other Sites with the same slope class. This indicates the presence of spatial heterogeneity in fertilization practices, variations in cultivation intensity, or differences in phosphorus fixation within the soil. Phosphorus fixation occurs either through precipitation with Ca ions in high-pH soils or through strong binding with Fe and Al oxides in acidic soils, processes that are primarily governed by soil mineralogy, particularly the presence of apatite and Fe/Al oxides (He et al., 2023).

Natural shrubland with slopes >40% showed moderate phosphorus availability (179.74 mg/100 g). In these soils, the availability of P is likely sustained by the weathering process of primary minerals that gradually release phosphate, together with the contribution of organic matter from decomposed vegetation litter. The process of mineralization of organic residues can be an essential source of P in natural ecosystems, especially when external inputs, such as fertilizers, are absent (Condron et al., 2005; Tiessen et al., 1994). However, steep slopes can increase the potential for phosphorus (P) loss through erosion and surface runoff, resulting in lower availability compared to moderately sloped horticultural land (McDowell et al., 2001).

Overall, these results suggest that the availability of P in the soil is governed not only by fertilizer application but also by complex interactions among topographic, mineralogical, land management, and biogeochemical factors. A comprehensive understanding of these processes is essential for developing efficient and sustainable phosphorus nutrient management strategies. The data also reveal striking differences between land-use systems. Horticultural soils, especially on moderate slopes (9–15%), benefit from higher nutrient contents (N and P) and active management, although some sites show lower biological activity. In contrast, shrubland systems, despite the absence of fertilizer inputs, support high microbial activity, strong water retention, and elevated organic matter content, all of which contribute to their ecological resilience. Horticultural land on steeper slopes (26–40%) also maintains good soil fertility but is vulnerable to erosion.

These findings highlight the need for land management strategies tailored to the slope class and type of land use. Effective management on moderate to steep slopes is crucial to mitigate soil degradation resulting from erosion and nutrient depletion. The key strategies include maintaining organic inputs sustainably, through the application of organic fertilizers, the return of crop residues, and the cultivation of cover crops to support the formation of stable aggregates and increase soil capacity to store carbon and nutrients (Lal, 2004; Six et al., 2002). Moreover, practices that minimize physical soil disturbance, such as minimum tillage or no-till, help preserve soil pore structure, reduce the risk of compaction, and maintain soil microbial habitats that play an important role in nutrient cycles (Hamza & Anderson, 2005; Batey, 2009). Such conservation approaches are particularly relevant in volcanic highland agricultural ecosystems, where soils are generally fertile but susceptible to degradation under intensive, unsuitable management.

Integrating slope-based management strategies with appropriate land use practices is expected to maintain soil health, ensure the sustainability of agricultural productivity, enhance soil carbon storage to reduce greenhouse gas emissions, and safeguard overall ecosystem functions (Sanchez, 2019; FAO, 2017). Table 2 provides a more detailed comparison of soil properties between horticultural land and shrubland. Descriptive analysis showed that soils in horticultural land had a higher average pH value (±6.10) than those in shrubland (±5.53). This difference may be attributed to the natural calcification of volcanic parent materials rich in alkaline minerals, the effects of buffering, and the intensification of agricultural activities. In several highland areas, including Kejajar District, Wonosobo, farmers routinely apply dolomite to increase soil pH and improve soil structure, thereby enhancing the availability of nutrients, such as Ca, Mg, and P (Kasno, 2020; Enesi et al., 2023.

Nutrient concentrations, such as total nitrogen and available phosphorus, were also higher in horticultural soils, reflecting the intensive use of fertilizers in cultivation systems (Zhang et al., 2020). Nevertheless, the biological and physical parameters of the soil, such as soil respiration, organic carbon content, and moisture, showed higher values in the shrubland. These conditions suggest that even without external inputs, shrub soils maintain better biological qualities and soil structure, supporting long-term sustainability (Lal, 2015; Six et al., 2002).

Table 1. Soil characteristics in different types of land use

Site	Land Use	Slope	pH H_2O	CEC	OC	pH NaF	BD	SR	SM	TN	AP
1	H	26–40	6.74	29.12	7.11	10.84	1.03	13.20	26.48	0.28	189.60
2	H	9–15	5.79	29.91	7.16	11.32	1.01	33.00	27.07	0.44	224.70
3	H	9–15	5.76	23.58	8.58	11.54	0.80	12.34	28.70	0.59	173.50
4	S	>40	5.53	30.97	8.86	10.63	0.78	36.48	35.09	0.51	179.74

Note: Land Use (H = Horticulture, S = Shrubland); Slope (%); CEC (cmol(+)/kg); OC (Organic C (%)); BD (Bulk Density (g/cm³)); SR (Soil Respiration (mg C/kg/day)); SM (Soil Moisture (%)); TN (Total N (%)); AP (Available P (P_2O_5 HCl 25%, mg/100g))

On the other hand, the intensification of horticultural practices may enhance chemical fertility but has the potential to decrease soil microbial activity and degrade physical properties (de Vries et al., 2013). These findings underscore the importance of implementing ecologically based land management adapted to the slope class and type of land use, especially in volcanic highland areas that are vulnerable to soil degradation (Barrios, 2007). The strategy includes the application of integrated organic inputs, soil amendments such as dolomite in acidic soils, land cover conservation, and a reduction in tillage intensity to maintain soil health and sustainable productivity (FAO, 2017).

Table 2. Comparative descriptive statistics of the physical, chemical, and biological soil properties by land use

Parameter	Horticulture (Mean ± SD)	Shrubland
pH H_2O	6.10 ± 0.57	5.53
CEC (cmol(+)/kg)	27.54 ± 3.40	30.97
Organic C (%)	7.62 ± 0.78	8.86
pH NaF	11.23 ± 0.36	10.63
BD (g/cm³)	0.95 ± 0.12	0.78
Soil respiration (mg C/kg/h)	19.51 ± 11.19	36.48
Soil moisture (%)	27.42 ± 1.13	35.09
Total Nitrogen (%)	0.44 ± 0.15	0.51
P_2O_5 HCl 25 % (mg/100g)	195.93 ± 25.77	179.74

The differences in soil characteristics between horticultural land and shrubland have direct implications for soil quality and productivity in volcanic highland areas, such as Kejajar, Wonosobo. The higher pH values in horticultural soils (6.10) compared with shrubland (5.53) fall closer to the optimal range for nutrient availability in vegetable crops (FAO, 2000). This may be influenced by liming using dolomite, which horticultural farmers commonly apply in Kejajar to neutralize soil acidity and supply calcium and magnesium (Puspitasari, Septiana, & Razie, 2024; Hopit, Susana, & Astina, 2020).

The relatively high concentrations of total nitrogen and available phosphorus in horticultural soils indicate adequate chemical fertility to support the growth of short-lived plants. However, the higher soil respiration rates and organic carbon contents in shrubland suggest that the ecosystem has more active microbial activity and organic matter decomposition processes. These conditions are essential for long-term nutrient cycling, as soil microorganisms contribute to the mineralization and stabilization of soil aggregates (Six et al., 2004).

Soil moisture in shrubland (35.09%) was higher and closer to field capacity than in horticultural land (27.42%). Moisture levels near field capacity are ideal for microbial activity and water availability for plants, as they minimize water stress without causing anaerobic conditions (Hillel, 1998). On the other hand, a lower bulk density in shrubland (0.78 g/cm³) indicates a looser and more porous soil structure that enhances water retention and aeration (Brady & Weil, 2016).

Another important finding is that, although horticultural land shows high chemical fertility, its physical and biological qualities are relatively lower than those of shrubland. This indicates that horticultural cultivation practices in the study area focus predominantly on the management of chemical inputs through fertilization. At the same time, less attention is given to physical properties (e.g., improvement of soil structure, aeration, and porosity) and biological properties (e.g., microbial and soil fauna activities). This supports the view that improving soil chemical fertility alone is not enough to increase the productivity and sustainability of agricultural systems. This is because the chemical, physical, and biological properties of soil are interdependent components and must be managed in an integrated manner (Lal, 2015; Altieri et al., 2015).

Therefore, although horticultural cultivation in the study area contributes to improved chemical fertility, intensive tillage practices have the potential to degrade the physical and biological quality of the soil in the long term. Sustainable management strategies, such as reduced tillage, the application of organic amendments, the use of cover crops, and crop diversification, should be considered. These practices not only maintain chemical fertility but also improve the physical and biological functions of the soil, thereby supporting the sustainability of horticultural agroecosystems in volcanic mountainous areas such as Dieng.

3.2. Mineral Composition, Geogenic Sources, and Potential Trace Elements: Implications for Soil and Productivity

X-ray diffraction (XRD) analysis showed significant variation in mineral composition among sampling sites, reflecting the combined influence of geogenic and anthropogenic factors. Figure 2 illustrates the variation in mineralogical composition across the geological formations examined. Samples from horticultural soils (Sites 1-3) contained minerals such as pyrite, apatite, epidote, and cristobalite, which are known to be associated with the release of harmful trace elements. Notably, Site 2 exhibited the most tremendous mineral diversity, with pyrite (3.58%), apatite (4.11%), cristobalite (19.08%), and epidote (7.25%) being the most prominent minerals. Pyrite (FeS_2) is a sulfide mineral that can oxidize under aerobic conditions to produce sulfuric acid, thereby lowering soil pH and mobilizing heavy metals such as arsenic (As), lead (Pb), cadmium (Cd), and copper (Cu) (Fan et al., 2016; Cao et al., 2021). Apatite, which is commonly known as a source of phosphate, can also contain heavy metals, such as Pb, Cd, and uranium (U), depending on its geological origin (Zhao et al., 2020). Epidote and sillimanite can indirectly contribute to the process of metal accumulation through adsorption processes or coexistence with trace elements, such as chromium (Cr), manganese (Mn), and aluminum (Al) in acidic conditions (Sparks, 2003; Sánchez España et al., 2011).

This condition indicates that heavy metal sources in the soil originate not only from anthropogenic activities, such as intensive agriculture, but also from the soil's parent materials, which contain metal-bearing minerals. For example, Site 3 exhibited a very high apatite content (13.31%) in combination with moderate pyrite (2.73%), indicating a high potential for metallic element release through a combination of geogenic weathering and anthropogenic inputs from intensive phosphate fertilization. In contrast, Site 4, derived from natural shrubland, was dominated by clay (55.42%) and sillimanite (9.74%), with no presence of pyrite and apatite. This indicates a more advanced degree of weathering and a lower risk of heavy metal release. However, sillimanite in acidic soils still has the potential to increase aluminum toxicity, which may lead to impaired root growth and disrupted microbial activity (Kabata-Pendias, 2011). These findings align with global studies that highlight two primary sources of heavy metals in soils: geogenic and anthropogenic, emphasizing the importance of understanding the migration and mobilization mechanisms of each type (Mandal et al., 2024; Wang et al., 2023).

Furthermore, land use also plays a crucial role in shaping mineral dynamics and risks associated with trace elements. Intensively cultivated horticultural land, which receives continuous fertilizer and pesticide inputs, exhibits the coexistence of pyrite, apatite, and cristobalite. This coexistence suggests that anthropogenic activity can accelerate the release of heavy metals from soil minerals by altering soil chemical properties, particularly pH and redox conditions. For example, the high content of apatite and pyrite in Site 3 increases the risk of Pb and Cd mobilization, especially in soils with low pH and high redox activity (Alloway, 2013; Zhao et al., 2020). By contrast, natural shrubland exhibits better mineralogical stability with a lower risk of mobilizing trace elements, although sillimanite remains a concern due to its potential contribution to aluminum toxicity.

Topography is also a crucial factor in controlling mineral weathering and the mobility of heavy metals. At Site 1, which is located on moderately steep slopes (slope 26–40%), the presence of feldspar (65.49%) along with pyrite and apatite indicates a heightened risk of erosion. Such erosion processes can accelerate the exposure of subsoil layers and enhance the mobilization of heavy metals to the surface environment (Fan et al., 2016). In contrast, situated on very steep slopes (>40%) but still covered with shrub vegetation, Site 4 does not exhibit the presence of pyrite or apatite, indicating a lower inherent risk of sulfide contamination; however, the potential for aluminum toxicity remains a concern.

Table 3 summarizes the potential trace elements derived from various soil minerals in Kejajar and their implications for soil and plants. Although the concentration of heavy metals in the study area remains largely within sub-toxic limits, their presence and gradual accumulation may pose significant risks to the sustainability of horticultural systems in volcanic highlands. Trace elements, such as Cu, Zn, Pb, As, and Cd, have the potential to disrupt long-term soil fertility through several mechanisms, including: (i) inhibiting the absorption of macro- and micronutrients; (ii) reducing soil microbial activity; and (iii) accumulating in crop tissues, thereby compromising both yield quality and food safety (Acharya et al., 2023; Alloway, 2013; Kabata-Pendias, 2011). These negative impacts are likely to be more pronounced on steep slopes prone to erosion, as erosion processes can expose heavy metal-bearing minerals, thereby increasing the likelihood of absorption by plants (Deer et al., 2013; Velde, 1995).

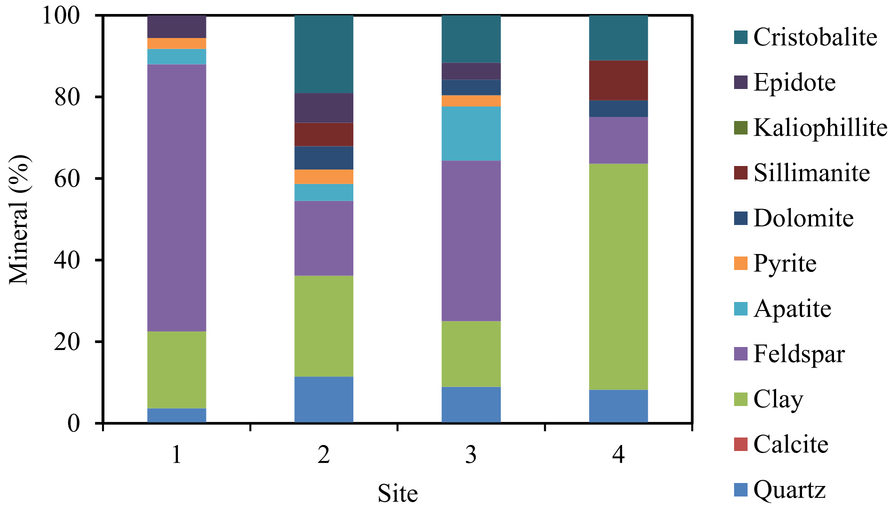

Figure 2. Soil Mineral Composition across Different Geological Formations Based on XRD Analysis Using Bulk Powder Samples Prepared with a Malvern Panalytical Empyrean Series 3 (Floor-Stand Powder X-ray Diffractometer)

Table 3. Potential trace elements from soil minerals in Kejajar and their implications for soil and plants

Mineral Type	Main Trace Elements	Implications for Soil & Crops	References
Epidote	Fe, Mn, Cu, Zn	Excess Cu & Zn reduce microbial activity, disrupt nutrient balance, cause chlorosis, and decrease vegetative growth.	Acharya et al., 2023; Alloway, 2013; Deer et al., 2013
Clay Minerals (Illite, Kaolinite)	Pb, Zn, Cu, Mn	Pb binds to clay fractions, reduces the availability of essential nutrients, inhibits photosynthesis, and decreases plant growth.	Acharya et al., 2023; Kabata-Pendias, 2011; Velde, 1995
Pyrite	Fe, S, As, Pb, Cd	Oxidation of pyrite accelerates soil acidification; As & Cd disrupt microbial communities, lower plant biomass, and inhibit root development.	Acharya et al., 2023; Smedley & Kinniburgh, 2002
Apatite	Ca, P, Sr, As	The long-term accumulation of As and Cd interferes with nutrient absorption and reduces plant growth.	Acharya et al., 2023; Filippelli, 2008
Feldspar	K, Na, Ca, Al, Si (trace Pb, Zn)	Pb/Zn in the clay fraction binds with Fe/Al oxide, potentially causing phytotoxicity when highly accumulated.	Deer et al., 2013; Acharya et al., 2023
Dolomite	Ca, Mg, Fe, Mn	Excess Fe & Mn triggers micronutrient imbalances, causing chlorosis and Mn toxicity in plants.	Klein & Dutrow, 2007; Alloway, 2013
Cristobalite & Quartz	Pure SiO_2	No direct effects on nutrients, but the silica surface can absorb heavy metals and affect their bioavailability.	Deer et al., 2013

Recent production statistics offer a notable example of the decline in horticultural productivity in Wonosobo. As shown in Table 4, cabbage production decreased from 29.3 thousand tons in 2020 to 17.2 thousand tons in 2023, while leek production dropped from 35.7 thousand tons in 2021 to 26.45 thousand tons in 2022 (BPS Wonosobo Regency, 2020; 2023). In addition, Figure 3 illustrates the downward trend in potato and cabbage yields between 2017 and 2021. Potato production declined from 462 thousand quintals in 2017 to 409 thousand quintals in 2021, while cabbage decreased from 347 thousand quintals in 2017 to 297 thousand quintals in 2021. Although potato yields remain higher than those of cabbage, both commodities demonstrate a consistent decline in recent years. These statistics and visualizations are not merely descriptive; they serve as concrete examples of how horticultural production has been declining over time.

This overall decline cannot be attributed solely to agronomic or climatic drivers, but may also be linked to the gradual accumulation of potentially toxic trace elements in volcanic soils, which impair crop performance. Global evidence shows that even at low concentrations, elements such as Cd, Pb, As, and Hg can disrupt soil biological processes, impair plant physiology, and ultimately reduce long-term productivity (Acharya et al., 2023). Accordingly, the results emphasize the urgency of implementing integrated land management strategies that include regular monitoring of trace elements, utilizing low-contaminant fertilizer sources, and applying remediation techniques such as biochar amendment, phytoextraction, or nanomaterial-based adsorbents (Smedley & Kinniburgh, 2002). These approaches are particularly critical for sustaining horticultural farming systems in steep volcanic landscapes such as Kejajar.

Table 4. Production of cabbage and leek in Kejajar from 2020 to 2023

Commodity	Production 2020	Production 2021–2023*	Trend Indications	References
Cabbage	29,319 tons	2023: 17,166 tons	Significant decline	(wonosobokab.bps.go.id, web-api.bps.go.id)
Leek	35,756 tons	2021: 35,704.8 tons 2022: 26,450 tons	Dramatic decline	(BPS 2020-2023)

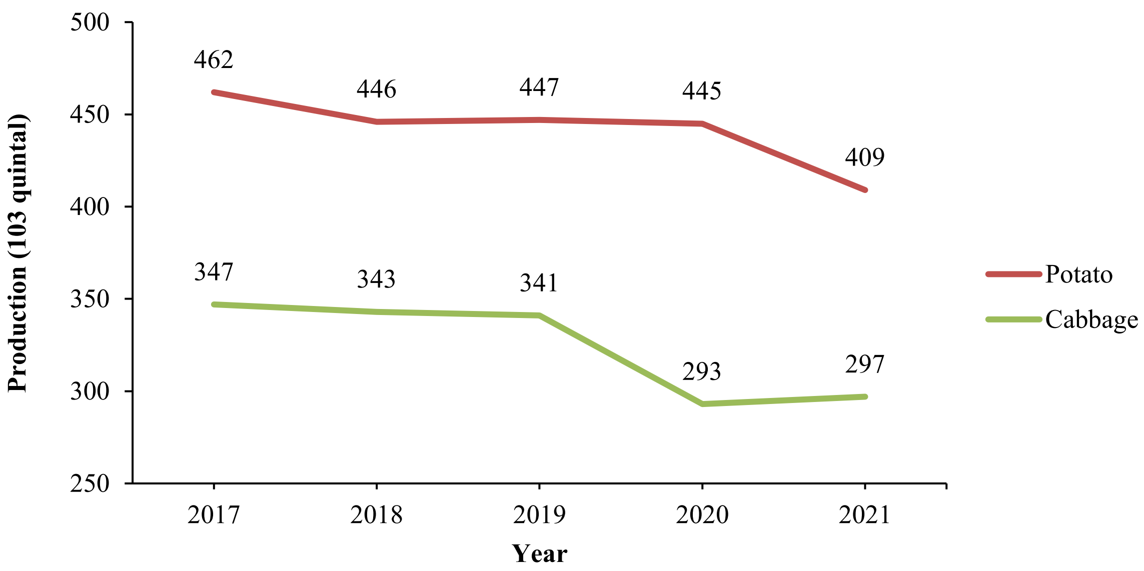

Figure 3. Potato and Cabbage Production in Kejajar District (in thousand quintal), 2017–2021 (source: Central Statistics Agency of Central Java Province, 2022)

4. Conclusion

This study found that Andisols dominate the volcanic highlands of Kejajar District, characterized by high cation exchange capacity, low bulk density, rich organic matter, and strong water-holding ability. Mineralogical analysis revealed the presence of feldspar, epidote, clays, apatite, and pyrite, which can release both essential (Zn, Cu, Fe, Mn) and toxic (Cd, Pb, As) trace elements through weathering and human activity. Despite high chemical fertility, horticultural lands exhibited poorer physical and biological soil quality than shrublands, indicating that management practices primarily focus on chemistry. This imbalance highlights the need for integrated soil management that addresses the chemical, physical, and biological aspects. Additionally, the accumulation of geogenic trace elements under intensive use may harm soil quality, plant health, and productivity. Therefore, sustainable volcanic horticulture requires strategies such as monitoring minerals and trace elements, controlling pH levels, reducing the use of contaminated fertilizers, improving organic matter stability, and applying suitable remediation technologies.

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