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Essential mineral profiles in soils and forages in Indonesia's active volcanoes: Implication for beef cattle nutrition in the eruption-impacted areas

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ABSTRACT

A study was conducted to explore the essential mineral concentrations of volcanic soils and forages in different eruption-impacted areas and discuss the possible effects on beef cattle nutrition. A total of 75 forage and topsoil samples were collected in the eruption-impacted areas of five active volcanoes located on different islands in Indonesia: Agung Mt. (Bali), Gamalama (North Maluku), Lokon (Noth Sulawesi), Merapi (Central Java), and Sinabung (North Sumatra). The samples were analyzed for the essential macro minerals (Ca, P, Mg, K, Na, S) and trace elements (Fe, Zn, Cu, Mn, Co, Se). Results found that Ca forage varied from 0.52 to 0.76 ppm, P: 0.09-0.36%, Mg: 0.26-0.39%, K:1.55-4.21%, Na: 0.09-0.12%, and S: 0.12-0.65%. The Fe concentration of 109-308 ppm was the most varied trace element in the forages, followed by Mn (30-186 ppm, and Zn (50-85 ppm). The soils Ca, Mg, Na, and S varied from 0.38-0.87, 0.07-0.71, 0.09-0.14, and 0.01-0.07%, respectively. The potential P and Mg ranged from 48.83-174.87 and 23.99-39.97 mg/100 g, respectively. The soil was considerably rich in Fe (142,230-20,252 ppm), followed by Mn (66-180 ppm), Zn (37-56 ppm), and Cu (10-60 ppm). Considering requirements for growing cattle, forage K, S, and Cu exceeded tolerable levels; they were favorable to Ca, Mg, Zn, Co, and Se concentrations, but P and Na were insufficient. In conclusion, the essential minerals most likely to limit beef cattle's nutritional status and productivity in the eruption-impacted areas are K, S, Cu, P, and Na.

Keywords: Eruption, Essential mineral, Forage, Volcanic soil, Volcanoes.

INTRODUCTION

Mineral concentration in forages is an essential factor in cattle nutrition. Livestock requires minerals for essential structural, physiological, and metabolic functions (Wu, 2018). The essential minerals are divided into macro and microminerals. Macro minerals include calcium (Ca), phosphorus (P), magnesium (Mg), sodium (Na), chloride (Cl), potassium (K), and sulfur (S). Micromineral are iron (Fe), copper (Cu), zinc (Zn), manganese (Mn), iodine (I), selenium

(Se), and cobalt (Co). Mineral Ca, P, and Mg are significant components and mechanical stability of the skeleton and teeth. Na, K, and Cl regulate the cell's electrolytes, acid-base balance, and osmotic pressure (Wu, 2018). Na, P, and Zn regulate feed intake. Ca, Mg, Se, Mn, Zn, and Cu are cofactors of various enzymes. Fe, Co, and I are components of hemoglobin, vitamin B12, and thyroid hormones) (Wu, 2018). Adequate intake of minerals to meet animal requirements is essential to maintaining their growth, health, and reproduction (McDowell, 1985). Mineral imbalances and/or deficiencies can result in decreased growth, immune suppression, and reproductive failure, which results in significant economic losses for livestock businesses (McDowell *et al*., 1993).

As part of the Pacific Ring of Fire, Indonesia has around 76 active volcanic Mt.ains spread along the island (Hariyono and Liliasari, 2017). The volcanoes are a center for agriculture and livestock farming due to their fertile soil and cool climate (Rozaki *et al*., 2023; Razoaki *et al*., 2022; Tampubolon *et al*., 2017; Zainnudin, 2010). Beef cattle are the most popular farm animals as an integral part of agricultural farming for dough power and a source of organic fertilizer (Khalil *et al*., 2024). They are raised in small flock sizes (2-6 heads/farm) in different breeds, rearing, and feeding systems (Khalil *et al*., 2024). The ruminant animal is fed on crop by-products and forage plants grown in various areas of crop plantation, forest edges, riverbanks, roadsides, and idle land (Khalil *et al*., 2024).

When a volcano erupts, it spews ashes and other volcanic materials composed of various rocks, sands, and silts (Newhall, 2000; Voight, 2000), causing animal loss and health problems due to exposure to volcanic materials, crops and forage damages, and animal mitigation constraints, resulting in flock size decrease and economic loss (Khalil *et al*., 2024). Forage plants would be regrown or recovered about one to six months after the eruption, depending on factors such as rainfall, the plant species, proximity to the eruption center, and the extent of damage (Khalil *et al*., 2024; Saputra *et al*., 2022; Smather and Dombois, 1974). Numerous studies reported that minerals of volcanic materials have a beneficial effect on volcanic soil and forages post-eruption by increasing soil fertility and forage production (Hartati *et al*., 2023; Tulp *et al*., 2023; Umami *et al*., 2015), but at the same time, it has a potency to alter mineral composition in forages, leading to inadequacy or imbalance in the mineral intake of grazing cattle (Linhares *et al*., 2021). Ashfall and other volcanic materials are composed of various chemicals and minerals. The minerals usually present in volcanic materials depend on the magma's chemistry from which it erupted (Tulp *et al*., 2023; Mihai *et al*., 2023). Setiawati *et al*. (2024) reported that the dominant essential minerals in volcanic ash and soil of Mt. Semeru, East Java, were calcium (Ca), iron (Fe), and potassium (K). After weathering, volcanic ash provides plants with essential macro- and micronutrients, including Ca, Na, K, Mg, Zn, Fe, Cu, and Mn (Khan *et al*., 2024).

Forage plants provided a major source of essential minerals for grazing cattle in the volcanic Mt.ains. The inadequacy or imbalance in mineral composition might adversely affect the growth, milk production, immune function, reproduction, and overall health of grazing cattle post-eruption (Linhares *et al*., 2021). Linhares *et al*. (2021) reported from Portugal that the uneven distribution of essential nutrients in topsoil (Co and Se) and pasture grass (Co, Cu, Se, and Zn) and their deficiency can lead to several health problems in grazing cattle in Sao Miguel Island (Azores). Therefore, assessing mineral nutrition might be critical for beef cattle nutrition in eruption-impacted areas due to mineral imbalance in volcanic soils and forage post-eruption. Different volcanoes have different geological materials, resulting in different impacts on mineral compositions in the volcanic soils and forages.

The present study was carried out to evaluate the forage minerals content and their relationship with soil mineral concentrations and to discuss the potential undesirable effects on grazing cattle in the eruption-impacted areas of active volcanic Mt.ains in Indonesia. Identifying imbalanced or deficient minerals might help cattle farmers implement soil treatment or feed supplements to minimize undesirable health effects or nutritional disorders in grazing cattle.

MATERIALS AND METHODS

General Description of Study Sites

The study was conducted in five active vol-

Table 1. Sampling sites of forage plants and soils in the eruption-impacted areas in five volcanoes in Indonesia

Sampling sites	Name of volcanic mountains:				
	Agung	Gamalama	Lokon	Merapi	Sinabung
Province	Bali	North Maluku	North Sulawesi	Central Java	North Sumatra
Regency/city	Karang Asem	Ternate	Tomohon	Magelang	Karo
District	Rendang	West Ternate	North Tomohon	Dukun	Naman Teran
Village/subdistrict	Besakih	Takome	Wailan	Krincing	Sigarang-garang

canic Mt.ains on five islands in Indonesia. They were: Agung Mt.ain (Bali Island), Gamalama Mt.ain (North Maluku), Lokon Mt.ain (North Sulawesi, Merapi Mt.ain (Central Java), and Sinabung Mt.ain (North Sumatra) (Table 1). They had 2-3 eruptions in the last ten years. They spewed volcanic ash and other hazardous materials, resulting in natural disasters on crops, properties, public infrastructures, feed, and livestock in eruption-impacted areas. The selected volcanoes have different characteristics in eruption, height and topography, vegetation, agroclimatic, and agricultural and livestock farming systems (Khalil *et al*., 2024).

Mt. Agung is in Karang Asem Regency, Bali province. Geographically, Mt Agung is located at the coordinates 8°20’27”S and 115° 30’12”E. The highest point is 3031 m asl (above sea level). The stratovolcano was recorded as first erupted in 1843, re-erupted in 1963-1964, and 207-2019 (Devi *et al*., 2019). Mt. Lokon is in Tomohon city, Minahasa, North Sulawesi, approximately 25 km South of Manado. The coordinated position of Mt. Lokon is between 1° 21,5' N and 124º 47,5' E with an elevation of 1597.5 m asl. Mt. Lokon's activity is in the Tompaluan crater, located on the saddle between the peaks of Lokon and Empung. Mt Lokon erupted in June 2011 and August 2015 (Senduk and Abdurrachman, 2023; Kriswati *et al*., 2012). Tomohon is well-known as a center for various horticultural and flower farming in North Sulawesi province (Khalil *et al*., 2024).

Gamalama volcano (1,715 m asl) is in Ternate city, North Maluku. Mt. Gamalama recorded its first eruption in 1538. An eruption in 1775 caused the deaths of approximately 1300 people. The volcano erupted in 1990, 2012, 2014, and 2018. The longest eruption occurred in 2011 (Marfai *et al*., 2021). Mt. Merapi is the most active volcano in Indonesia. The stratovolcano is in Central Jawa and Yogyakarta province, with the highest elevation of about 1700 m. Mt. Merapi often erupts and causes natural disasters, especially in the prone areas of Magelang and Sleman Regency and the Special Region of Yogyakarta. Multiple severe eruptions occurred in 2010, 2018, 2021, and 2023 (Widyantoro *et al*., 2018). Mt. Sinabung is the most active volcano in North Sumatra, Karo Regency, North Sumatera Province. Geographically, the summit lies at 03◦10 N and 98◦23.5 E at an altitude (height) of 2460 m asl. Karo highland around the Sinabung cultivates various horticultural and fruit crops and supplies vegetables and fruit in North Sumatra. Sinabung Volcano first erupted in 2010 and re-erupted periodically by May 2016, June 2019, August 2020, and March 2021 (Nurwihastuti *et al*., 2019; Kadavi *et al*., 2017; Said Muzambiq *et al*., 2017; Tarigan, 2015).

Sampling Sites

Forage plants and soil samples were taken in the most eruption-impacted areas (Table 1). There are Besakih village (Mt. Agung), Takome sub-district (Mt. Gamalama), Wailan sub-district (Mt. Lokon), Krincing (Mt. Merapi), and Sigarang garang (Mt. Sinabung). Forage plants in the selected locations were severely damaged by volcanic materials composed of gravel, sand, and ash, leading to primary succession (Khalil *et al*., 2024). Besakih is a village in the Rendang sub-district, Karangasem Regency, Bali Province. Besakih village of approximately 21.23 km² is located about 6 km from the crater center of Mt. Agung. Three villages close to Mt. Agung's center are often severely impacted by the eruption of Mt. Agung, namely Besakih, Temukus, and Kedundung (Devi *et al*., 2019).

Takome is a sub-district in West Ternate District, Ternate City, North Maluku Province. Four sub-districts in West Ternate are exposed to volcanic material due to the eruption of Mt. Gamalana, namely Takome, Togafo, Loto, and Afetaduma sub-districts. Takome sub-district was reported as the most vulnerable site (Hidayat *et al*., 2023). Wailan is a sub-district in North Tomohon district, Tomohon City, North Sulawesi province. When it erupts, Mt. Lokon's volcanic material is usually spread evenly across three southern Tomohon sub-districts, namely Matani, Wailan, and Saroinsong sub-districts (Karisoh *et al*., 2024).

Krinjing is a village in the Dukun sub-district, Magelang, Central Java, Indonesia. Krinjing village is often the worst affected since it is located closest to the crater center and only about 4.5 km from it. The roofs of the residents' houses were covered in ash, including fields and crops (Sari *et al*., 2022; Christia, 2012). The eruption of Mt. Sinabung severely affected four districts, namely Naman Teran, Berastagi, Dolat Rayat, and Merdeka. Sigarang-Garang village in Naman Teran District, Karo Regency, was one of the hardest-hit areas. Located on the northern slopes of Mt. Sinabung, the village was devastated by torrents of volcanic ash, hot lava, and subsequent cold lava floods, leaving it in ruins. The disaster began in 2010 and continues to impact the region as of 2022 (Martualina *et al*., 2024; Nurwihastuti *et al*., 2019).

Collection of Forage and Soil Samples

Samples of forages were collected in the selected areas where cattle farmers usually collected forage to feed their animals, or their farm animals were frequently grazed and tethered. The map, imagery interpretation, and guidance from officers of Volcano Observation Posts (Pos Pengamatan Gunung Api) were used to determine sampling locations by following the purposive sampling methods described by Aini *et al*. (2019). A map of volcanic ash distribution was obtained from the Volcano Observation Posts at each active volcano. Sampling locations were divided into three distances from the eruptive crater (eruption center): near, moderate, and far by considering the distribution pattern of volcanic materials (Neall, 2006). On the surrounding craters, the volcanic materials may have accumulated to great thickness, producing fertile volcanic soils, while the finer particles (ash) are distributed in more considerable distances downwind (Neall, 2006).

Samples were taken at five sampling points at each distance location using a quadrant plate meter of 0.5 x 0.5 m^2. All plant materials inside the plate meter were cut 5-10 cm above ground level and placed in labeled plastic bags. Soil samples were taken from the same sampling points from which the forage samples were taken. Samples of soil were obtained using a stainless-steel sampling auger to a depth of 10-15 cm (topsoil). There were, in total, 15 samples of forage and soils on each site.

Sample Preparation and Analysis

A total of 15 fresh plant samples were collected from each study site. The samples of fresh plants were chopped at 2-3 cm length, and then the five samples from each distance were composited, giving three samples from each collecting site (15 total samples of all sites). Representative samples of about 150 g were taken and dried in an oven at 60ºC for 48 hours and ground in meal form. The samples were analyzed for dry matter (DM) and essential macro minerals (Ca, P, Mg, K, Na, S) and trace elements (Fe, Zn, Cu, Mn, Co, Se). The DM content was analyzed by following the procedures described by AOAC (2016). The concentration of minerals was determined using the atomic absorption spectrophotometer (AAS, 1980).

Soil samples were freed from plant roots and other foreign contaminants, spread thinly on a clean sheet of paper, and dried under the sun. The air-dried samples were reduced to their particle sizes by manual grinding using a glass bottle and then sieved through a 2-mm sieve. The soil samples were mixed, and composites were made using the same procedures as the forage sample. As a result, three soil samples belonged to each site, obtaining 12 soil samples. The samples were analyzed for DM and macro minerals (Ca total, P potential, Mg total, K potential, Na total, S total) and trace elements (Fe, Zn, Cu, Mn, Co, Se). The total calcium, magnesium, and sulfur were analyzed using a flame photometer according to the procedures described by Eviati and Sulaeman (2012). The potential potassium was measured using an Atomic Absorption Spectrophotometer (Eviati and Sulaeman, 2012). The potential phosphorus was analyzed using the Bray method (ISRIC, 2022). All analysis results were reported on a dry matter basis.

Statistical Analysis

Data were statistically analyzed in one-way variance analysis using a randomized block 5x3 design, consisting of 5 volcanoes and 3 different distances as replicates per volcano. The variance analysis was followed by Duncan post hoc multiple comparisons to estimate significant differences between means at $p<0.05$. The results were expressed as mean ± SD. Coefficient correlations (r) were established for mineral concentrations in soils and forages. The determined forage mineral means concentrations were compared with cattle mineral requirements. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 18.0

RESULTS AND DISCUSSION

The mineral composition of soil samples is presented in Table 2. The macro-mineral content of soils showed significant differences in calcium (Ca), phosphorus (P), magnesium (Mg), potassium (K), and sulfur (S). Soils from Mt. Merapi, Mt. Gamalama, Mt. Sinabung, and Mt. Agung exhibited high Ca concentrations of 0.7-0.8%. The lowest Ca concentration was observed in soils from Mt. Lokon ($p < 0.05$). Phosphorus content varied considerably between and within the studied volcanoes. The highest P levels were found in soil from Mt. Lokon, which were not significantly different from those of Mt. Merapi, Mt. Agung, and Mt. Sinabung. Soils from Mt. Gamalama had the lowest P content.

Magnesium levels ranged from 0.07% to 0.71%, with soils from Mt. Gamalama containing the highest Mg concentration, followed by Mt. Lokon. The lowest Mg concentrations were observed in soils from Mt. Sinabung, which did not differ significantly from those of Mt. Merapi and Mt. Agung. Potassium content was lowest in soils from Mt. Merapi, with values not significantly different from those of Mt. Gamalama, Mt. Agung, and Mt. Lokon. The highest K concentrations were found in soil from Mt. Sinabung. Sodium (Na) content ranged from 0.09% to 0.14%, with no significant differences observed among the volcanoes. Sulfur (S) was the least abundant macro-mineral in the volcanic soils, with mean concentrations below 0.1%. Soil from Mt. Sinabung had the highest S concentrations, which were not significantly different from those of Mt. Lokon, Mt. Gamalama, and Mt. Agung. The lowest S levels were detected in soils from Mt. Merapi.

Compared to mineral critical levels, the soils of Mt. Agung were rich in Ca, K, and S. They exhibited favorable levels of Mg, P, Na, and S. The soils of Mt. Gamalama contained high levels of Ca and Mg but were deficient in P. Mt. Lokon's soils were enriched in P, Mg, K, and S but low in Ca. Soils from Mt. Merapi were rich in Ca and P and displayed favorable levels of K and Na but were low in Mg and S. The soils of Mt. Sinabung were high in Ca, P, K, Na, and S, favorable in P, but deficient in Mg. The Ca, Mg, and K contents in the soils of Mt. Sinabung in this study were significantly lower than data from Khusrizal *et al*. (2017) who reported that the mean Ca, Mg, and K content of 8.1, 2.3, and 2.3%, respectively. No significant differences in Na content were observed among the volcanoes. Interestingly, while volcanic eruptions release substantial aMt.s of sulfur, the S concentration in volcanic soils was generally low, except in Mt. Sinabung. This phenomenon might be attributed to the high water solubility of sulfur from non-magmatic sources compared to magmatic minerals, facilitating its leaching into environmental water (Ohba and Nakagawa, 2002).

The concentration of macro minerals from all volcanic soils is much higher than those reported as soil reference levels suggesting deficiencies. However, soil Ca in Mt. Lokon, P in Mt. Gamalama, and Mg in Mt. Merapi dan Sinabung are relatively low and suggested as essential minerals that could limit plant growth nutrients due to many factors affecting mineral availability. Tulp *et al*. (2023) reported that Na, Ca, and Fe were the highest mineral concentrations in volcanic soil derived from The Montserrat Soufriere Hills volcano, Plymouth City, UK. Other essential mineral concentrations varied widely. The phosphorus varied from 255 to 677 ppm, potassium from 54 to 663 ppm, magnesium from 411 to 1299 ppm, sulfur from 1081 to 2789 ppm, and manganese from 135 to 210 ppm (Tulp *et al*., 2023).

Volcanic soils had a considerably high content of Fe of 14-20 g/kg. Although it is included in the micronutrient group, iron provides more than other macronutrients such as P, K, and Mg. The highest Fe was found in the soil sample of Mt. Lokon, which was not significantly different from the other volcanic soils of Mt. Gamalama and Mt. Agung. The possibility was related to Fe behavior, immobile or insoluble, and remained in

Table 2. Mineral mean concentration in soil samples (means ± standard of deviation) collected from eruption-impacted areas in five active volcanic mountains in Indonesia

Mineral	Agung	Gamalama	Lokon	Merapi	Sinabung	Critical levels* (ppm)
Macro minerals						
– Ca total (%)	0.76^{a}±0.02	0.83^{a}±0.14	0.38^{b}±0.05	0.87^{a}±0.05	0.74^{a}±0.12	< 70
– P potential (mg P_2O_5/100 g)	83.38^{bc}±16.16	48.83^{c}±3.87	174.87^{a}±44.49	157.25^{ab}±50.94	98.55^{abc}±36.64	< 10
– Mg total (%)	0.37^{b}±0.13	0.71^{a}±0.09	0.52^{ab}±0.24	0.10^{c}±0.08	0.07^{c}±0.02	< 30
– K potential (mg K_20/100 g)	30.54^{ab}±0.02	28.96^{b}±4.02	33.47^{ab}±6.47	23.99^{b}±1.14	39.97^{a}±11.80	< 59
– Na total (%)	0.10±0.13	0.09±0.11	0.12±0.02	0.11±0.15	0.14±0.19	< 62
– S total (%)	0.04^{ab}±0.01	0.04^{ab}±0.01	0.05^{ab}±0.04	0.02^{b}±0.01	0.07^{a}±0.04	< 10
Micro minerals:						
– Fe (ppm)	17954.90^{ab}±3604.25	18926.99^{ab}±636.03	20251.75^{a}±1714.55	15364.24^{bc}±171.77	14229.76^{c}±1556.59	< 2,5
– Zn (ppm)	56.11±23.57	44.79±4.72	50.19±8.00	45.76±3.70	36.83±17.57	< 1
– Cu (ppm)	46.49^{b}±9.18	57.8^{a}±6.71	59.96^{a}±1.29	28.73^{c}±3.37	9.53^{d}±1.21	< 0.3
– Mn (ppm)	127.96^{ab}±65.91	179.76^{a}±26.91	162.21^{ab}±93.54	138.53^{ab}±34.20	66.01^{b}±4.24	< 5
– Co (ppm)	4.55^{ab}±0.56	5.47^{a}±0.43	4.34^{b}±0.81	3.78^{bc}±0.61	3.16^{c}±0.08	
– Se (µg/100 g)	9.25^{ab}±0.16	9.99^{ab}±0.29	6.03^{b}±4.88	11.45^{a}±0.35	10.71^{a}±0.33	

* McDowell (1985) and Rhue and Kidder (1983)

Table 3. Mineral mean concentration in forage samples (means ± standard of deviation) collected from eruption-impacted areas in five active volcanic mountains in Indonesia

Mineral	Agung	Gamalama	Lokon	Merapi	Sinabung	Critical Level*)	Maximum tolerable level**
Macro minerals (% DM)						(% DM)	(% DM)
– Ca	$0.66^{abc}\pm0.06$	$0.59^{bc}\pm0.07$	$0.75^{ab}\pm0.11$	$0.76^{a}\pm0.02$	$0.52^{c}\pm0.13$	< 0.30	
– P	$0.24^{bc}\pm0.06$	$0.09^{d}\pm0.02$	$0.36^{a}\pm0.05$	$0.31^{ab}\pm0.06$	$0.22^{c}\pm0.05$	< 0.25	
– Mg	$0.39^{a}\pm0.06$	$0.26^{b}\pm0.02$	$0.36^{ab}\pm0.02$	$0.29^{ab}\pm0.03$	$0.26^{b}\pm0.07$	< 0.10	0.40
– K	$3.12^{b}\pm0.41$	$1.55^{c}\pm0.33$	$4.21^{a}\pm0.82$	$3.00^{b}\pm0.45$	$2.49^{b}\pm0.47$	< 0.5	3.00
– Na	0.03±0.01	0.04±0.02	0.05±0.04	0.02±0.01	0.02±0.01	< 0.06	
– S	$0.14^{c}\pm0.02$	$0.12^{c}\pm0.04$	$0.35^{b}\pm0.10$	$0.16^{bc}\pm0.04$	$0.65^{a}\pm0.19$	< 0.08	0.50
Micro minerals:						(ppm)	(ppm)
– Fe (ppm)	$108.56^{b}\pm8.63$	$270.51^{ab}\pm152.86$	$208.94^{ab}\pm31.60$	$307.58^{a}\pm77.41$	$192.42^{ab}\pm116.46$	< 50	500
– Zn (ppm)	71.48±23.57	50.30±21.01	68.38±13.59	68.67±13.85	85.81±16.15	< 30	500
– Cu (ppm)	$167.82^{ab}\pm167.30$	$19.22^{b}\pm17.41$	$55.03^{ab}\pm16.76$	$211.64^{a}\pm71.46$	$9.71^{b}\pm3.16$	< 8	40
– Mn (ppm)	$74.91^{b}\pm65.64$	$186.34^{a}\pm83.94$	$61.57^{b}\pm33.24$	$30.34^{b}\pm3.43$	$182.89^{a}\pm47.37$	<40	1000
– Co (ppm)	$9.48^{b}\pm0.41$	$11.22^{a}\pm0.71$	$11.19^{a}\pm0.78$	$10.69^{a}\pm0.40$	$11.64^{a}\pm0.20$	< 0.10	25
– Se (µg/100 g)	$1.01^{c}\pm0.04$	$1.33^{b}\pm0.08$	$0.83^{d}\pm0.02$	$1.10^{c}\pm0.08$	$1.71^{a}\pm0.06$	<0.10	5

* Lalman and Holder (2023) and ** NRC (2000)

the soil (Aini *et al*., 2019). Iron is an essential micronutrient for plant growth and development, playing a critical role in various physiological processes (Haris *et al*., 2023). The high concentration of Fe in the volcanic soil has implications for forage growth and recovery post-eruption because Fe is the micronutrient plants need in small quantities (Aini *et al*., 2019). However, excessive iron uptake can lead to iron toxicity, causing damage to the plant's cell membranes, reducing growth and yield, and affecting the plant's overall health (Haris *et al*., 2023). Other microminerals in relatively high concentrations included Mn, Zn, and Cu. Soils of Mt Lokon, Gamalama, Agung, and Merapi had higher Fe, Mn, and Cu concentrations than those in Mt. Sinabung. Soils at Mt. Sinabung had the lowest Fe, Zn, Cu, Mn, and Co. Trace minerals Co and Se were found in low concentration and differed amongst the volcanoes.

The essential mineral of volcanic forages is presented in Table 3. The table indicates that forages from areas affected by volcanic eruptions exhibited significant differences in concentrations of calcium (Ca), phosphorus (P), potassium (K), magnesium (Mg), and sulfur (S). Forages from Mt. Merapi and Mt. Lokon had significantly higher Ca concentrations than those from Mt. Gamalama and Sinabung. The P concentration was highest in forages from Mt. Lokon, comparable to that of Mt. Merapi, but significantly higher than in forages from Mt. Sinabung and Mt. Gamalama. Forages from Mt. Gamalama exhibited the lowest P concentration, with a significant decrease in P content observed in forage samples collected farther from the crater.

Forages from Mt. Lokon had the highest K concentrations ($p < 0.05$), followed by those from Mt. Agung, Mt. Merapi, and Mt. Sinabung. Forages from Mt. Gamalama showed the lowest K content. No significant differences were observed in the forages' sodium (Na) concentrations. The highest S concentration was recorded in forages from Mt. Sinabung ($p < 0.01$), followed by Mt. Lokon, which was not significantly different from Mt. Merapi. Forages from Mt. Agung and Mt. Gamalama had the lowest S concentrations. As shown in Table 4, except for P and S, there was a low correlation of minerals in volcanic soils and forages. Minerals in forages were mainly negatively correlated with minerals in the soils. The forage mineral is not significantly affected by mineral concentration in the volcanic soils.

Table 4.Coefficient correlation (r) of mineral concentration in soil and forages

Mineral	(r)
Macro mineral:	
Ca	-0.31
P	0.70
Mg	0.15
K	0.12
Na	-0.19
S	0.65
Trace mineral:	
Fe	-0.09
Zn	-0.03
Cu	-0.15
Mn	-0.30
Co	0.48
Se	-0.13

Compared to the nutritional requirements of growing cattle, the concentrations of calcium (Ca) and magnesium (Mg) in forages from all study sites were favorable for cattle nutrition. However, forages from volcanic areas were deficient in phosphorus (P) and sodium (Na). Phosphorus deficiency was notable in forages from Mt. Gamalama, Mt. Sinabung, and Mt. Agung. The P concentration in forage from Mt. Gamalama (0.09%) was substantially lower than the critical level of 0.25% recommended for the diet of growing cattle. The P content in forages largely depended on the P availability in soils. Low soil P levels also negatively affected the Ca:P ratio in forages, posing risks of P deficiency (hypophosphatemia), malnutrition, and nutrient malabsorption in cattle. Chronic P deficiency can result in reduced feed intake, protein malnutrition, impaired bone growth and development, and infertility (Wu, 2018). Phosphorus in volcanic soils is predominantly an appetite mineral, highly soluble under acidic conditions for vegetation growth (Mihai *et al*., 2023). However, other elements present in ash-rich soils, such as non-crystalline forms of aluminum and iron, can facilitate the formation of compounds that immobilize phosphorus, rendering it insoluble and unavailable to plants (Mihai *et al*., 2023).

Sodium (Na) was identified as the most critical essential mineral. The Na concentrations in forages from all volcanic regions were lower than the critical levels reported for forages, indicating widespread deficiencies. This finding aligns with the low Na content observed in the soils (Table 2). All forage samples from volcanic areas exhibited low Na concentrations, with mean values ranging from 0.02% to 0.05%, below the minimum requirement of 0.06%. As shown in Table 4, the lack of correlation between Na content in the soil and forage could be the causing factor for limited concentration in the forages. Na concentration in the soil was negatively correlated with Na concentration in forage.

Sodium plays a vital role in several physiological processes in cattle, including the formation, retention, concentration, and pH regulation of body fluids such as protoplasm and blood (Wu, 2018). It is also essential to produce digestive juices and properly functioning nerves and muscles (Wu, 2018). Soil and forages in the studied regions were deficient in Na, with forage Na concentrations consistently below the critical threshold of 0.06%. Deficiency in Na can lead to reduced osmotic pressure, body dehydration, and hypotension. Clinical symptoms of Na deficiency in cattle include reduced feed intake, poor weight gain, diminished utilization of digested proteins and energy, and reproductive disorders (Wu, 2018).

Forage mineral concentrations of potassium (K) and sulfur (S) at Mt. Lokon and Mt. Sinabung exceeded the maximum tolerable levels, posing potential health risks to cattle. Forage samples collected closer to the eruption centers exhibited higher K concentrations. Potassium is essential for maintaining body fluid balance, regulating the pH of body fluids, and supporting rumen digestion (Wu, 2018). At Mt. Lokon, forage K levels exceeded the maximum tolerable limit of 3% dry matter (DM). Excessive K intake (hyperkalemia) can lead to reduced feed intake and impaired growth, fatigue, muscle weakness, abnormal heart rhythms (arrhythmia), bradycardia, cardiac arrest, and, in severe cases, death (Wu, 2018).

Sulfur is essential for protein synthesis and animal milk and hair production. Sulfur deficiency can result in poor performance, hair loss, excessive salivation, and tearing. Most volcanic forages, except those from Mt. Sinabung, contain sulfur concentrations favorable for livestock nutrition. However, the sulfur content in forages from Mt. Sinabung significantly exceeds the maximum tolerable level of 0.35%. Diets with excessive sulfur disrupt the acid-base balance in animals, reduce feed intake and growth performance, and may lead to lesions in the brain's gray matter (Wu, 2018).

The concentration of microminerals such as Fe, Cu, Mn, Co, and Se in volcanic forages differed significantly. Forage samples from Mt. Merapi exhibited the highest Fe content, which was not significantly different from those observed in forages from Mt. Lokon, Mt. Gamalama, and Mt. Sinabung. In contrast, forages from Mt. Agung had the lowest Fe content. The concentrations of Cu and Mn showed substantial variation, both within individual Mt.ains and across different Mt.ains. The Fe content in the forages analyzed in this study was slightly lower than the mean Fe content of Napier grass (377.9 ppm) cultivated on the volcanic slopes of Mt. Merapi in the Magelang Regency, as reported by Hartati *et al*. (2023). The volcanic material from Mt. Merapi primarily consists of older volcanic deposits containing 90.7–95.2% plagioclase, 2.5–4.1% pyroxene, and 1.04–3.88% hornblende. The order of total nutrient concentration, from highest to lowest, was Fe > Ca > Mg > P > K > Na > Zn (Hartati *et al*., 2023). On the other hand, when occurring in high concentrations in plant tissue (above 500 mg Fe kg^{-1} dry leaf mass), it might cause iron toxicity. Fe can disrupt the cell redox balance towards a pro-oxidant state, inducing alterations in the morphological, metabolic, and physiological traits of the plants and generating oxidative stress (Mihai *et al*., 2023)

The highest copper (Cu) concentration (211.6 ppm) was observed in forage samples from Mt. Merapi, which was not significantly different from the Cu concentrations in samples from Mt. Agung (167.8 ppm) and Mt. Lokon (55.0 ppm). The lowest Cu concentration was found in forage from Mt. Sinabung (9.7 ppm). Conversely, forage from Mt. Sinabung exhibited the highest manganese (Mn) concentration, followed by forage from Mt. Gamalama. Zinc (Zn) concentrations ranged from 50.3 to 85.8 ppm, with no significant statistical differences among the sites studied. Cobalt (Co) and selenium (Se) concentrations displayed minimal variation within and between the study sites. Forage from Mt. Merapi contained the highest Co concentration, which was not significantly different from those observed in samples from Mt. Sinabung, Mt. Gamalama, and Mt. Lokon. The lowest Co concentration was found in forage from Mt. Agung. Selenium concentrations were highest in samples from Mt. Sinabung, followed by Mt. Gamalama, Mt. Merapi, Mt. Agung, and Mt. Lokon.

Trace mineral concentrations, except for copper (Cu), were at favorable levels for cattle nutrition. However, special attention is warranted for Cu due to its elevated levels in volcanic forages from Mt. Agung, Merapi, and Lokon, which exceed the maximum tolerable limits for growing cattle. According to Wu (2018), Cu is essential for proper iron utilization in animal tissues, hemoglobin formation, and keratin synthesis, which supports hair and wool growth. Notably, forage Cu concentrations were significantly higher at Mt. Agung and Merapi. As a strong oxidizing agent, excessive Cu can lead to adverse effects, including stomach pain, nausea, diarrhea, tissue damage, and disease in animals (Wu, 2018).

CONCLUSION

The essential mineral concentration of volcanic soils and forages in the eruption-impacted areas varied amongst the volcanoes. Except for P and S, there are fewer minerals correlated in forages with minerals in the volcanic soils. This variation in mineral concentrations of forages could have significant implications for the nutritional status of grazing cattle. Considering mineral requirements for cattle, forage plants exceeded tolerable levels of high K, S, and Cu content; they were favorable to Ca, Mg, Zn, Co, and Se concentrations but were deficient in P and Na. It is suggested that the essential minerals most likely to limit cattle productivity in the eruption-impacted areas are P, Na, K, S, and Cu. Consequently, grazing animals at this location need continued mineral supplementation to prevent diseases caused by nutrient deficiency and support optimum animal productivity. For future studies, surveys should be conducted measuring the actual intake of micro and micro minerals and mineral status in the blood of the cattle in the area to confirm the deficiency and/or excessive mineral status.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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