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Distribution of Soil Organic Carbon along an Elevation Gradient on Kaba Volcano, Bengkulu Province, Indonesia

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ABSTRACT

Climate change is a global issue largely driven by increasing atmospheric carbon dioxide levels. Many studies have focused on reducing CO2 emissions to mitigate its impacts. Volcanic soils are recognized for their high capacity to sequester carbon, second only to deep-sea reservoirs. However, limited research has examined soil organic carbon in volcanic soils on Kaba Volcano, Bengkulu, Indonesia. This study investigated the distribution of soil organic carbon along an elevation gradient on Kaba Volcano. Nine soil samples, both disturbed and undisturbed, were collected at a depth of 10 cm from three elevations: foothill, hillside, and hilltop. Undisturbed samples were taken using a 70-mm core cylinder to determine bulk density, while disturbed samples were collected with a shovel to analyze soil organic carbon, pH, and particle-size distribution. Soil organic carbon was measured using the Walkley–Black method, soil pH with a pH meter in KCl solution, and particle size using wet sieving and the pipette method. Results showed the highest soil organic carbon at the hillside, though not significantly different from the foothill, while the hilltop had the lowest content. Lower organic carbon at the hilltop may be related to drier conditions and reduced vegetation cover.

Keywords: Carbon cycle, Carbon sequestration, Climate change, Soil forming factors, Volcanic gases

INTRODUCTION

Since the Industrial Revolution in the 19th century, human activities have significantly increased carbon dioxide (CO,) emissions into the atmosphere. This rise has prompted considerable concern among researchers, leading to the development of various strategies to address the issue, including emission reduction and removal, CO, sequestration, and carbon capture, utilization, and storage (CCUS) technologies. After the deep ocean, soil represents the largest carbon reservoir, storing up to 1,580 petagrams (Pg) of organic carbon globally (Rodeghiero et al., 2009).

Volcanic soils are unique, formed from materials derived from deeper layers of the Earth, and are capable of storing more organic carbon than typical soils (Park et al., 2023). This distinctive property is primarily attributed to the presence of amorphous materials within the soil. Volcanic soils also enhance vegetation growth and increase net primary production, thereby contributing to greater accumulation of soil organic carbon.

Climate plays a crucial role in soil weathering, alongside other soil-forming factors, by influencing both the direction of weathering processes and the accumulation of soil organic carbon. Among climatic variables, water availability is particularly important in driving soil development. In mountainous landscapes, moisture levels generally increase with elevation.

The vital role of volcanic soils in storing soil organic carbon has led to a growing number of studies on this topic. Volcanic soils located along the Ring of Fire - such as those in New Zealand, Japan, the western region of South America, and Iceland - have been extensively studied. However, research on the soil organic carbon content of volcanic soils in Indonesia remains limited, despite numerous studies focusing on other aspects of Indonesian volcanic soils.

Although numerous studies have investigated soil organic carbon, research focusing on volcanic soils, particularly in tropical regions, remains limited. To date, no studies have examined the development

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of soil organic carbon in volcanic soils of Kaba Volcano in Rejang Lebong Regency, Bengkulu Province. Additionally, there is a lack of information on soil physical and chemical properties, as well as on how moisture, influenced by elevation, affects soil organic carbon accumulation on this volcano. This study aims to investigate the distribution of soil organic carbon and its relationship with other soil properties, such as pH and bulk density, along an elevation gradient on Kaba Volcano.

MATERIALS AND METHODS

Study area

Kaba Volcano is an active volcano located in Selupu Rejang, Rejang Lebong Regency, Bengkulu Province, Indonesia. It is geographically located between 102°35'E and 102°45'E and 03°30'S and 3°37'S. Kaba Volcano covers an area of around 146.5 km^2 and has an elevation of up to 1952 m above sea level (a.s.l). Kaba is an area of a natural tourism park. According to Norris et al. (2020), the topography of Kaba Volcano includes hilly, undulating, plateau, and highland areas, with slopes ranging from 15% to 45%.

In relation to biodiversity, Norris et al. (2020) reported that vegetation in the area of Kaba Volcano was dominated by *Molineria capitulata* at lower elevation (1300-1400 m a.s.l), *Thysanolaena latifolia* at middle elevation (1500-1600 m a.s.l), and *Dicranopteris linearis* at higher elevation (1700 – 1900 m a.s.l).

According to Sihombing et al. (2020), Kaba Volcano was formed through geological processes that resulted in a volcanic landscape. This area is characterized by geological structures comprising rocks and soils derived from volcanic eruptions. The stratigraphy of Kaba Volcano consists of at least two major units: volcanic breccia and andesite-basalt volcanic rock, as identified by Gafoer et al. (1992). Kaba Volcano has experienced several eruptions, with records dating back to 1834. However, since 2000, it has shown no significant volcanic activity.

Soil sampling

Soil samples were taken from three different locations on Kaba Volcano, including the foothill (sample A1, A2, and A3) with an elevation of 1379 m a.s.l., hillside (sample B1, B2, and B3) with an elevation of 1619 m a.s.l., and hilltop (sample C1, C2, and C3) with elevation of 1933 m a.s.l. On each site, three undisturbed and disturbed soil samples were collected (nine soil samples in total). Locations of sampling sites are presented in Figure 1.

Undisturbed soil samples were taken using a 70 mm core cylinder for determining their bulk density. Whereas disturbed soil samples were taken using a shovel, followed by quartering and drying at air temperature for other soil analyses, including soil organic carbon content, sand, silt, and clay content,

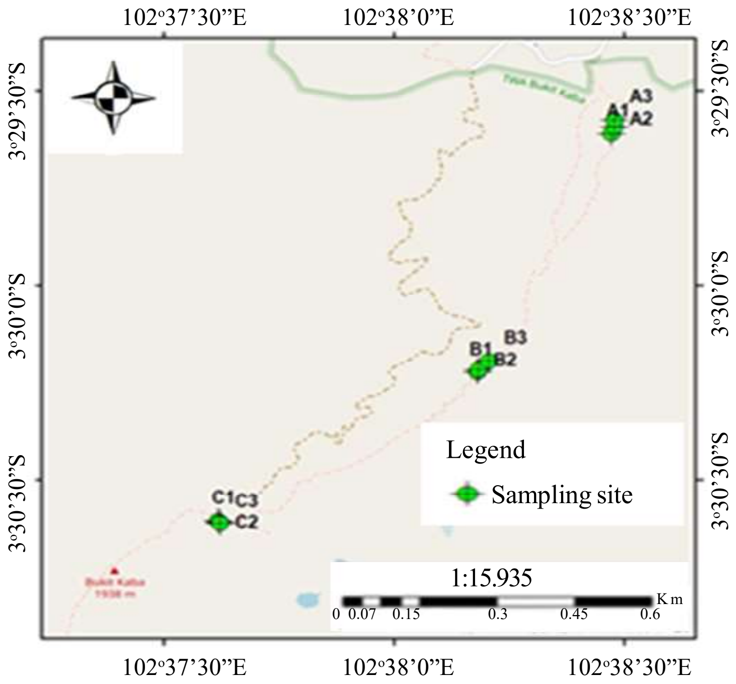

Figure 1: Map of sampling site.

and soil pH. Information on sampling sites is presented in Table 1.

Soil sample analyses

Soil organic carbon was analyzed using the Walkley–Black method, following the procedure described by Mylavarapu et al. (2014). In this method, 0.5 g of air-dried soil was oxidized with 1 N K, Cr, O‡ under acidic conditions by adding concentrated H_2SO_4 . The concentration of soil organic carbon was determined from absorbance measurements. Soil pH was measured using a pH meter in a 1 M KCl solution at a soil-to-solution ratio of 1:2.5. Prior to measurement, the soil–KCl mixture was shaken for 24 hours. Particle size distribution was analyzed using a combination of wet sieving and the pipette method. Bulk density was determined by drying the core samples overnight at 105 °C in an oven and weighing.

Data analysis

Significant differences in soil parameter values among the studied samples were analyzed using a single-factor ANOVA with Tukey's HSD post hoc test at $p < 0.05$ in IBM SPSS Statistics 28.0.

RESULTS AND DISCUSSION

Physical and chemical soil properties

Some basic soil characteristics of the volcanic soil of Kaba Volcano are presented in Table 2. As

Table 1. Information about the sampling site.

Sampling location	Site	Depth (cm)	Elevation (m a.s.l)	Latitude	Longitude	Vegetation
Foothill	A1	0-10	1379	3°29'36.491"	102°38'28.478	*Molineria capitulata* (Lour),
	A2	0-10	1357	3°29'35.353"	102°38'28.902	*Clerodendrum laevifolium*,
	A3	0-10	1367	3°29'34.311"	102°38'28.904	*Cristella parasitica* (L.)
Hillside	B1	0-10	1619	3°30'13.316"	102°38'10.963	*Thysanolaena latifolia*,
	B2	0-10	1620	3°30'13.023"	102°38'11.061	*Cyrtococcum patens* (L.),
	B3	0-10	1612	3°30'11.595"	102°38'12.489	*Dicranopteris curranii*
Hilltop	C1	0-10	1944	3°30'36.269"	102°37'37.095	*Dicranopteris linearis*
	C2	0-10	1942	3°30'36.595"	102°37'37.386	(Burm.f.), *Melastoma*
	C3	0-10	1933	3°30'36.725"	102°37'37.385	*malabathricum* (L.), *Rhododenron indicum* (L.)

Table 2. Physical and chemical soil properties observed along the elevation gradient on Kaba Volcano.

Sample	SOC (%)	pH	Sand content	Silt content	Clay content	Bulks density ($Mg\ m^{-3}$)
			(%)			
A1	5.64	5.49	81.79	10.09	8.12	0.90
A2	7.27	5.04	79.48	12.3	8.22	0.69
A3	6.57	5.36	77.64	14.24	8.12	0.79
Mean(SD)	6.49(0.82)^{b}	5.30(0.23)^{b}	79.6(2.08)^{a}	12.2(2.08)^{a}	8.15(0.06)^{ab}	0.79(0.11)^{a}
B1	9.49	3.45	81.56	10.21	8.22	0.882
B2	6.04	4.01	81.82	10.07	8.11	0.703
B3	9.18	3.87	79.46	12.31	8.22	1.046
Mean(SD)	8.24 (1.56)^{b}	3.78(0.29)^{a}	80.9(1.29)^{a}	10.9(1.25)^{a}	8.18(0.06)^{b}	0.88(0.17)^{a}
C1	3.45	3.82	79.68	16.24	8.08	0.964
C2	1.58	3.79	72.05	20.01	7.94	1.389
C3	2.77	4.17	82.15	9.89	7.96	1.22
Mean(SD)	2.60(0.95)^{a}	3.93(0.21)^{a}	78.0(5.27)^{a}	15.4(5.11)^{a}	7.99(0.08)^{a}	1.19(0.21)^{a}

SOC = soil organic carbon; different letters indicate significant difference within column (Tukey HSD, $p < 0.05$).

shown in Table 2, variation in fundamental soil properties, such as particle-size distribution (sand, silt, and clay content), pH, and bulk density, was observed among the studied sites.

Sand content in the studied sites ranged from 78% at the hilltop to 81% at the hillside, while silt content varied from 10.9% at the hillside to 15.4% at the hilltop. Clay content was relatively consistent across all three locations, with no statistically significant differences, averaging approximately 8%. The sand content observed in this study is notably higher than that reported for volcanic soils in other countries and even in other regions of Indonesia. For instance, the sand content in topsoil of the Galapagos Islands ranged from 2.4% to 48% (Candra et al., 2021), while in Hawaii it ranged from 1% to 51%, with a mean of 10.1% (Hodges, 2022). Volcanic soils developed from Tangkuban Perahu Volcano in Indonesia had a mean sand content of 18%, ranging from 8% to 42.8% (Anindita et al., 2022). In contrast, the sand content reported in this study (69%-86%) is comparable to that of volcanic soils at Mount Kelud, as reported by Putra et al. (2022).

Clay content in this study is considerably lower than that reported in other studies. For example, volcanic soils in Hawaii had a mean clay content of 49.1%, ranging from 37% to 78% (Hodges, 2022). However, it is slightly higher than that of volcanic soils in Iceland, which ranged from 1.3% to 2.7% (Arnalds et al., 1995).

Soil bulk density was less than 0.9 Mg m^{-3} at the foothill and hillside, but exceeded 0.9 Mg m^{-3} at the hilltop. A bulk density below 0.9 Mg m^{-3} is typical of volcanic soils with andic properties (Soil Survey Staff, 2014). The higher bulk density observed at the hilltop suggests that the soil in this area is less developed than at the foothill and hillside. This limited development is likely due to drier conditions at the hilltop, which can slow soil formation. Similar findings have been reported in other volcanic regions; for instance, soils on Tambora Volcano in Sumbawa, East Nusa Tenggara, also exhibited bulk densities greater than 0.9 Mg m^{-3} (Anda et al., 2023). Compared to other regions in Indonesia, these drier conditions contribute to slower soil weathering and development.

Soil pH (measured in KCl) in this study ranged from 3.5 at the hillside to 5.5 at the foothill. The lowest soil pH at the hillside is likely associated with its proximity to sources of volcanic gas emissions,

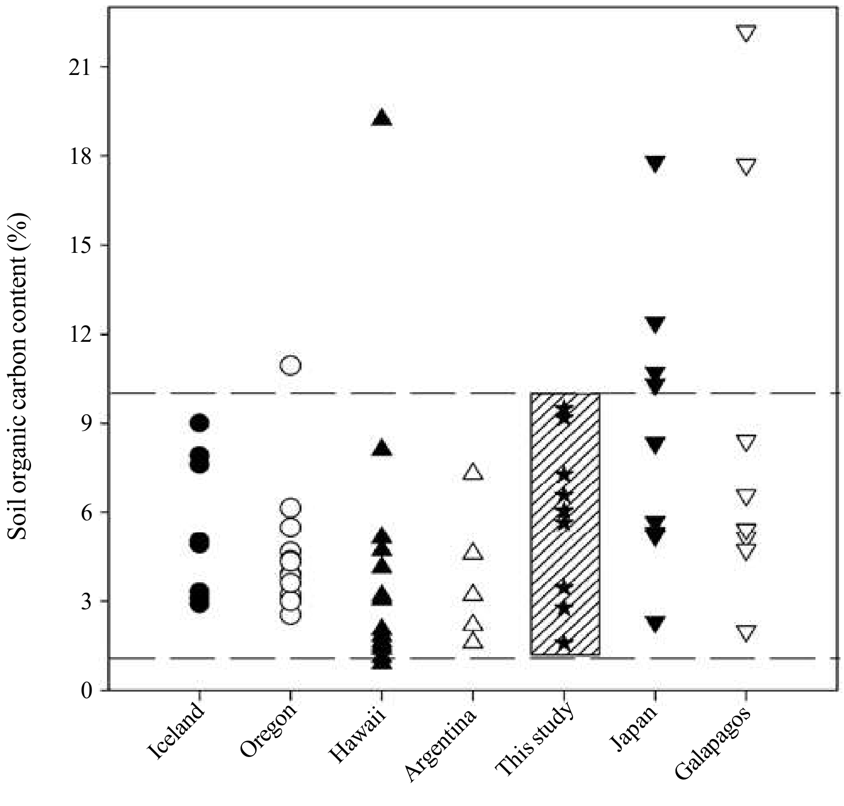

Figure 2. Soil organic carbon content of volcanic soils observed in Kaba Volcano compared to other studies from Iceland (Arnalds et al., 1995); Oregon (Brown, 1974); Hawaii (Hodges, 2022); Argentina (Broquen et al., 2005); Japan (Shoji et al., 1993) and Galapagos (Candra et al., 2021).

such as sulfur dioxide (SO_2) and carbon dioxide (CO_2), which can react with water to form acidic compounds. Lower soil pH due to SO_2 exposure near the caldera was also reported at Kîlauea, Hawaii, in a study conducted by Cox (1983). According to Shoji et al. (1993), volcanic soils with a pH in water above 5 are conducive to the formation of allophanic Andisols. In contrast, those with a pH below 5 tend to develop into non-allophanic Andisols.

Soil organic carbon content distribution

In this study, soil organic carbon content ranged from 1.58% at the hilltop to 9.49% at the hillside, with no statistically significant difference observed between the hillside and foothill. Most of these data fall within the range reported for volcanic topsoils in both Indonesia and other countries. For example, Lyu et al. (2024) reported a mean soil organic carbon content (topsoil) of 6.79%, ranging from 2.26% to 15.24%, in volcanic soils in East Java and North Sumatra. In Hawaii, the mean organic carbon content of volcanic topsoils was 4.12% (Hodges, 2022), while in Iceland it was 5.5% (Arnalds et al., 1995). A comparison of soil organic carbon content from Kaba Volcano with that reported in other studies is presented in Figure 2.

Chemical and physical soil properties along the elevation gradient

In mountainous landscapes, higher elevations typically receive more moisture than lower ones due to decreasing temperatures with increasing altitude, which causes water vapor to condense (Yan et al., 2024). Greater water availability is generally associated with higher net primary production, thereby increasing soil organic carbon inputs. However, in this study, we observed lower soil organic carbon content at the hilltop compared to the foothill and hillside. This disparity was likely due to volcanic gas emissions. The hilltop area was more directly exposed to volcanic gases such as sulfur dioxide (SO_2) and carbon dioxide (CO_2), which react with water to form acids, resulting in more acidic soils. Consequently, vegetation cover is reduced in this area, leading to lower organic carbon inputs.

Additionally, the steeper slopes at the hilltop contribute to greater surface runoff, further reducing soil moisture. These combined factors - limited vegetation, steep terrain, and high runoff - create drier conditions at the hilltop compared to the foothill and hillside. Vegetation density at the study sites is illustrated in Figure 3.

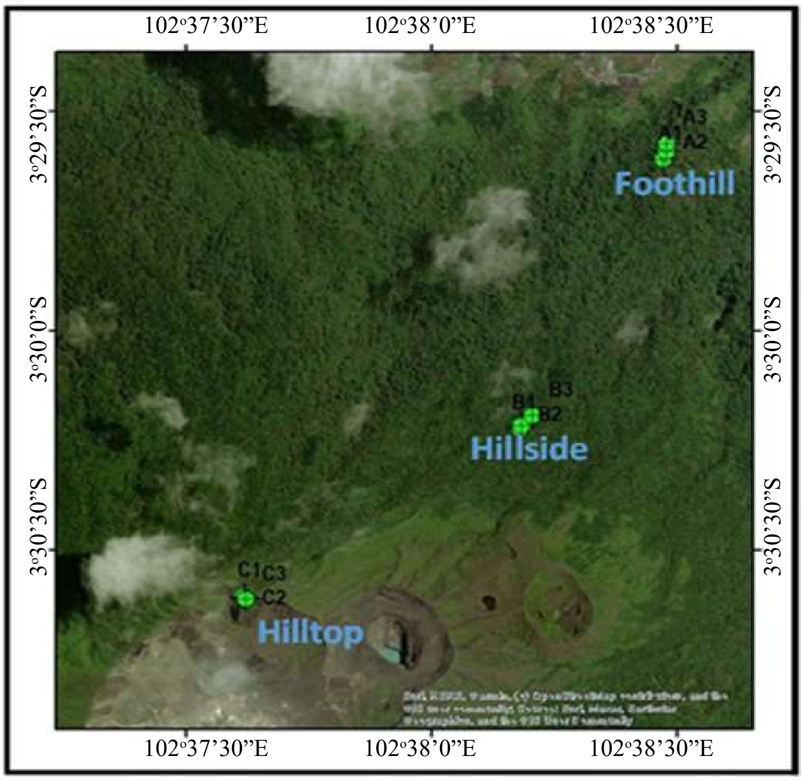

Figure 3. Vegetation density conditions of the studied sites shown from a satellite image.

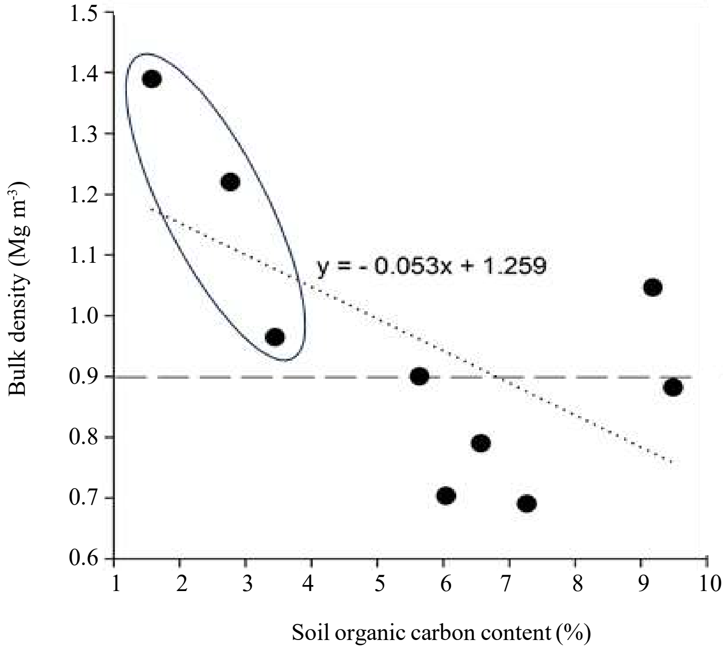

Figure 4. The relationship between soil organic carbon and bulk density; points covered by ellipses are samples from the drier site (hilltop).

Soil organic carbon content is associated with soil pH and bulk density. In our study, we found that higher soil organic carbon was associated with lower soil bulk density, as reported in many studies (e.g., Athira et al., 2019). Soil organic carbon increases soil porosity, making it less compacted. The relationship between soil organic carbon and bulk density is displayed in Figure 4.

Soil organic carbon also affects soil pH, as its decomposition produces acidic compounds such as humic acid, fulvic acid, and carboxylic acids, which lower soil pH (Malan, 2015). It is consistent with our findings: the hillside, characterized by higher soil organic carbon, had a lower pH than the foothill, which had lower organic carbon content. However, at the hilltop, despite the low soil organic carbon, the soil pH was also low. In this case, the low pH is unlikely to be related to organic carbon levels but rather to exposure to volcanic gas emissions, as previously discussed.

CONCLUSIONS

Soil organic carbon, which influences other soil properties such as pH and bulk density, varied across volcanic soils along the elevation gradient of Kaba Volcano. Contrary to expectations, soil organic carbon was lowest at the hilltop, despite it typically being higher at such elevations. This anomaly is likely due to more intense volcanic gas emissions at the summit, which increase soil acidity. These acidic conditions may have affected the types and density of vegetation able to grow there. Additionally, the steeper landscape at the hilltop likely reduced the soil's ability to retain water, resulting in drier conditions than at lower elevations, as evidenced by the highest observed bulk density (> 0.9 Mg m^{-3}) at the hilltop. Overall, the study found that higher soil organic carbon content was generally associated with lower soil bulk density and pH. However, at the hilltop, where soil organic carbon was low, soil pH was also unexpectedly low - most likely due to the influence of volcanic gas emissions.

The variation in soil organic carbon along the elevation gradient on Kaba Volcano, Bengkulu Province, Indonesia, indicates that its accumulation results from the combined influence of multiple environmental factors. Although the number of soil samples and sampling depths was limited, environmental factors exert a general influence on soil organic carbon accumulation. As such, the results can be generalized and applied in contexts with similar conditions.

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