Journal of Smart Agriculture and Environmental Technology
e-ISSN:3021-8802
Vol. 2, No. 2, August 2024
https://josaet.com | https://doi.org/10.60105/josaet.2024.2.2.50-60

Research Paper

Soil Development and Land Suitability for Cacao on Sandstone and Pumice Breccia in the Semilir Formation in Ponjong District, Gunungkidul Regency, Indonesia

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Article History: Received: November 7, 2023, Accepted: March 4, 2024

Abstract
The parent material of the Semilir Formation, which consists of breccia pumice and sandstone, was located in the villages of Sawahan and Umbulrejo, Ponjong district, and it influences the genesis and soil types. This study utilized survey and laboratory analysis methods. Two soil profiles were studied: the first profile was located in Sawahan Village with breccia pumice as the parent material, while the second profile was in Umbulrejo Village with sandstone as the parent material. The research results indicated that soils developed from breccia pumice had diagnostic horizons of umbric epipedon and argillic endopedon with an advanced soil development stage. Soils developed from sandstone had diagnostic horizons of umbric epipedon and cambic endopedon with a young soil development stage. This affects the chemical properties of the soil. Soils formed from pumice breccia tend to have base saturation of less than 50% with low exchangeable bases, while soils formed from sandstone have base saturation of >50% with high exchangeable bases. Soils developed from breccia pumice and sandstone have soil classification as Typic Paleudults and Typic Dystrudepts. These soil types are suitable for cocoa plant cultivation; however, they require mechanical conservation through terrace construction and improved drainage by incorporating organic materials or compost into the soil, which can significantly enhance soil porosity, enabling better water retention and drainage.

Keywords
Pumice breccia, Sandstone, Semilir formation, Soil classification, Soil genesis

1. INTRODUCTION

Various soils in Yogyakarta have been extensively studied, and the majority of the area knows the types of soil and their potential. However, some areas in Yogyakarta are still mountainous and have not had their potential well-documented. Therefore, many aspects need to be researched regarding morphology, soil classification, and land use potential.

The villages of Sawahan and Umbulrejo, Ponjong District, Gunungkidul are part of the Western South Mountain Zone (Yuditama et al., 2022). This region stands out due to its unique landscape, which differs from other areas, and the way of life of its inhabitants, which has developed through adaptation to the physical environment. The majority of the land in the Kapanewon of Ponjong is used for cultivation (Nuraini and Pramono, 2013). Ponjong District, in Gunungkidul Regency, receives high precipitation due to its high elevation, which is in sync with high humidity. The environmental conditions are dominated by hilly terrain, serving as rain catchment areas, and featuring natural caves and rivers as water sources. The abundant water in the Ponjong District serves as a source of evaporation, significantly influencing the frequency of precipitation. The closer an area is to this source of evaporation, the more frequently it experiences rain.

In geological terms, this region belongs to the Semilir Formation. The Semilir Formation, located in the villages of Sawahan and Umbulrejo, Ponjong District (Figure 1), is known to contain exposed rocks, including (1) pumice breccia, (2) lapilli tuff interbeds, (3) carbonate lapilli tuff, and (4) sandstone. This is because the Semilir Formation was deposited in an environment that transitioned from the sea to the land (Surono, 2008). The Semilir Formation in the villages of Sawahan and Umbulrejo, Ponjong District (Figure 1).

The presence of various rock constituents and high precipitation in the Ponjong District, Gunungkidul Regency, is one of the factors that can influence the nature and characteristics of the soil. The soil-forming factors, including parent material, climate, organisms, topography, and time, have the potential to affect the weathering processes, resulting in several soil variations with potentially different characteristics. Therefore, Kapanewon Ponjong is an intriguing area for research concerning soil genesis and classification.

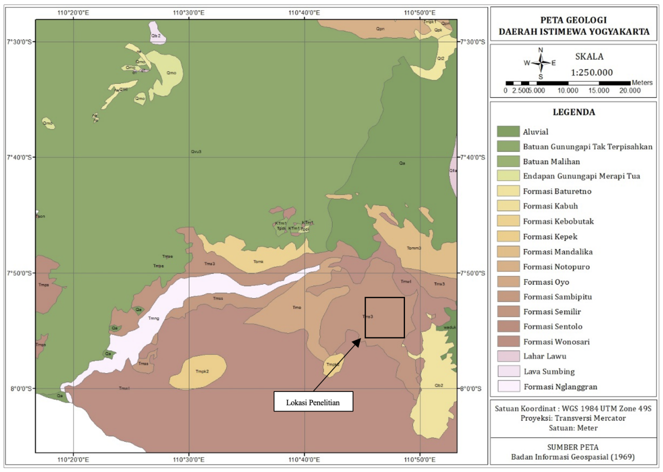

Figure 1. Geological Map of the Research Area according to the National Geospatial Information Agency (1969)

This research aimed to identify soil genesis based on the differences in parent materials and to classify soil types according to the Soil Taxonomy, National Soil Classification, and World Reference Base for Soil Resources (WRB). Additionally, the research aims to evaluate land suitability and limiting factors for cocoa cultivation in Ponjong District, Gunungkidul Regency. Understanding soil genesis, classification, and land suitability for cocoa is crucial as it helps in understanding soil properties and conditions. This knowledge serves as a foundation for land utilization and improving cocoa production.

2. EXPERIMENTAL SECTION

2.1 Research Location

The research location is in the villages of Sawahan and Umbulrejo, Ponjong District, Gunungkidul Regency, D.I. Yogyakarta, Indonesia at an elevation ranging from 500 to 600 m asl. Ponjong District falls into a somewhat wet climate category, this is based on calculating rainfall data so that it is obtained. The temperature in Kapanewon Ponjong has an average monthly temperature of 23.79°C and a soil temperature of 25.29°C, classifying it as an isohiperthermic soil temperature regime with a Udic moisture regime.

The research location, in the villages of Sawahan and Umbulrejo, Ponjong District features undulating topography with hilly landforms. The soil profile locations are situated at elevations ranging from 584 m asl to 600 m asl, with steep slopes. Land use in Ponjong District is primarily dedicated to terrace farming. The widely developed commodity there is cocoa plants (Figure 2), dominating the locations from upstream to downstream. However, cocoa production has not reached its maximum potential due to several influencing factors. One of them is the soil type, according to Hidayanto et al. (2020) Typic Paleudults and Typic Dystrudepst, which generally have low water retention capacity. This means that during excessive rainfall, the soil's low water retention capacity renders it ineffective for the plants. Therefore, an evaluation of land suitability for cocoa is conducted to identify limiting factors in cocoa production and to apply appropriate interventions.

Figure 2. Cacao Commodity in Ponjong District, Gunung Kidul, Indonesia

2.2 Materials and Methods

This research was conducted using a survey method. The selection of observation locations for soil profiles in the villages of Sawahan and Umbulrejo, Ponjong District, Gunungkidul Regency, was carried out intentionally (purposive sampling). Two soil profiles were created based on the Land System Map, resulting in two soil profile points with similar land use (terrace farming), steep slopes, and relatively similar elevations ranging from 500 to 600m asl. The first soil profile was in Sawahan village, Ponjong District, and the second soil profile was in Umbulrejo village, Ponjong District. Both locations had soils derived from the constituent rocks of the Semilir Formation, including sandstone and pumice breccia. This area is characterized by high precipitation. The research was conducted from January to August 2023. Laboratory analyses were carried out at the Soil Resources Laboratory at UPN "Veteran" Yogyakarta and the Agricultural Technology Assessment Center in Ungaran.

The materials and equipment used in this research include geological maps of Sawahan and Umbulrejo Villages, land use maps of Sawahan and Umbulrejo Villages, slope maps of Sawahan and Umbulrejo Villages, topographic maps of Sawahan and Umbulrejo Villages, aspect maps of Sawahan Village, and land system maps resulting from overlay analysis. These maps and data sources were instrumental in conducting the research, enabling the selection of appropriate locations and the analysis of various environmental and topographical factors in the study area

The soil physical properties include texture, bulk density, bulk volume, porosity, and soil chemical properties include pH in the extract of H_2O, KCl, and K_2SO_4, electrical conductivity (EC), cation exchange capacity (CEC), exchangeable cation (Ca, Mg, K, Na), organic carbon, base saturation (BS) and sand mineral fraction

3. RESULTS AND DISCUSSION

3.1 Rock Lithology and Depositional Environment

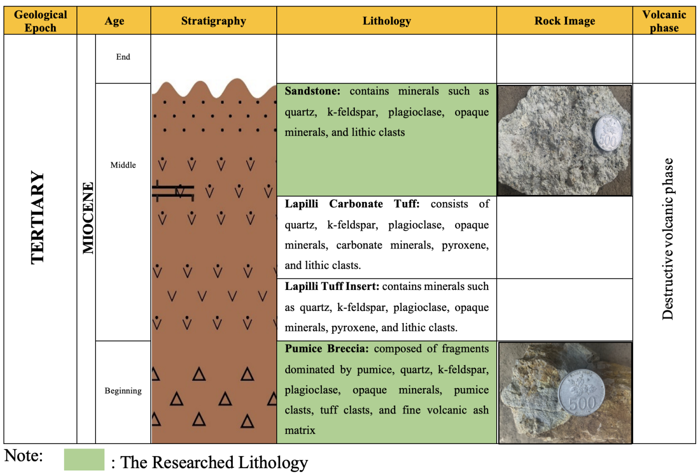

Figure 3. Lithology of Sandstone and Pumice Breccia Found in the Stratigraphy of the Semilir Formation

The soil in Ponjong District consists of mineral soil derived from the parent materials of the Semilir Formation, which includes sandstone and pumice breccia. These rock constituents indicate that this formation was deposited in an environment transitioning from the sea to land. According to Morina et al. (2014), sandstone and pumice breccia originate from a shallow marine depositional environment during a volcanic destructive phase. According to Christopher and Kendall (2001), pumice breccia is associated with a marine depositional environment, while sandstone is related to a transitional environment (Figure 3). Pumice breccia contains larger and lighter volcanic materials compared to sandstone, which means that lighter materials will be transported farther than heavier materials.

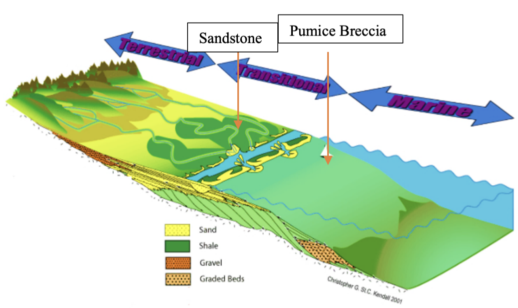

Figure 4. Classification of Depositional Environment according to (Christopher and Kendall, 2001)

3.2 Soil Genesis and Soil Morphology

The genesis of the two soil profiles studied shows differences in both physical and chemical properties based on the composition of their parent rock materials (Table 1). The parent rock of the first soil profile, Breccia pumice, is composed of fragments dominated by pumice, quartz minerals, k-feldspar, plagioclase, opaque minerals, pumice clasts, tuff clasts, and fine volcanic dust matrix. The parent rock of the second soil profile, sandstone, consists of quartz minerals, k-feldspar, plagioclase, opaque minerals, and lithic clasts.

Both rocks originate from an ancient volcano that erupted and deposited in a shallow marine environment. The influence of this deposition largely depends on the receiving soil material and the origin of the transported material (Nurcholis et al., 2019). However, Breccia pumice has a longer pathway compared to sandstone, resulting in Breccia pumice having highly weather-resistant minerals and being acidic, making the soil developed from it resistant to weathering. Sandstone is intermediate, causing the soil derived from it to undergo easier weathering, releasing Si, Al, and Fe, resulting in high clay content in the soil. This affects the soil chemistry, where soil formed from Breccia pumice tends to have a base saturation of < 50% with low exchangeable bases, whereas soil formed from sandstone has a base saturation of > 50% with high exchangeable bases.

The soil morphology that develops from pumice breccia and sandstone in the Semilir Formation located in the Kapanewon of Ponjong Figure 4.

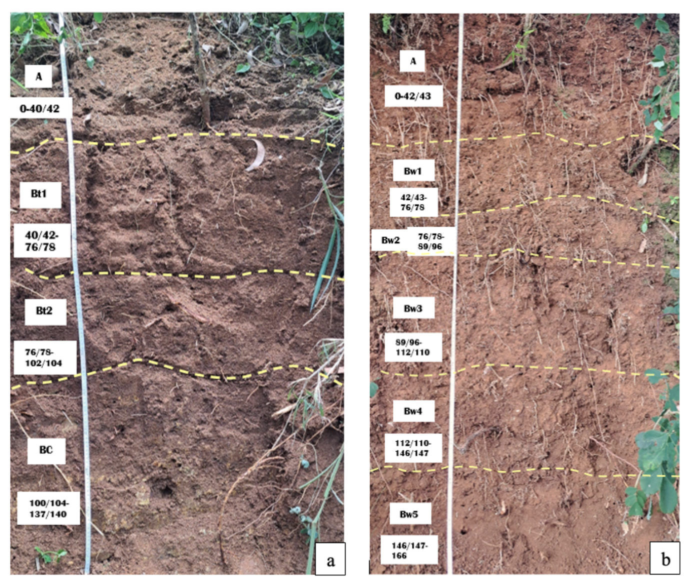

Figure 5. The Soil that Develops from Pumice Breccia (a), The Soil that Develops from Sandstone (b)

The soil that develops from pumice breccia has four horizons with gradual horizon boundaries, including A-Bt1-Bt2-BC (Figure 3.a). Horizon A-Bt1 has a clay loam texture, a 7.5YR color, and an angular blocky structure. Horizon Bt2-

BC has a clay texture, a 5YR color, and an angular blocky structure. As noted by Fatai et al. (2017), the color of Ultisol soil in the upper soil layers is typically brownish-yellow and becomes more reddish with increasing depth. The soil experiences an increase in clay content and organic carbon as the soil depth increases. Additionally, this soil exhibits oxic characteristics. The profile features an umbrik epipedon and an argillic endopedon.

The soil developed from the sandstone parent material (Figure 5.b), which is part of the constituents of the Semilir Formation, is located in the villages of Umbulrejo and Sawahan, in the Kapanewon of Ponjong, Gunungkidul. It is situated at an elevation of 584m asl, with a slope inclination of 28% (steep), facing the southwest. The soil developed from sandstone has six horizons with gradual horizon boundaries, including A-Bw1-Bw2-Bw3-Bw4-Bw5, and exhibits oxic properties. The profile features an umbrik epipedon and a cambic endopedon.

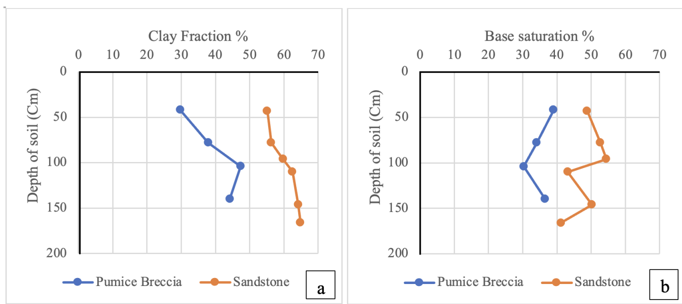

Figure 6. The increase in clay fraction (a) and the increase in base saturation (b)

Figure 5.a shows that the B horizon in the soil developed from pumice breccia at a depth of 78 cm to 104 cm experiences a significant increase in the clay fraction, ranging from 3-10%. As a result, this B horizon has an argillic epipedon. Additionally, the increase in the clay fraction is due to illuviation processes, resulting in this B horizon being symbolized as Bt1 and Bt2. This is consistent with the findings of Aditya et al. (2021), who explained that illuviation occurs due to the movement of clay fractions accumulating in the B horizon, influenced by high precipitation.

In contrast, the B horizon in the soil developed from sandstone at a depth of 78 cm to 166 cm experiences a less significant increase in the clay fraction. However, there is a noticeable color difference, leading to the development of a cambic epipedon. The symbol w (color development) is used, symbolizing it as Bw1, Bw2, Bw3, Bw4, and Bw5.

Based on Figure 5.b the base saturation (BS) in the soil developed from pumice breccia is < 50%, which is in line with the low exchangeable bases, resulting in lower fertility levels. This aligns with what (Damanik et al., 2013) explained, that the low exchangeable bases influence the low base saturation. In the case of soil developed from sandstone, the base saturation is $\geq$ 50%, which corresponds to high exchangeable bases (Table 3). This is consistent with what Syahputera and Fauzi (2015) mentioned, that low base saturation and the presence of the Bt horizon in soil developed from pumice breccia are characteristics of Ultisol soil. Conversely, high base saturation in soil developed from sandstone, along with the presence of the Bw horizon, is one of the characteristics of Inceptisol soil. Rajamuddin and Sanusi (2014) stated that Inceptisol soil is immature, with a weak profile development characterized by the presence of the Bw horizon and relatively high base saturation.

3.3 Soil Physical Properties

The results of the analysis of the physical properties of the soil in each layer of the soil profile including soil texture, bulk volume (BV), specific gravity (BD), and porosity are presented in Table 1. It can be seen that the first soil profile has two texture classes, namely Clay Loam and Clay, while the second profile only has one class, namely Clay.

Based on Tabel 1, the soil developed from pumice breccia has several horizons. Horizon A-Bt1 has a clay loam texture class, while horizon Bt2-BC has a clay texture class. Bulk density (BD) is the ratio of the soil mass to the particle volume plus pore space. The bulk density of this soil ranges from 1.03 g/cm^3 to 1.21 g/cm^3. The particle density of the soil developed from pumice breccia is quite high, measuring 2.28 g/cm^3, particularly in horizon Bt2, due to the presence of minerals such as quartz, which can increase the soil's bulk density.

The soil developed from sandstone also has multiple horizons, and all of them have a clay texture class (A-Bw1-Bw2-Bw3-Bw4-Bw5). The bulk density of this soil ranges from 1.02 g/cm^3 to 1.21 g/cm^3. Horizon A of this soil has a bulk density of 2.19 g/cm^3, which can be attributed to the content of the low coarse fraction and a high clay.

Both of these soils have nearly the same porosity. Soil porosity is the percentage of the total soil volume that is occupied by both water and air compared to the total soil volume. The soil developed from pumice breccia has an average porosity of 46.37%, while the soil developed from sandstone has an average porosity of 45.54%. The soil developed from pumice breccia has a higher porosity because pumice breccia consists of coarse materials with a relatively slower weathering rate. As a result, the dominance of coarse materials leads to a greater pore space in the developing soil.

3.4 Soil Chemical Properties

The chemical analysis results of the soil properties in both soil profiles include pH in the extract of H_2O, KCl and K_2SO_4, electrical conductivity (EC), cation exchange capacity (CEC), Ca, Mg, K, Na, and organic carbon content as presented in Table 2 and 3. In Table 2, the pH difference results are shown, which are utilized to determine the oxidic properties and various charges within each layer of

Table 1. The analysis results of soil texture, bulk volume (BV), bulk density (BD), and porosity

Horizon	Color of Soil	Soil Fractions (%)				Bulk Volume (g/cm^3)	Bulk Density (g/cm^3)	Porosity (%)
		Sand	Silt	Clay	Class			
The soil that developed from pumice breccia								
A	7.5YR ¾	33.39	36.88	29.73	CL	1.03	1.97	47.84
Bt1	7.5YR 4/4	30.38	31.67	37.94	CL	1.21	1.97	38.80
Bt2	5YR 4/6	23.08	29.56	47.36	C	1.11	2.28	51.15
BC	5YR ¾	26.42	29.35	44.24	C	1.17	2.25	47.67
The soil that developed from sandstone								
A	5YR ¾	18.79	26.09	55.13	C	1.12	2.19	48.77
Bw1	5YR 4/6	16.04	27.65	56.30	C	1.12	2.09	46.30
Bw2	7.5YR ¾	7.59	32.63	59.77	C	1.21	2.05	41.00
Bw3	7.5YR ¾	14.04	23.43	62.52	C	1.17	2.05	42.74
Bw4	7.5YR ¾	10.84	24.95	64.22	C	1.00	2.11	51.49
Bw5	5YR ¾	11.33	23.82	64.85	C	1.20	2.10	42.95

Note: CL: Clay Loam; C: Clay

both profiles. This process aids in identifying horizons and classifying the soil in both profiles.

Based on Figure 7.a, it indicates that the soil developed from pumice breccia in horizons A-Bt1-Bt2-BC has positive values, which suggests that the soil profile has oxic properties. Similarly, in the soil profile developed from sandstone, all horizons have positive values, indicating oxic properties.

In Figure 7.b, the soil developed from pumice breccia in horizon A has negative values, smaller than -0.5, which suggests the possible presence of variable-charge clays. In horizons Bt1-Bt2-BC, the positive values indicate the potential presence of variable-charge clays. In the case of the soil developed from sandstone, horizons A-Bw1-Bw2 have negative values, suggesting the absence of variable-charge clays, while horizons Bw3-Bw4-Bw5 have positive values, indicating the possible presence of variable-charge clays.

Table 3, shows that the electrical conductivity of both soil profiles ranges from 0.55 mS/cm to 0.89 mS/cm. The soil developed from pumice breccia exhibits a decreasing trend in electrical conductivity with increasing soil depth. This is influenced by the increase in organic matter content, which acts as an insulator and reduces the electrical conductivity in the soil. On the other hand, the soil developed from sandstone maintains a stable electrical conductivity due to the presence of cations (exchangeable bases), which tends to enhance the presence of salt ions in the soil solution (Suud et al., 2015).

Both soil profiles experience an increase in organic carbon with increasing soil depth (Table 3). This is influenced by the good porosity of both soils, which provides excellent drainage and aeration, maintaining optimal soil moisture conditions for organic matter decomposition by soil microorganisms. Additionally, both soil profiles are located in areas with high rainfall, leading to intensive leaching of the soil. Consequently, Organic-C increases with soil depth.

The presence of organic carbon affects the cation exchange capacity (CEC), resulting in both soil profiles having nearly the same CEC values. Both soils experience a decrease in CEC in horizons closer to the parent material. This aligns with the condition of soils close to the parent material, which tends to have an increase in the sand fraction and a decrease in organic carbon content, reducing their cation-exchange capacity.

Exchangeable bases in the soil developed from pumice breccia and sandstone (Table 2) tend to have a significant amount of Ca^{2+} and Mg^{2+} cations in horizons closer to the parent material, while K^{+} and Na^{+} levels are low. This can be attributed to leaching caused by high rainfall. This leaching affects electrical conductivity (EC) and base saturation (BS). Furthermore, the soil developed from sandstone exhibits a base saturation of >50% with high exchangeable bases, whereas the soil developed from pumice breccia tends to have a base saturation of <50% with low exchangeable bases.

3.5 Resistant Mineral of Coarse Sand Fraction

The identification of highly weather-resistant minerals in the sand fraction from each layer of both profiles is presented in Table 4. The analysis results indicate that quartz minerals (SiO_2), comprising Milky Quartz and Clear Quartz, and opaque minerals in the first profile were found in greater quantities compared to the second profile. In Table

Table 2. The analysis results of pH in H_2O, KCl, and K_2SO_4

Horizon	pH			ΔpH	
	H_2O	KCl	K_2SO_4	K_2SO_4 - H_2O	KCl - H_2O
The soil that developed from pumice breccia					
A	4.17	4.003	4.92	0.4	-0.17
Bt1	3.8	4.13	4.9	1.1	0.33
Bt2	4.08	4.13	5.15	1.07	0.05
BC	4.01	4.43	5.08	1.07	0.42
The soil that developed from sandstone					
A	5.3	3.91	5.41	0.11	-1.39
Bw1	4.86	4.3	5.32	0.46	-0.56
Bw2	4.65	4.4	5.29	0.64	-0.25
Bw3	4.42	4.68	5.38	0.96	0.26
Bw4	4.22	4.59	5.5	1.28	0.37
Bw5	4.1	4.58	5.48	1.38	0.48

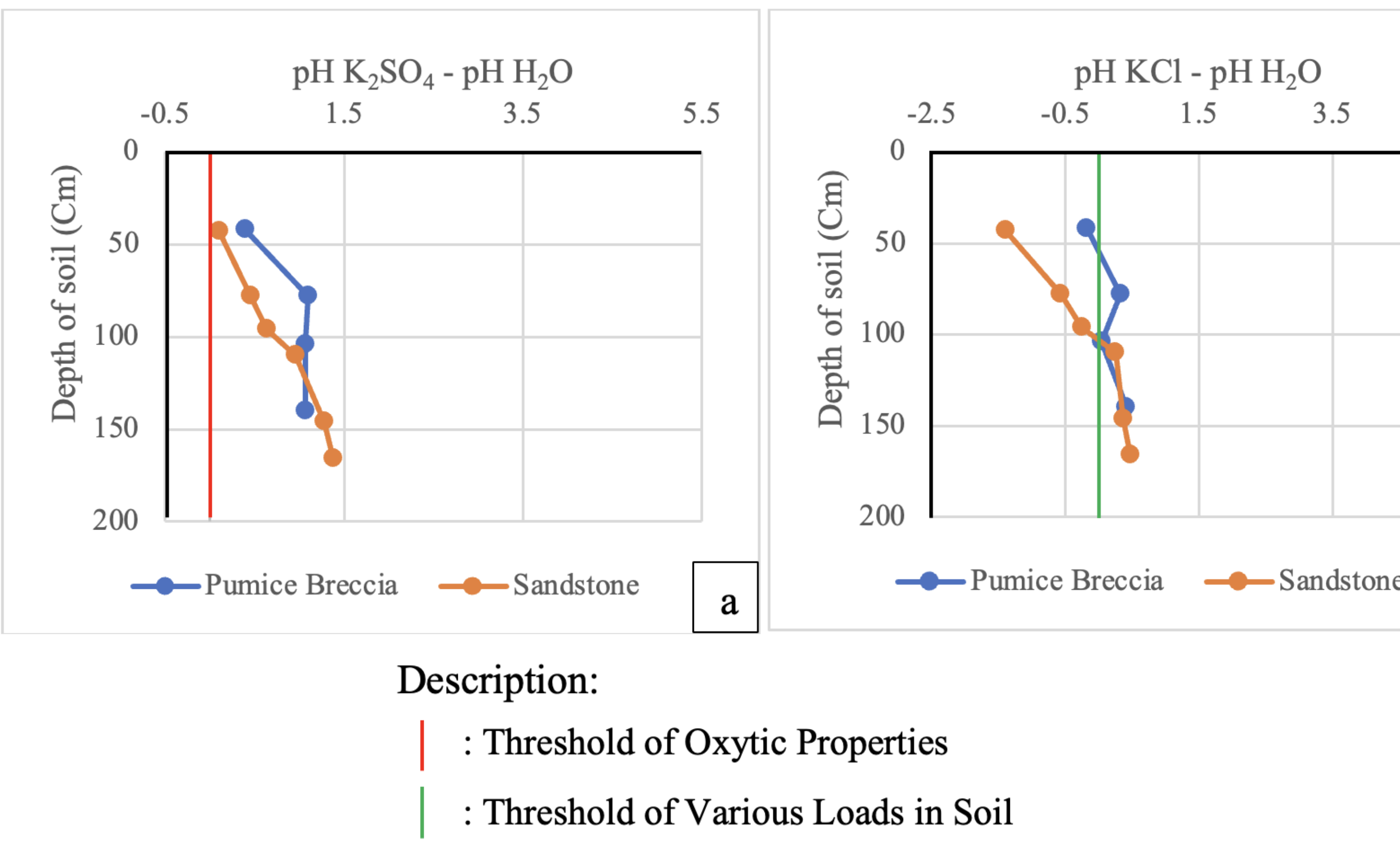

Figure 7. (a) ΔpH (K_2SO_4-H_2O) and (b) ΔpH (KCl-H_2O) in the soil developed from pumice breccia and sandstone

Table 3. The analysis result of EC, Organic Carbon, Exchangeable Cation (Ca, Mg, K, Na), CEC, CEC of Clay, and Base Saturation

Horizon	EC	Organic - C (%)	Exchangeable Cation (cmol(+) /kg)				CEC	CEC of Clay	BS (%)
			Ca^{2+}	Mg^{2+}	K^+	Na^+			
The soil that developed from pumice breccia									
A	0.89	0.8	5.51	2.35	0.33	0.06	21.15	71.14	39.01
Bt1	0.56	0.78	4.02	1.85	0.33	0.09	18.43	48.58	34.13
Bt2	0.55	1.02	3.82	1.68	0.25	0.07	19.21	40.56	30.30
BC	0.59	0.87	4.44	1.79	0.25	0.07	17.91	40.48	36.57
The soil that developed from sandstone									
A	0.78	0.85	7.62	2.94	0.24	0.08	22.28	40.41	48.83
Bw1	0.68	0.57	8.74	3.18	0.21	0.07	23.14	41.10	52.72
Bw2	0.8	0.98	10.24	3.63	0.28	0.07	26.12	43.70	54.44
Bw3	0.76	0.85	7.63	2.82	0.28	0.09	25.06	40.08	43.18
Bw4	0.84	1.04	6.98	2.55	0.25	0.09	19.66	30.61	50.20
Bw5	0.82	1.12	5.23	1.99	0.29	0.08	18.42	28.40	41.21

4, it's evident that clear quartz dominates over milky quartz in the breccia pumice. This is due to a lengthy and complex crystallization process that occurred in the breccia pumice, which was ejected far from its origin. This distance caused the originally milky quartz to undergo significant friction and high pressure, enhancing the clarity of the quartz.

Table 4. The Resistant Mineral of Coarse Sand Fraction in Soils

Horizon	Resistant Mineral Composition				
	Opaque	Muddy Quartz	Clear Quartz	Zircon	Amount (%)
The soil that developed from pumice breccia					
Bt1	34	2	40	1	76
Bt2	38	1	47	-	86
BC	30	1	35	-	66
The soil that developed from sandstone					
Bw3	29	2	7	-	38
Bw4	23	2	15	-	40
Bw5	33	3	21	-	57

Table 4, shows that the soil developed from pumice breccia has a higher proportion of refractory sand-sized minerals compared to the soil developed from sandstone. This indicates that the soil developed from pumice breccia has undergone more intensive weathering than the soil developed from sandstone. The abundance of opaque minerals can be attributed to environmental conditions with high rainfall or poor drainage, leading to the accumulation of iron-rich minerals in the form of opaque minerals. Opaque minerals primarily consist of magnetite and ilmenite, both of which are shiny black in color (Allen and Hajek, 1989). These minerals belong to the group of refractory minerals, and they often dominate the primary mineral composition in the soil. Soils dominated by opaque minerals indicate advanced weathering and a deficiency in nutrient sources.

The abundance of clear quartz in pumice breccia is due to a long and complex crystallization process that occurred in pumice breccia when it was ejected from its source. This process resulted in the initially muddy quartz becoming clear due to high friction and pressure, which increased the clarity of the quartz. The presence of a high amount of quartz indicates that the soil has undergone advanced development, has low nutrient reserves, and the parent material of the soil is acidic. Additionally, quartz can provide structural stability to soil aggregates, maintaining the integrity and resistance of soil structure against erosion (Abdillah, 2020).

3.6 Weathereable Mineral Composition of Coarse Sand Fraction

The results of the identification of easily weathered minerals in the sand fraction from each layer of both profiles are presented in Table 5. The analysis indicates that easily weathered minerals, including weathered minerals, rock fragments, andesine, labradorite, and hypersthene, are more abundant in the soil of the second profile compared to the soil of the first profile.

Table 5 shows that the soil developed from sandstone has a higher content of rock weathering, rock fragments, andesine, and labradorite compared to the soil developed from pumice breccia. The presence of rock weathering and rock fragments in the soil indicates that it has undergone the weathering of minerals, breaking the crystalline

Table 5. The Wetheareable Mineral Composition Coarse Sand Fraction in Soils

Horizon	Weathereable Mineral Composition					
	Weathered Mineral	Rock Fragment	Andesine	Labradorite	Hipersten	Amount (%)
The soil that developed from pumice breccia						
Bt1	5	5	2	3	6	21
Bt2	4	3	-	2	3	12
BC	6	3	3	9	7	28
The soil that developed from sandstone						
Bw3	17	9	2	15	3	46
Bw4	12	6	7	20	7	52
Bw5	13	9	6	10	2	40

structure of rocks and releasing essential nutrients such as calcium (Ca) and magnesium (Mg) (Suryani et al., 2015). The presence of rock fragments, andesine, and labradorite in the soil developed from sandstone suggests that this soil has not experienced advanced weathering. This is because the weathering process has not been sufficient to alter the minerals inside the rock fragments, which are easily weathered minerals, although their types are not detected. The amount of easily weathered minerals (weatherable minerals) can reflect the nutrient reserves in the soil available for long-term plant growth.

The soil developed from pumice breccia has a higher content of hypersthene compared to the soil developed from sandstone. Hypersthene is an easily weathered mineral, and its presence in the soil serves as a source of calcium (Ca) and magnesium (Mg). Hypersthene is a silicate mineral that belongs to the pyroxene group. It typically has a dark brown to blackish-green color and a submetallic luster (Abdillah, 2020). The presence of relatively high levels of hypersthene indicates that the soil has undergone weathering processes.

3.7 Horizons and Diagnostic Characteristics

The soil profile developed from pumice breccia in the Semilir Formation has an epipedon with a moist color value of 3, a thickness of >18 cm (40/42 cm), and a base saturation of less than 50% (39.01%), classifying it as an umbrik epipedon. The lower distinguishing horizon (endopedon) shows an increase in clay content of 8.21%, making it an argillic endopedon.

The soil profile developed from sandstone in the Semilir Formation also has an epipedon with a moist color value of 3, a thickness of >18 cm (42/43 cm), and a base saturation of less than 50% (41.21%), classifying it as an umbrik epipedon. The lower distinguishing horizon (endopedon) does not exhibit a significant increase in clay content, and it has a cation exchange capacity (CEC) >16 cmol(+) per kg, categorizing it as a kambic horizon.

3.8 Soil Development Processes

The pumice breccia and sandstone originate from ancient volcanoes and were ejected and deposited in a shallow marine environment. However, pumice breccia had a longer travel path compared to sandstone, resulting in pumice breccia having high weathering-resistant minerals and acidic properties. This makes soils derived from pumice breccia resistant to weathering. Sandstone is intermediate, so soils derived from it weather easily and can release Si, Al, and Fe, leading to higher clay content in the soil. This affects the chemical properties of the soil. Soils formed from pumice breccia tend to have base saturation of less than 50% with low exchangeable bases, while soils formed from sandstone have base saturation of >50% with high exchangeable bases.

According to Birkeland (1984), as cited in Manik et al. (2017), soils with strong soil development are characterized by the presence of a B horizon with increased clay content and a more developed structure. Soils with early-stage development are characterized by an A-Bw horizon. Therefore, soils developed from pumice breccia exhibit strong development, while soils developed from sandstone show early-stage development.

3.9 Soil Classification

1. Soil developed from pumice breccia:
   a. Soil Classification according to Soil Taxonomy
      The presence of argillic horizons and a base saturation (SB) of less than 35% classifies the soil as an Ultisols order. Its udic soil moisture regime places it in the Udults suborder. The absence of densic, lithic, paralithic, or petroferric contacts within 150 cm from the mineral soil surface and no decrease in clay content by 20% or more categorizes it as the Paleudults group. Distinct soil characteristics qualify it for the Typic Paleudults subgroup.
   b. National Soil Classification
      There are no hydromorphic features or argillic

Table 6. Land suitability of Typic Paleudults and Typic Dystrudepts for Cacao

Soil	Land Requirements and Characteristics	Data	Rating	Class
Typic Paleudults	**Temperature (tc)**	23.29 ºC	S1	S1
	Water availability (wa)			
	- Annual Rainfall	2612.79	S2	S2
	- Number of Dry Months	3.6	S2	S2
	Oxygen availability (oa)			
	- Drainage	A bit inhibited	S2	S2
	Rooting medium (rc)			
	- Texture	C, Cl	S1	S1
	- Soil depth (cm)	140 cm	S1	S1
	Nutrient retention (nr)			
	- CEC (cmol/kg)	<24 cmol/kg	S1	S1
	- Base saturation (%)	<50%	S1	S1
	- pH H_2O	<5	S3	S3
	- Organic-C (%)	0.8-1.02	S2	S2
	Erosion danger (eh)			
	- Slope (%)	37%	S3	S3
	Land preparation (lp)			
	- Rock on the surface	<5	S1	S2
	- Rock outcrops	5-15	S2	S2
	Land suitability	S3 eh, S2 wa, oa dan lp		
Typic Dystrudepts	**Temperature (tc)**	23.29 ºC	S1	S1
	Water availability (wa)			
	- Annual Rainfall	2612.79	S2	S2
	- Number of Dry Months	3.6	S2	S2
	Oxygen availability (oa)			
	- Drainage	A bit inhibited	S2	S2
	Rooting medium (rc)			
	- Texture	C	S1	S1
	- Soil depth (cm)	166 cm	S1	S1
	Nutrient retention (nr)			
	- CEC (cmol/kg)	18-26 cmol/kg	S1	S1
	- Base saturation (%)	>50%	S1	S1
	- pH H_2O	<5	S3	S3
	- Organic-C (%)	0.8-1.12	S2	S2
	Erosion danger (eh)			
	- Slope (%)	28%	S3	S3
	Land preparation (lp)			
	- Rock on the surface	<5	S1	S1
	- Rock outcrops	<5	S1	S1
	Land suitability	S3 eh, S2 wa, oa		

B horizons in the soil, so it does not belong to the Gleisol soil type. The presence of an argillic B horizon with the maximum clay content at a depth of 140 cm classifies the soil as Nitosol. The soil has a base saturation (BS) of less than 50% in the B horizon, placing it in the Nitosol District soil type.

c. Soil Classification according to World Reference Base for Soil Resource (WRB)
The soil has high clay activity and CEC (Cation Exchange Capacity) <24 cmol/kg, so it does not fall under the category of Lixisols. The soil has a base saturation (BS) of less than 50%, and the high clay activity is characterized by the presence of an argillic horizon, hence it falls into the category of Alisols. The soil has an argillic horizon starting at a depth of $\leq$ 100 cm from the soil surface, therefore meeting the primary qualification of Abruptic. The soil has a clay loam texture at a depth of >30 cm, thus meeting the additional qualification of Loamic.

2. Soil developed from sandstone:
   a. Soil Classification according to Soil Taxonomy
   The soil has cambic horizons extending to a depth of 100 cm, classifying it under the order Inceptisols. The soil exhibits other characteristics of being Udic in moisture regime, placing it under the suborder Udepts. With a base saturation (BS) of less than 50% and the presence of an umbric epipedon, it falls into the group Dystrudepts. The soil's BS content is >50%, therefore it belongs to the Typic Dystrudepts subgroup.
   b. National Soil Classification
   The soil does not have cambic B horizons, so it does not belong to the Cambisol soil type. The soil has a base saturation (BS) >50%, classifying it as Eutric Cambisol.
   c. Soil Classification according to World Reference Base for Soil Resource (WRB)
   The soil has a base saturation (BS) >50%, so it does not fall into the category of Alisols. The soil features cambic horizons at a depth of >50 cm from the surface, classifying it as Cambisols. It has cambic horizons with a base saturation >50% at depths between 20 cm and 100 cm, thus meeting the primary qualification of Eutric. The soil qualifies as Clayic due to its clay texture at depths between 20 cm and 100 cm.

3.10 Land Suitability for Cacao

I suggest that the author needs to emphasize a detailed discussion of the limiting factors for the Cacao plant, for example by stating clearly the symbols S3 eh, S2 wa, oa and lp (Table 6). Explain it in detail and give some inputs on how to increase actual land suitability to potential soil suitability. These analysis results have to be written in conclusions.

Assessment of land suitability for agriculture using matching includes aligning soil characteristics with land use requirements for agricultural commodities to be cultivated, and adjusting to soil conditions. The matching results show the following:

Addressing the slope factor (S3) in agriculture, especially for cocoa crops, through mechanical conservation via terracing is a great approach. Terracing helps in reducing soil erosion, conserving water, and creating more suitable conditions for planting crops on sloped terrain. The effort to improve water availability and drainage (S2) by incorporating organic materials or compost into the soil can significantly enhance soil porosity. This will enable the soil to retain water better and improve its drainage capacity. This practice helps to prevent waterlogging and ensures proper moisture levels for healthy crop growth.

Combining terracing for slope management with soil improvement techniques like adding organic matter can significantly enhance the agricultural viability of such areas, particularly for cultivating cocoa crops. These methods not only address the challenges posed by slope and drainage but also contribute to sustainable farming practices.

4. CONCLUSION

Based on the research results that have been conducted, the following conclusions:

a. The differences in parent material can influence the characteristics of soil. Pumice breccia is acidic, as predicted from the presence of numerous resistant minerals in the soil developed on it, making soils developed from it resistant to weathering. Sandstone is intermediate in acidity, as predicted from the presence of numerous easily weathered minerals, resulting in soils formed from it being more susceptible to weathering.
b. The soils developed from pumice breccia are classified according to the USDA Soil Taxonomy as Typic Paleudults; according to the National Soil Classification as Nitosol District; and according to the World Reference Base for Soil Resources as Loamic Abruptic Alisols. Soils formed from sandstone are classified according to the USDA Soil Taxonomy as Typic Dystrudepts; according to the National Soil Classification as Eutric Cambisol; and according to the World Reference Base for Soil Resources as Clayic Eutric Cambisols.

ACKNOWLEDGEMENT

We would like to our colleagues at Department of Soil Science, Universitas Pembangunan Nasional Veteran Yogyakarta, for helping us with fieldwork, sampling, and laboratory analysis.

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