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Soil fertility based on mineralogical properties to support sustainable agriculture management

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ABSTRACT

Detailed information on soil mineral composition has been crucial in providing the basis for designing sustainable agricultural practices, as this information offers long-term insights into natural soil fertility. This research aimed to further investigate the characteristics of soil mineral composition as a basis for managing soil fertility. Three soil profiles representing three different parent materials have been examined in the field, and soil samples have been collected for laboratory analysis. Profile 1 originates from the Raung Volcano Rock Formation (Qhvr). Profile 2 originates from the Sukamade Formation (Toms). Profile 3 originates from Puger Formation (Tmp). The presence of Mount Raung volcanic influence results in distinct soil characteristics in Profiles 2 and 3 compared to typical sedimentary and karst rock soils. The sand fraction minerals in all three profiles are predominantly composed of opaque minerals, followed by rock fragments, ferromagnesian mineral series (olivine, augite, hypersthene, and hornblende), plagioclase minerals (anorthite, biotite, and labradorite), iron concretions, epidote, and tourmaline. The clay fraction minerals in all three profiles consist of illite, kaolinite, and quartz. The minerals illite and ferromagnesian groups in all three profiles play a significant role in increasing the availability of potassium, calcium, and magnesium nutrients, thereby reducing the need for fertilizers for these elements. The soils in all three profiles naturally possess good fertility; however, designing a sustainable agricultural system requires consideration of the morphology, landform, and climate of all three profiles.

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1. INTRODUCTION

The physiography of Jember Regency can be divided into 3 parts, namely: the northern part of the quarter volcano lane (Argopuro and Raung mountains), the central part of the middle depression lane, and the southern part including the southern mountain lane (Van Bemmelen, 1949). Based on the geological map of the Jember sheet, the research area falls into 3 different geological formations, namely: the Raung Volcano Rock Formation consisting of lava, volcano breccia, lahar breccia, and tuff originating from Mount Raung and is of Quaternary age (Qhvr), next is the Sukamade Formation composed of claystone intercalated with siltstone and sandstone rocks of Tertiary age (Toms) and the Puger Formation composed of reef limestone intercalated with limestone breccia and tuffaceous limestone rocks of Tertiary age (Tmp) (Sapei et al., 1992).

Mount Raung is a strato-andesitic basaltic type volcano with a caldera measuring 1.75 × 2.25 km at its summit (Moktikanana & Harijoko, 2022). Based on previous research data, lithology, and eruption periods, the stratigraphy of Mount Raung, from the oldest to the youngest, is divided into four phases: Ijen Tua, Suket, Gadung, and Raung. Volcanic activity from all phases produces basal breccia, andesite, and pyroclastic materials (Heriawan et al., 2024; Sabila & Abdurrachman, 2018). Research findings by Sabila and Abdurrachman (2018) demonstrate that analysis of phenocryst abundance and geochemical data variations suggest that the magma series of Mount Raung belongs to the high-K calc-alkaline group originating from the plate convergence boundary in the subduction zone, producing a volcanic arc with characteristics of an active continental margin.

The Sukamade Formation is formed as a result of the deposition of clay, sand, and silt units at depths of 20 to 80 meters below sea level. The deposition process of the

Sukamade formation began from the early Middle Miocene and ended by the middle Miocene. The Sukamade, Merubetiri, and Batuampar formations underwent uplift and folding during the Middle Miocene epoch. This uplifting process led to the formation of hills and valleys. The composition of minerals includes quartz, feldspar, and lithics. Microscopic examination of thin sections of sandstone shows transparent color, grain size of 0.05 – 0.5 mm, mineral composition of quartz 25%, feldspar 35%, lithics 30%, ore minerals 5%, and clay 5% (Derebi, 2019).

According to Van Bemmelen (1949), the Puger Formation is classified within the southern mountain zone, which stretches from the western to the eastern part of the southern region of Java Island. Southern mountains are generally formed by clastic sedimentary rocks and carbonate rocks mixed with volcanic rocks of Tertiary age (Sapei et al., 1992; Surono, 2009). The Puger Formation unit lies above the Batuampar and Sukamade formations. The Puger Formation is formed due to sedimentation processes on the shallow sea floor, and this formation can emerge above the sea surface, forming karst hill landforms with elevations reaching 400 meters above sea level due to uplifting processes (Van Bemmelen, 1949).

The main concept in sustainable agricultural systems is to ensure that the system can produce quality and sustainable food (Tuğrul, 2019). Therefore, long-term stability and efficiency are crucial. Various research results have acknowledged that soil is the source of essential nutrients for plants, and the management of these nutrients will significantly impact plant growth, soil fertility, and agricultural sustainability (Gruhn et al., 2000). The composition and mineralogical properties (sand and clay) impact the soil's chemical, physical, and biological properties, which is a crucial point in sustainable soil management (Anda et al., 2012). Primary minerals are crucial in storing nutrient reserves, while secondary minerals play a significant role in holding cations and anions released from the weathering of primary minerals or fertilizer application (Kome et al., 2019).

The availability of nutrients, CEC, and the presence of toxic elements to plants are greatly influenced by the mineralogical composition of the soil. Soils with a high content of easily weatherable minerals will have better natural fertility compared to soils with a high content of resistant minerals (Ajiboye et al., 2019). Soils with 2:1 clay minerals will have a higher natural fertility level than soils with 1:1 clay minerals or iron-aluminum oxides and hydroxides.

Sustainable agricultural cultivation requires collecting diverse data on soil characteristics, encompassing chemical, physical, biological, and soil mineralogy aspects. However, research specializing in managing agricultural cultivation based on soil mineralogical characteristics is very rare. As a result of this lack of research, the recommendations often fail to consider the nutrient reserves stored in primary minerals, as well as the failure to understand the crucial role of soil mineralogy in plant growth. This research aims to provide a deeper understanding of soil mineralogical characteristics as a foundation for soil fertility management.

2. MATERIAL AND METHODS

The research was conducted in Jember Regency, East Java Province, Indonesia, from October 2022 to October 2023. Three soil profiles representing three different parent materials have been examined in the field, and soil samples (Figure 1) have been collected for laboratory analysis, with the differences in parent materials identified through variations in geological formation units. Profile 1 originates from the Raung Volcano Rock Formation (Qhvr), composed of lava, volcanic breccia, laharic breccia, and tuff. Mount Raung is an active volcano, with its most recent eruption occurring on July 27, 2022 (Global Volcanism Program, 2022). Profile 2 originates from the Sukamade Formation (Toms), composed of claystone with intercalations of siltstone and sandstone (Sapei et al., 1992).

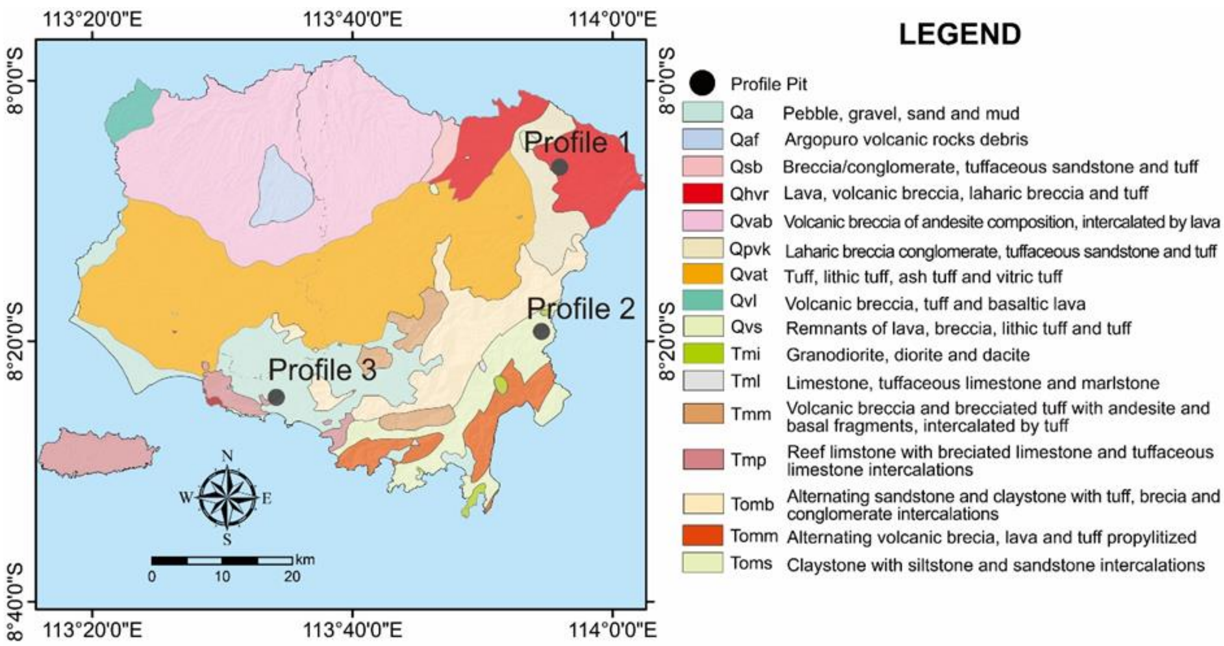

Figure 1. Geological map of research area and soil sampling point

Table 1. General information on the study area

Soil Profile	Parent Material	Landuse	Elevation (m.asl.)	Slope (%)	Annual Rain Fall (mm)	Geographical Position	
						East Longitude	South Latitude
1	Volcanic rock	Intercropping of pine and coffee	559.5	6	2378.5	113°55'56.66"	8° 6'37.88"
2	Sedimentary rock	Coffee plantation	659.3	21	1878.67	113°54'29.68"	8°19'25.87"
3	Limestone	Teak forest	178	15	1404.53	113°34'35.20"	8°24'21.63"

Table 2. Soil Morphology in the research area

Horizon	Depth (cm)	Soil Color	Structure	Root
		Profile 1		
Ap	0 – 25	5 YR $^3/_2$	Gr	VM
AC	25 – 35	5 YR $^4/1$	Gr	N
R1	35 – 47	-	-	N
R2	47 – 72,5	-	-	N
C	72.5 – 112	2.5 YR $^3/_1$	SG	N
2A	112 – 150	7.5 YR $^4/_4$	Gr	VF
		Profile 2		
Ap	0 – 10	7.5 YR $^3/3$	Gr	M
A1	10 – 40	5 YR $^4/_3$	Gr	VF
A2	40 – 81	7.5 YR $^3/_4$	SAB	VF
Bw1	81 – 114	5 YR $^3/_4$	SAB	VF
Bw2	114 – 142	5 YR $^4/_6$	AB	VF
Bw3	142 - 180	7.5 YR $^4/_6$	AB	N
		Profile 3		
AC	0 – 24	5 YR $^3/_2$	SAB	M
CA	24 – 40	7.5 YR $^3/_3$	PL	M
R		Not analyzed		

Notes: Gr=grain, SG=single grain, SAB=sub angular blocky, AB=angular blocky, VM = very many, M = many, N = none, F = few, VF = very few.

The Sukamade Formation is formed due to the deposition of claystone, sandstone, and siltstone units at depths of 20 to 80 meters below sea level. The deposition process of the Sukamade Formation began in the early middle Miocene and ended in the mid-middle Miocene. The Sukamade Formation underwent uplift and folding during the middle Miocene period. This uplift process resulted in the formation of hills and valleys (Derebi, 2019). Profile 3 originates from puger formation (Tmp), composed of reef limestone with brecciated limestone and tuffaceous limestone intercalations. The location of the three profiles and their environmental conditions are summarized in Table 1. The morphology of each soil profile was described according to the field book for describing and sampling soils (Schoeneberger et al., 2012). For mineralogical and chemical analysis, soil samples were collected from profile pits according to pedogenic horizons and stored in properly labeled sample bags. Samples taken from the pedogenic horizons were air-dried at room temperature (25 ± 2°C) in the laboratory and sieved using a 2 mm sieve.

Actual soil pH was measured by mixing soil and aquadest with a ratio of 1: 2.5 m/v, and potential pH was measured by mixing soil with 1 M KCl with a 1: 2.5 m/v ratio. Cation-exchangeable bases (K, Na, Ca, Mg) and cation exchange capacity (CEC) were determined using the ammonium acetate extraction method at pH 7. The Walkley and Black method determined soil organic carbon (SOC) (van Reeuwijk, 2002). The mineralogical composition of the sand fraction is determined by the line counting method with a polarizing microscope. The mineralogical composition of clay fractions was determined qualitatively using an X-ray diffractometer (XRD). Determination of soil texture was done using the pipette method. Determination of bulk density (BD) was done using the ring sample, and particle density was determined based on measurements of the mass and volume of soil particles.

3. RESULTS

The morphological description of the soil from the three profiles is presented in Table 2. The dominant soil colors in all three profiles are 5YR and 7.5YR, with colors other than these only found in the C horizon of profile 1. The soil color in horizons R1 and R2 of Profile 1 cannot be determined using the Soil Munsell Color Chart because these horizons do not consist of soil; rather, they are composed of parent material, and their colors are excessively dark. The variation in soil color within Profile 1 is greater compared to Profiles 2 and 3. This difference can be attributed to lithological discontinuities within Profile 1. The color of the soil is significantly influenced by the type of minerals, iron compounds, moisture content, and organic materials. Iron compounds impart a reddish or yellowish hue to the soil, moisture content affects the soil's darkness or brightness, and organic materials contribute to its black color Ap horizon in Profile 2 exhibits a dark brown color due to its relatively high organic material content, which amounts to 2.37% (Table 4).

The research results indicate that the horizon sequence in Profile 1 is Ap - AC - R1 - R2 - C – 2A, in Profile 2 is Ap - A1 - A2 - Bw1 - Bw2 - Bw3, and in Profile 3 is AC – CA - R. Profile 1 has a unique horizon sequence. Profile 1 exhibits distinctiveness in the form of lithological discontinuity, characterized by the presence of buried horizon (2A) and R horizon. The buried horizon and R in Profile 1 are entirely influenced by the volcanic activity of Mount Raung. The R1 horizon has a gravel content of 70.63% (w/w), while the R2 and C horizons have gravel contents of 51.82% and 6.90%, respectively (Table 3).

Table 3 presents the three profiles' sand particle size fraction content and other physical properties. It shows that the sand fraction content in the soil ranges from 7 to 98 percent, the silt fraction ranges from 0 to 49 percent, and the clay fraction ranges from 2 to 77 percent. The textural class in horizon A ranges from sandy loam to clay. The textural classes in horizons C and R are sandy.

Table 3. Physical properties of soil in the research area

Horizon	Depth (cm)	Soil Texture (Pippet)			Texture Class	BD	PD	Gravel Content (%)
		Sand	Silt	Clay		----- (g cm^{-3}) -----		
				Profil 1				
Ap	0 – 25	41	40	20	L	1.08	2.56	-
AC	25 – 35	59	29	12	SL	1.31	2.85	-
R1	35 – 47	98	0	2	S	1.14	2.08	70.63
R2	47 – 72,5	97	1	2	S	1.21	2.12	51.82
C	72.5 – 112	96	1	2	S	1.13	2.34	6.90
2A	112 – 150	55	38	7	SL	0.76	2.97	-
				Profil 2				
Ap	0 – 10	31	25	45	C	1.04	3.79	-
A1	10 – 40	27	29	43	C	0.85	3.03	-
A2	40 – 81	40	25	35	CL	0.92	2.87	-
Bw1	81 – 114	21	31	48	C	0.99	3.06	-
Bw2	114 – 142	18	36	46	C	0.87	3.33	-
Bw3	142 – 180	12	49	39	SiCL	0.80	3.71	-
				Profil 3				
AC	0 – 24	22	25	53	C	0.89	2.69	-
CA	24 – 40	7	16	77	C	0.95	3.44	-
R	>40					Not analyzed		

Notes: C = clay, L = loam, S = sand, SL = sandy loam, SiCL = silty clay loam, BD = bulk density, PD = particle density, - = not analyzed

Table 4. Soil chemical properties

Horizon	Depth (cm)	pH		OC (%)	Cation-exchangeable bases (NH_4OAC pH 7)					BS (%)
		H_2O	KCl		Ca	Mg	K	Na	CEC	
					----------------		cmol$_c$ kg^{-1}		----------------	
					Profile 1					
Ap	0 – 25	6.018	4.21	0.26	6.53	1.39	1.48	0.11	8.89	106.97
AC	25 – 35	5.91	4.25	1.76	2.10	0.43	0.61	0.10	1.65	196.36
R1	35 – 47	6.6	4.37	0.09	0.37	0.10	0.09	0.05	1.29	47.29
R2	47 – 72,5	6.78	4.32	0.09	2.24	0.79	0.80	0.15	1.25	318.40
C	72.5 – 112	6.89	3.97	0.09	0.40	0.15	0.13	0.07	1.20	62.50
2A	112 - 150	6.65	5.11	1.40	10.10	1.35	0.80	0.22	5.42	230.07
					Profile 2					
Ap	0 – 10	6.11	5.28	2.37	14.12	2.88	5.45	0.15	20.01	112.94
A1	10 – 40	6.27	5.29	1.58	13.98	2.72	3.64	0.21	15.11	136.00
A2	40 – 81	6.5	5.45	1.05	11.23	2.39	3.78	0.19	19.66	89.47
Bw1	81 – 114	6.6	5.44	0.70	13.68	2.72	5.48	0.25	18.22	121.46
Bw2	114 – 142	6.51	5.44	0.79	11.54	3.79	7.00	0.33	23.86	94.97
Bw3	142 - 180	6.26	7.66	0.61	5.11	3.00	6.82	0.45	17.50	87.89
					Profile 3					
AC	0 – 24	6.75	5.93	1.76	39.18	2.60	1.92	0.18	33.21	132.13
CA	24 – 40	7.83	6.8	0.97	60.06	2.34	1.70	0.38	42.67	151.11
R	>40				Not analyzed					

Soil bulk density ranges from 0.76 to 1.31 g cm^{-3}, while soil particle density values range from 2.08 to 3.79 g cm^{-3}. The highest bulk density value is found at horizon AC of Profile 1, which is 1.31 g cm^{-3}. The high bulk density value at horizon AC of profile 1 indicates soil compaction. Soil compaction at horizon AC prevents coffee plant roots from penetrating this horizon. The particle density values range from 2.08 to 3.71 g cm^{-3}, with the particle density value in Profile 2 being above the average soil particle density of 2.65 g cm^{-3}. The soil pH (H_2O) values range from moderately acidic (5.91) to moderately alkaline (7.83) (FAO, 2008). All soil samples' pH (KCl) values are lower than the pH (H_2O) values, except in horizon CA3 of Profile 2, indicating that the net charge of the soil colloid is positive. The organic C content of the soil was higher in horizon A than in horizons B, C, and R (Table 4). Organic C content ranges from 0.26% to 2.37%. The highest organic C value was found in Profile 2, horizon Ap.

Potassium (K^+) exchangeable values can vary from very low (0.09 cmol kg^{-1}) to very high (7.00 cmol kg^{-1}). Exchangeable potassium values below 1 were only found in

Profile 1, except for horizon Ap. The CEC values range from 1.20 to 42.67, with Profile 3 having the highest average CEC value. The base saturation values of all samples are over 60%, except for horizon R1 (47.29%). The highest base saturation value is found in horizon R2 of Profile 1, which is (318.40%). Base saturation values exceeding 100% indicate the presence of base cations outside the soil colloid system that were included in the analysis.

The mineral composition of the sand fraction from the three profiles is presented in Table 5. Opaque minerals are the most abundant, followed by rock fragments, ferromagnesian mineral series (olivine, hornblende, augite, and hypersthene), then plagioclase group (labradorite, biotite), iron concretions, weathering minerals, and epidote. Sporadic minerals include zircon, quartz, volcanic glass, anorthite, sillimanite, staurolite, diopside, and cassiterite. The clay mineral fraction found in all three profiles consists of illite, kaolinite, and quartz (Table 6). Profile 1 has moderate amounts of quartz, followed by moderate to rare proportions of illite, and minor amounts of kaolinite in the Ap horizon, rare in the AC horizon, and no kaolinite in the 2A horizon. The dominant minerals in Profile 2 are illite, followed by kaolinite and quartz in moderate to minor amounts. The mineral composition in Profile 3 consists of minor amounts of quartz, followed by rare amounts of illite and kaolinite.

4. DISCUSSION

The majority of soil solid fractions are composed of soil minerals, both primary and secondary, which directly or indirectly exert significant influence on the reserves and availability of plant nutrients (Anda et al., 2012; Singh & Schulze, 2015; Sukarman et al., 2020). Soil minerals also affect the stability and retention of soil organic matter, availability of macro and micronutrients, and soil physical properties (Kome et al., 2019). The research findings indicate that the weatherable mineral content (sand fraction) in all three profiles ranged from 22 to over 40%. These figures fall within the high to very high category according to the classification by the Indonesian Soil Research Institute (2006). Previous studies on the amount of weatherable minerals in soils affected by Mount Raung volcanic materials also demonstrated elevated levels of weatherable minerals (Bowo et al., 2024; Muslim et al., 2020). Values below 22 are only found in horizon R1 and 2 of Profile 1 and horizon Bw3 of Profile 2. This indicates that the nutrient reserves in these three profiles are high to very high (Anda et al., 2012; Sukarman et al., 2020).

Olivine minerals were found in all three soil profiles. This is an interesting discovery, considering that olivine is a weatherable mineral compared to other silicate minerals forming rocks (Goldich, 1938), and the environment where it was found is highly conducive to aggressive weathering processes (Bowo et al., 2024). Wilson (2004) stated that olivine usually cannot persist as a mineral in most soils, sediments, and sedimentary rocks. Olivine in profiles 2 and 3 is suspected to originate from volcanic ash from Mount Raung, as Mount Raung is still active, and the distance between these profiles and Mount Raung is less than 60 km, allowing volcanic ash from eruptions to reach these profiles. The last eruption of Mount Raung was on July 27, 2022 (Global Volcanism Program, 2022). The assumption that olivine in profiles 2 and 3 originates from Mount Raung is further supported by mineralogical analysis results in profile 1, where olivine minerals from the parent material of Mount Raung volcanic rocks were found (Table 5). The addition of new materials from Mount Raung's volcanic activity allows olivine to still be found in profiles 2 and 3 because the soil in these profiles experiences rejuvenation. This opinion is also reinforced by data on Mount Raung's volcanic activity, which has occurred more than 60 times since the 16th century until now (Global Volcanism Program, 2022).

The volcanic ash from Mount Raung also contributes to the high base saturation in profiles 2 and 3. The base saturation values in all three profiles exceed 100%, indicating the presence of soluble salts, lime, and free cations not bound by soil complexes (Maranhão et al., 2020). The high base values in all three profiles affect the soil pH, which ranges from 6 to 7. These pH values are highly conducive to supporting plant growth (McGrath et al., 2014; Utomo et al., 2016).

The soil in profile 3, based on the geological map of the Jember sheet (Sapei et al., 1992), originates from the parent material of reef limestone intercalated with limestone breccia and tuffaceous limestone rocks. Analysis of the sand and clay fractions did not find calcite and dolomite minerals, which are constituents of limestone rocks. This is due to aggressive weathering processes, causing these minerals to be completely weathered away, leaving traces of very high exchangeable Ca levels (Table 4). Several previous studies have indicated that soils derived from limestone parent material have relatively high exchangeable Ca levels (Alnaimy et al., 2023; Maranhão et al., 2020; Oraiz et al., 2021).

The minerals illite, plagioclase, and ferromagnesian groups significantly enhance the availability of potassium, calcium, and magnesium nutrients in all three profiles. The high content of these elements in the mineral structure creates conditions where they are released during the mineral weathering process and become essential nutrient sources for plant growth (Lee et al., 2021; Singh & Schulze, 2015; Vink & Knops, 2023). These findings are consistent with the results of this study, where the levels of these elements are high in all profiles.

Based on the explanation above, it can be understood that the composition of sand and clay mineral fractions plays a crucial role in increasing CEC, BS, and the availability of K, Ca, Mg nutrients. These conditions are highly conducive for the cultivation of seasonal crops such as rice and maize (Al Viandari et al., 2023; G. Selassie et al., 2020), which are the most widely cultivated food crops by Indonesian farmers. Such ideal conditions also have the potential to persist for a long time, given the high mineral reserves, allowing for natural nutrient supply as these minerals weather. Moreover, the potential for additional easily weathered minerals remains due to eruptions from Mount Raung. Mount Raung is still active to this day, erupting every 1 to 15 years (Global Volcanism Program, 2022).

Table 5. Sand fraction mineralogy

Depth (cm)	Horizon	Op	Zr	Qr	Ic	Wm	Rf	Vg	Lb	Bt	An	Hb	Ag	Hp	Ol	Ep	Tm	Sl	St	Dp	Ks	Wtb	Rm
									Profile 1														
0 – 25	Ap	25	-	-	5	3	21	sp	6	4	-	-	19	12	3	2	sp	-	-	sp	-	49	51
25 – 35	AC	32	-	-	2	4	39	sp	4	2	-	-	11	6	-	sp	-	-	-	-	-	27	73
35 – 47	R1	11	-	-	-	1	63	-	-	sp	-	-	10	13	-	2	-	-	-	-	-	26	74
47 – 72,5	R2	66	-	-	sp	3	18	sp	2	3	-	-	4	2	-	2	sp	-	sp	-	-	16	84
72.5 – 112	C	75	-	-	-	5	12	-	-	2	-	1	3	2	-	sp	sp	-	-	-	-	13	87
112 - 150	2A	22	-	-	sp	7	17	-	21	12	-	2	14	3	2	sp	sp	-	-	-	-	61	39
									Profile 2														
0 – 10	Ap	55	sp	sp	-	2	15	sp	9	5	-	2	4	5	1	sp	2	-	-	-	-	30	70
10 – 40	A1	54	-	-	-	3	22	sp	3	6	-	5	4	2	1	sp	sp	-	-	-	-	24	76
40 – 81	A2	8	-	-	2	3	54	-	5	7	sp	7	3	5	3	2	1	-	sp	sp	-	46	54
81 – 114	Bw1	71	-	-	1	4	6	-	2	2	-	9	2	3	sp	sp	sp	sp	-	-	-	22	78
114 – 142	Bw2	59	-	-	-	5	13	-	3	sp	-	14	1	3	-	-	2	sp	-	-	-	28	72
142 - 180	Bw3	74	-	sp	sp	5	14	-	1	-	-	6	sp	-	-	sp	-	-	-	-	-	12	88
									Profile 3														
0 – 24	AC	9	-	-	7	6	40	Sp	8	12	sp	1	10	6	1	sp	-	-	-	sp	sp	44	56
24 – 40	CA	55	-	-	2	3	16	-	3	4	-	4	7	5	1	-	-	-	-	-	-	27	73
>40	R						Not analyzed																

Notes: OP = Opaque, Zr = Zircon, Qr = Quartz, Ic = Iron concretion, Wm = Wheathering minerals, Rf = Rock fragment, Vg = Volcanic glass, Labradorite, Bt = Bytownite, An = Anorthite, Hb = Hornblende, Ag = Augite, Hp = Hypersthene, Ol = Olivine, Ep = Epidote, Tm = Tourmaline, Sl = Silimanite, St = Staurolite, Dp = Diopsite, Ks = Kasiterite, sp = Sporadic, - = None, Wtb = Weatherable mineral (Ca-Na Plagioclase, amphibole, pyroxene, olivine, tourmaline and wheathering minerals), Rm = Resistant mineral (opaque, iron concretion and rock fragment), The criteria for weatherable mineral and resistant mineral were adopted from Hunt (1972)

Table 6. Clay mineralogy of three soil profile

Horizon	Depth (cm)	Ilite	Kaolinite	Quartz
		Profil 1		
Ap	0 – 25	(+)	+	++
AC	25 – 35	++	(+)	++
2A	112 – 150	+	-	++
		Profil 2		
Ap	0 – 10	++	++	++
A2	40 – 81	++	++	+
Bw2	114 – 142	+++	++	+
Bw3	142 – 180	+++	+	(+)
		Profil 3		
AC	0 – 24	(+)	(+)	+
CA	24 – 40	(+)	(+)	+
R	>40		Not analyzed	

Notes : +++ = Dominant, ++ = Moderate, + = Minor, (+) = Rare, - = None

From the mineralogy and soil fertility perspective, food crops can be chosen as an option for sustainable agricultural management strategies for all three profiles. This is due to the results of mineralogical analysis and soil fertility indicating high nutrient reserves and soil fertility (ISRI, 2006; Mujiyo et al., 2022; Sukarman et al., 2020). However, this choice may be less wise when viewed from the three profiles' morphology and landform perspective. The soil profile in Profiles 1 and 3 is considered shallow, meaning the soil's ability to provide water for plants is limited. This problem is exacerbated by the sandy soil texture in Profile 1, which has low water-holding capacity (Olorunfemi et al., 2016; Sainju et al., 2022).

The landforms in Profiles 2 and 3 are situated in folded hills and karst formations, positioned at the hilltops, making it difficult to access water and relying solely on rainfall for plant needs. The climatic conditions in both profiles further exacerbate water availability issues as they exhibit a ustic moisture regime, implying dry soil conditions for more than 3 months (Soil Survey Staff, 2022). Therefore, while food crops may be a choice for sustainable agricultural management from a mineralogical perspective (Anda et al., 2015), the morphological and landform aspects of the soil profiles must be carefully considered when selecting the appropriate crops for cultivation to ensure optimal production sustainability.

Based on the soil analysis results, environmental conditions, and explanations above, soil fertility management in all three profiles is directed towards utilizing annual crops. This selection takes into account the morphology, landform, and climatic conditions in formulating soil fertility management strategies to support sustainable agriculture. The most suitable plants for Profile 1 are pine and resin trees. Both have long and strong roots, capable of penetrating the hardpan layer in the AC horizon and searching for water more effectively than annual crops. This is in line with the agroecological conditions in Profile 1, and both also have high economic value, as evidenced by (Albaugh et al., 2008; Wasis et al., 2018). Meanwhile, robusta coffee is the optimal choice for Profile 2. Coffee plants require deep soil and abundant nutrient to support high productivity (Silva et al., 2019; Tien et al., 2015). This aligns with the characteristics of Profile 2 soil, which has a deep soil layer and high availability of potassium, calcium, and magnesium, thereby minimizing the need for fertilizers for these nutrients. As for Profile 3, it is recommended to maintain its current condition and designate it as a teak forest. This is due to the shallow soil profile in Profile 3, making it more suitable for teak forests, in line with sustainability and ecosystem balance considerations.

The findings of this research illustrate the significant impact of volcanic materials from Mount Raung on the soil characteristics in the study area, overall enhancing soil fertility. However, this research also underscores the importance of considering factors such as morphology, landform, and climate in designing sustainable agricultural strategies. While fertile soil is a valuable asset, achieving sustainable agriculture requires careful consideration of environmental factors such as morphology, landform, and climate.

5. CONCLUSION

The volcanic materials from Mount Raung greatly influence the soil characteristics in all three profiles. The presence of Mount Raung's volcanic influence causes the soil characteristics in Profiles 2 and 3 to differ from those of sedimentary rocks and karst soils in general. The sand fraction minerals in all three profiles consist primarily of opaque minerals, followed by rock fragments, ferromagnesian mineral series (olivine, augite, hypersthene, and hornblende), plagioclase minerals (anorthite, biotite, and labradorite), iron concretions, epidote, tourmaline, and sporadic minerals such as zircon, quartz, volcanic glass, sillimanite, staurolite, diopside, and cassiterite. The clay fraction minerals in all three profiles consist of illite, kaolinite, and quartz. Illite and ferromagnesian groups play a significant role in increasing the availability of potassium, calcium, and magnesium nutrients. The soils in all three profiles naturally have good fertility, but designing a sustainable agricultural system requires consideration of the morphology, landform, and climate of the three profiles.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests that may appear and influence the work reported in this paper.

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