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Spatial Variability of Soil Health in Volcanic-affected Agroecosystems for Superior Crop Development: A Case Study of Kelud Mountain, Indonesia

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ABSTRACT

Background: This study assesses post-eruption soil health on Mount Kelud to support the development of superior commodities such as pineapple. Utilising a modified Cornell Soil Health Assessment (SHA) method, the analysis integrates physical, chemical and biological soil properties. This parameter combination of land characteristics includes slope and NDVI (Normalized Difference Vegetation Index).

Methods: A physiographic survey and land unit classification based on land use and criticality levels were employed. Statistical analyses (normality tests, ANOVA and correlation) were performed using RStudio, while spatial analyses used overlay and interpolation methods in ArcGIS.

Result: SHA post-eruption has criteria healthy (63.30%) and moderately healthy (36.70%) and KBA has the highest. Key parameters significantly influencing SHA included porosity (0.77), sand composition (-0.70), BD (-0,49), permeability (-0.44), pH (r=0.36), earthworm population (0.73), organic matter (0.37), slope (-0.62) and NDVI (0.56). Integrating soil and land indicators into spatially distributed SHA mapping offers a strategic approach to land management and supports the targeted cultivation of pineapple as a leading post-eruption crop.

Key words: Land characteristic, NDVI, Post-eruption land management, Soil quality, Spatial analysis, Topographic.

INTRODUCTION

Since 1000 AD, Mount Kelud has experienced 30 significant eruptions and most recently in February 2014 (Niasari *et al*., 2021; Tsana *et al*., 2022). The 2014 eruption was particularly significant, ejecting more than 200 million tons of material, resulting in widespread ashfall and secondary hazards such as lahars and landslides (Bachri *et al*., 2019; Santoso *et al*., 2024). In addition, pyroclastic material was spread to >700 km and consisted of sand and gravel particles (>2 mm) and had a thickness of >20 cm (Putra *et al*., 2022; Wilujeng *et al*., 2020). The thickness of the volcanic deposits can cause the soil layer to be buried, decreasing the organic carbon content in the soil, which impacts soil health (Troll *et al*., 2017; Ustiatik *et al*., 2023). Based on actual conditions, farmers utilise the land for agricultural cultivation to increase community income after the eruption.

Improving agricultural production and sustainability are the main goals of soil health research. Soil health assessment can be measured using soil health indicators based on physical, chemical and biological properties (Moebius-Clune *et al*., 2016). However, soil health assessment has yet to integrate the influence of topography and vegetation density as indicators. The novelty in this study lies in combining soil properties with land characteristics such as slope (Fortuna *et al*., 2023) and normalised difference vegetation index (Zhang *et al*., 2019). Spatial land monitoring of post-volcanic eruptions must be carried out by utilising Geographic Information System (GIS) and remote sensing technology to mitigate disaster impacts, to analyse ecological impacts of volcanic eruptions on vegetation and soil health (Crovo *et al*., 2021).

This research aims to assess the health index of sandy soil after the eruption of Mount Kelud in 2014 based on a combination of physical, chemical and biological soil properties with land characteristics in the form of slope and NDVI. In addition, the level of soil health can be determined using GIS and sensing data for spatial land monitoring to provide solutions for developing superior commodities of Mount Kelud.

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MATERIALS AND METHODS

Research location

The research was conducted in the Mount Kelud area, specifically in Ngancar District, Kediri Regency, from April to August 2024 during the dry season. The study was conducted during the dry season so that soil conditions matched actual conditions, were not affected by rainfall and facilitated survey accessibility, given the varied topography of the land. The research locations are presented in Fig 1, which are scattered in the field and garden, because this location is a potential area for developing superior commodities. The research area experiences minimal rainfall in August (±19 mm/month) and peak precipitation in December (±400 mm/month), with annual average air temperatures ranging from 21°C to 31°C, based on CHIRPS spatial rainfall data and temperature records obtained from the Copernicus platform.

Experimental design

The land map unit uses land use characteristics and criticality conditions, comprising 10 land units, with each land unit taking 3 points as replicates. The land units are KBA (garden, no critical land), KBB (garden, potentially critical), KBC (garden, moderately critical), KBD (garden, critical), KBE (garden, highly critical), LDA (field, no critical land), LDB (field, potentially critical), LDC (field, moderately critical), LDD (field, critical) and LDE (field, highly critical). The research was conducted in the post-eruption area within a radius of 5-20 km from Mount Kelud.

Data analysis and laboratory analysis

Soil health assessment is done by scoring land aspect data using the Cornell method to analyse soil property factors and combine the influence of land aspects in the form of topography and vegetation density (Table 1). A percentage value was generated from the overall soil health score (Formula 1). The soil health classes consist of five levels representing the degree of soil health: unhealthy (0-20), less healthy (20-40), moderately healthy (40-60), healthy (60-80) and very healthy (80-100) (Moebius-Clune *et al*., 2016).

$$SHA = \frac{\text{Total score}}{\text{The highest score}} \times 100\% \quad \text{.....Formula 1}$$

Spatial analysis

Survey maps were made using the spatial data overlay method in the form of the results of land use interpretation

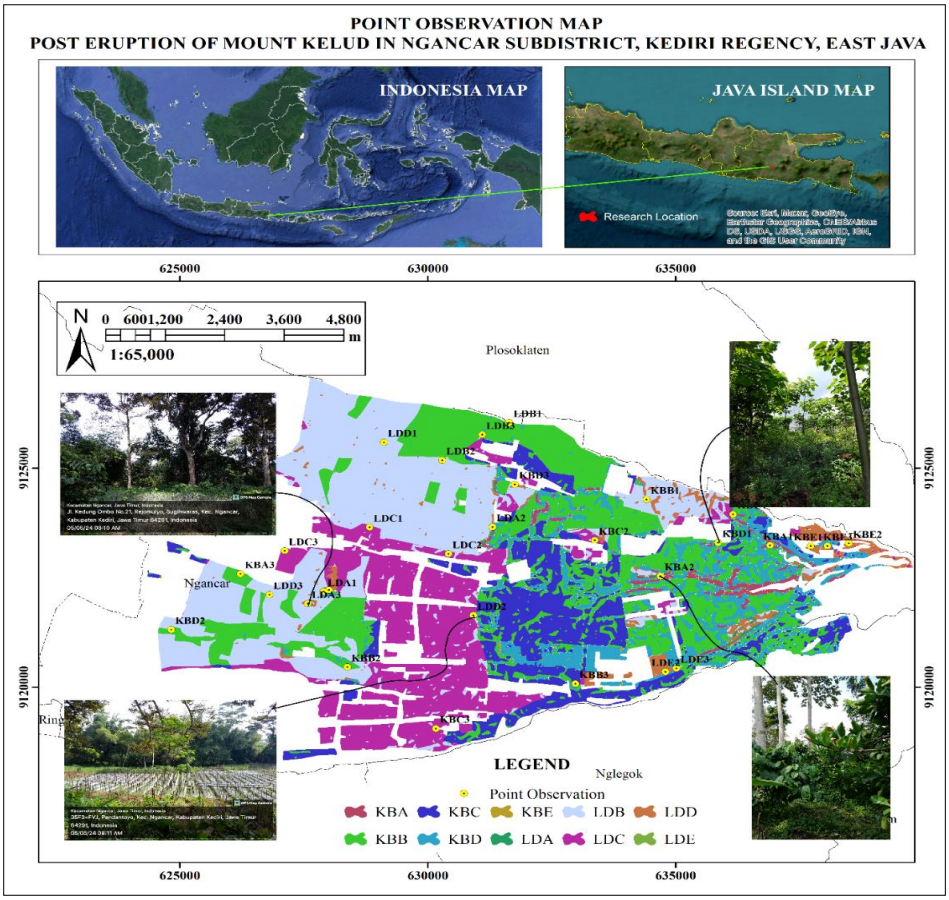


Fig 1: Map of soil sampling.

Table 1: Parameters of the research.

Parameter	Method	Range of value	Score	Reference
Soil physical characteristic				
Bulk density (g/cm^3)	Volumetric method	<0.90	5	(Guo, 2021; Moebius-Clune *et al*., 2016)
		0.90-1.00	4	
		1.00-1.20	3	
		1.20-1.40	2	
		>1.40	1	
Permeability (cm/hour)	Constant-head permeameter	2.00-6.30	5	(Hamdi *et al*., 2022)
		6.30-12.5	4	
		00.50-2.00	3	
		>12.50	2	
		<0.50	1	
Soil Texture	Pipette method	Silty loam, loamy, silty clay loam,	5	
		silty clay loam, sandy loam sandy	4	
		clay loam, clay loam, silty clay loam	3	
		sand, loamy sand Sandy clay,	2	
		clay, silty clay	1	
Soil porosity (%)	Volumetric method and gravimetric method	60-80	5	
		40-60	4	
		40-20	3	
		80-100	2	
		<20	1	
Soil chemical characteristics				
pH (H_2O)	Conductometric measurement	6-7.5	5	(Guo, 2021; Moebius-Clune *et al*., 2016)
		5.5-6	4	
		7.5-8.5	3	
		4.5-5.5	2	
		<4.5 and >8.5	1	
C-Organic (%)	Walkley and black	>5.00	5	
		3.00-5.00	4	
		2.00-3.00	3	
		1.00-2.00	2	
		<1.00	1	
N tota l (%)	Kjeldahl method	>0.75	5	
		0.50-0.75	4	
		0.20-0.50	3	
		0.10-0.20	2	
		<0.10	1	
P_2O_5 (ppm)	Bray II	>15.00	5	
		10.00-15.00	4	
		7.00-10.00	3	
		4.00-7.00	2	
		<4.00	1	
K_2O (me/ 100 g soil)	Flame photometry			
		>1.00	5	
		0.60-1.00	4	
		0.31-0.59	3	
		0.10-0.30	2	
		<0.10	1	

Table 1: Continue...

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CEC (me/ 100 g soil)	Ammonium acetate	>40.00	5	
		24.00-40.0	4	
		016.00-24.00	3	
		5.00-16.00	2	
		<5.00	1	
Base saturation (%)	Ammonium acetate	>80.00	5	
		60.00-80.00	4	
		40.00-60.00	3	
		20.00-40.00	2	
		<20.00	1	
Soil biological characteristics				
Soil organic matter	Walkley and black	>5.00	5	(Moebius-Clune *et al*., 2016)
		3.00-5.00	4	
		2.00-3.00	3	
		1.00-2.00	2	
		<1.00	1	
Earthworm population (Number of individuals)	Field count	>6	5	
		5-6	4	
		3-4	3	
		1-2	2	
		0	1	
Land characteristic				
Slope (%)	Land physiography identification and DEM analysis	0-3	5	(Sholikah *et al*., 2025)
		3-8	4	
		8-15	3	
		15-30	2	
		>30	1	
Dense vegetation (Normalized difference vegetation Index)	Spectral transformation	>0.50	5	Modification (Hartoyo *et al*., 2021)
		0.40-0.50	4	
		0.20-0.40	3	
		0.03-0.20	2	
		<0.03	1	

using Sentinel 2A data in June 2024 and interpretation of topographic conditions using DEM data. Land unit maps were created using the intersect overlay method, based on land use and land criticality status. Spatial determination of soil fertility status was done using the inverse distance weighted (IDW) method, whereby geographically closer points are deemed to carry more weight in the interpolation of a given unknown point (Li, 2021). The application that can be used to process spatial data is ArcGIS.

Statistical analysis

The statistical analysis performed was a normality test (Fig 2), ANOVA, Duncan's new multiple range test (DMRT) and correlation. Testing for normality in research data is a fundamental step in statistical analysis that assumes data are normally distributed (Kwak and Park, 2019). All research parameter data must be normally distributed. Statistical analysis was conducted using RStudio.

RESULTS AND DISCUSSION

Soil health status affected by mount kelud eruption

This research location's soil health status assessment results show soil health values ranging from 49 to 67 (moderately healthy to healthy). ANOVA results showed significant differences in soil health assessment in various land units affected by the eruption of Mount Kelud 10 years ago. Based on Fig 3 and Table 2, the KBA has a higher soil health status than LDA. Gardens exhibit better soil health compared to fields due to a combination of factors, mainly driven by organic matter accumulation (Fahad *et al*., 2022), microbial activity and vegetation cover (Faraji and Karimi, 2022), which significantly influence soil properties and ecosystem functioning. Fields show significantly lower levels of SHA because these lands often rely on continuous cultivation and unsustainable farming techniques that deplete organic matter and reduce soil health (Dinh and Shima, 2024). Land variation, seasonal variation and land

cover type significantly affect soil health indicators. Environmental factors such as slope influence soil health

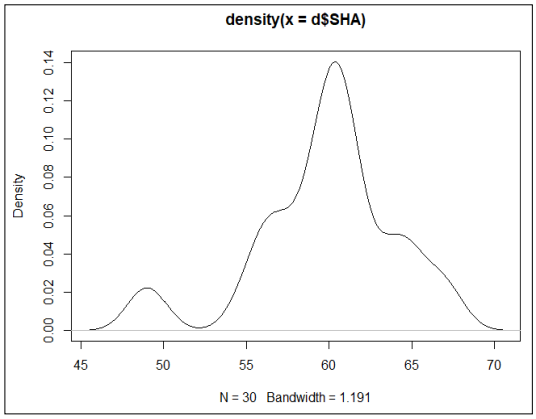


Fig 2: Normality distribution data of soil health assessment (SHA).

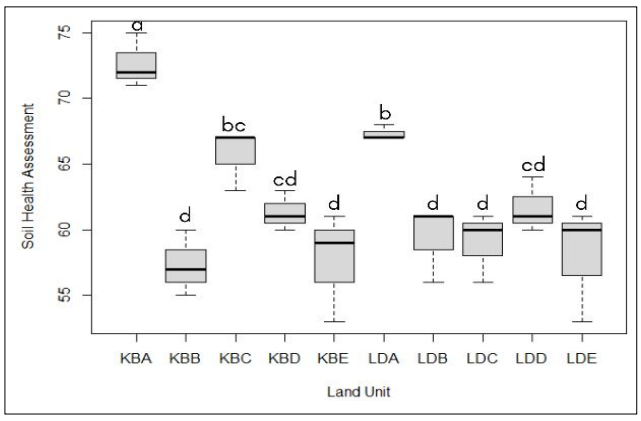


Fig 3: Soil health assessment index value in each land unit.

indices, indicating that land criticality may vary according to ecological context and seasonal changes (Kasperson *et al*., 2022; Manirakiza *et al*., 2025). Land criticality is dynamic, evolving based on environmental conditions and human management practices.

Relationship between characteristics of soil post eruption of mount kelud with soil health status

Fig 4 and Table 2 demonstrate that soil biological components, particularly earthworms (r = 0.73) and soil organic matter (SOM; r = 0.37), are positively correlated with soil health indicators. Earthworms serve as effective bioindicators by enhancing soil aeration, structure and nutrient recycling through organic matter decomposition (Iordache, 2023). SOM contributes to aggregate stability and nutrient availability, as supported by its correlation with total nitrogen (r = 0.43). These findings underscore the importance of organic amendments and soil structure management in promoting soil health and ecosystem productivity (Tahat *et al*., 2020).

Porosity is a soil physical trait highly correlated with soil health (r = 0.77). Increased soil porosity enhances root penetration and microbial respiration, both of which are essential for promoting vigorous plant growth and sustaining soil biological activity. Soil compaction, represented inversely by bulk density (BD, r = -0.49), reduces porosity and undermines soil health. The negative correlation between BD and SHA underscores the need for land management practices that reduce mechanical stress on soil, such as controlled traffic farming, cover crops and reduced tillage (Shaheb *et al*., 2021). High bulk density, indicative of soil compaction, restricts root penetration and limits water infiltration, impairing plant health and soil microbial function.

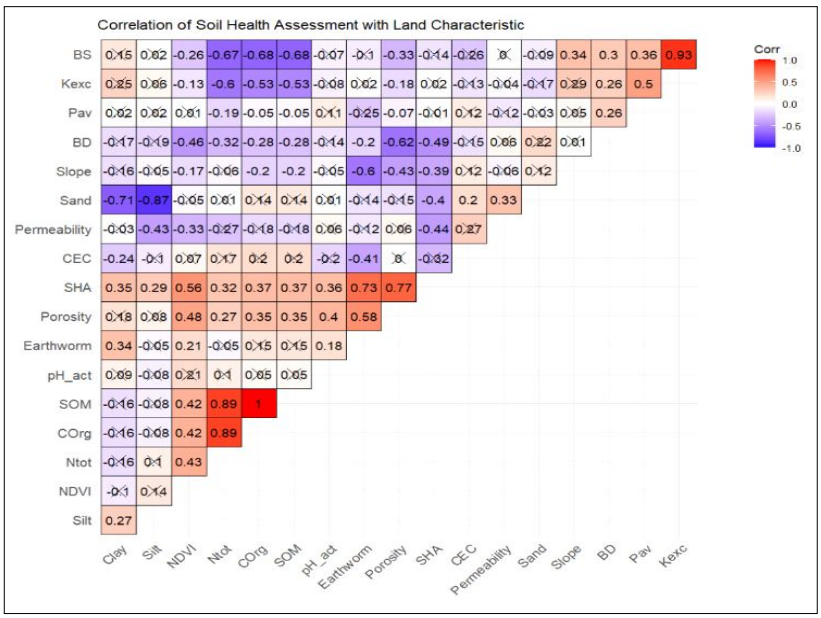


Fig 4: Relationship between soil physical, chemical and biological soil properties and land characteristics in soil health assessment.

Table 2: Land unit characteristic.

Land unit	BD	Permeability	Sand	Clay	Silt	Porosity	pH	C-Org	N	P	K	CEC	BS	SOM	Earthworm	Slope	NDVI	SHA
KBA	1.29±	5.39±	71.83±	10.73±	17.45±	61.25±	6.06±	3.08±	0.25±	80.99±	0.16±	11.98±	11.35±	5.32±	7.33±	3.00±	0.84±	72.67±
	0.18	1.05	18.03	8.93	9.14	1.88	0.04	0.82	0.03	74.81	0.03	0.28	0.39	1.42	0.58	1.73	0.04	2.08
KBB	1.37±	13.61±	80.62±	4.56±	14.82±	53.28±	4.84±	2.25±	0.20±	106.01±	0.16±	14.56±	16.56±	3.88±	1.00±	7.67±	0.68±	57.33±
	0.04	4.01	4.83	0.59	4.94	4.78	1.50	0.19	0.03	39.92	0.04	1.16	2.05	0.33	0.00	0.58	0.14	2.52
KBC	1.29±	6.57±	82.84±	4.66±	12.50±	54.72±	5.95±	2.16±	0.20±	76.18±	0.25±	11.38±	36.60±	3.72±	3.67±	10.67±	0.83±	65.67±
	0.13	0.39	2.11	4.22	.295	3.39	0.34	0.19	0.01	38.96	0.03	0.79	0.36	0.33	0.58	5.03	0.10	2.31
KBD	1.22±	11.18±	83.05±	3.66±	13.29±	55.88±	5.86±	2.65±	0.24±	54.04±	0.12±	15.42±	17.71±	4.57±	1.33±	11.00±	0.79±	61.33±
	0.10	2.22	3.71	1.42	2.48	5.65	0.52	0.27	0.02	12.70	0.03	0.15	0.99	0.46	0.58	8.19	0.07	1.53
KBE	1.39±	9.04±	78.80±	6.33±	14.88±	46.02±	5.13±	2.03±	0.21±	61.85±	0.26±	12.70±	33.92±	3.50±	0.67±	20.00±	0.59±	57.67±
	0.02	2.76	2.73	2.97	2.59	5.00	0.59	0.10	0.02	5.62	0.02	0.55	0.58	0.17	0.58	9.54	0.38	4.16
LDA	1.29±	9.91±	76.90±	9.00±	14.09±	57.20±	5.74±	1.50±	0.13±	79.86±	0.42±	12.84±	47.37±	2.59±	7.00±	6.00±	0.67±	67.33±
	0.09	2.68	4.94	1.61	6.33	1.86	0.52	0.44	0.02	23.31	0.03	0.59	2.70	0.75	1.00	4.36	0.19	0.58
LDB	1.34±	17.42±	84.69±	6.16±	9.14±	53.30±	6.47±	2.10±	0.19±	60.07±	0.07±	12.69±	15.06±	3.61±	3.67±	5.33±	0.46±	59.33±
	0.07	4.84	7.97	4.24	4.71	2.26	0.23	0.45	0.06	15.68	0.02	0.20	1.26	0.78	0.58	2.52	0.08	2.89
LDC	1.46±	20.40±	82.34±	8.92±	8.75±	54.22±	5.35±	1.50±	0.13±	59.12±	0.30±	12.97±	37.47±	2.58±	4.67±	4.00±	0.41±	59.00±
	0.06	3.44	0.72	1.51	1.11	2.21	0.49	0.57	0.03	41.08	0.03	0.68	2.20	0.99	0.58	3.00	0.27	2.65
LDD	1.31±	16.51±	84.08±	8.09±	7.83±	55.26±	6.20±	2.37±	0.21±	128.81±	0.33±	14.75±	32.50±	4.08±	1.67±	19.33±	0.71±	61.67±
	0.04	7.32	6.73	0.25	6.94	3.27	0.24	0.48	0.04	37.96	0.02	1.12	1.70	0.83	.58	1.15	0.15	2.08
LDE	1.45±	11.64±	74.57±	8.03±	17.40±	48.36±	5.75±	1.33±	0.13±	19059±	0.44±	12.73±	53.72±	2.29±	0.33±	19.00±	0.44±	58.00±
	0.16	8.44	5.46	2.74	4.07	7.81	0.35	0.43	0.03	123.94	0.04	0.64	2.33	0.73	0.58	10.82	0.04	4.36

Sand content exhibited a significant negative correlation with soil health (r = -0.70), linked to sand particles' low nutrient and water retention capacity. The sand fraction predominates here due to pyroclastic material from the eruption of Mount Kelud. Consequently, the high sand content in this area can diminish soil health and hinder plant growth. Soils with a sandy dominance are susceptible to leaching and may need more intensive management to sustain their fertility (de Holanda *et al*., 2025).

Permeability negatively impacts soil health (r = -0.44). High permeability can lead to increased soil drainage, significant nutrient leaching and reduced water retention in the soil profile. As a result, this can decrease organic matter and microbial activity, weaken soil aggregation and fertility and ultimately compromise soil health (Bashir *et al*., 2021). Rapid permeability is affected by the dominant sand fraction, creating a soil matrix with a small surface area and high pore space. Fast drainage will inhibit the retention of water and nutrients, thus preventing the development of soil profiles to maintain soil health (Pandao *et al*., 2024).

Evaluations of soil health following eruptions reveal that soil pH (r= 0.36) is a crucial chemical factor influencing nutrient availability, microbial activity and vegetation recovery. Volcanic eruptions generate ash that alters soil chemical composition, causing changes in acidity. In fields impacted by the Mount Sinabung eruption, acidic pH values correspond to lower soil fertility due to the reduced availability of essential nutrients (Marbun *et al*., 2023). Furthermore, the low pH of post-eruption soils is partly due to a low CEC value (<16 me/100 g soil), which can limit the availability of N, P and K. Nonetheless, pH is the primary chemical property influencing soil health assessment at this research site. This is affected by the dominant sandy soil texture, leading to a limited nutrient supply and a reduced CEC. Overall, the key indicator of soil chemical characteristics in evaluating post-eruption soil health is the actual soil pH.

The negative relationship between slope and soil health (r = -0.62) is attributed to hydrological and geomorphological factors, particularly pronounced on steeper terrains (Sholikah *et al*., 2025). Slope values in this location range from 0-3% to >30% (Fig 5b). In sloped regions, gravitational forces heighten the speed of surface runoff, shortening the water's residence time on the soil surface and reducing its ability to infiltrate (Li and Pan, 2020). The removal of nutrient-rich topsoil compromises soil structure and fertility, adversely impacting its ability to sustain plant growth and uphold its hydrological functions (Schröder *et al*., 2024).

NDVI is a remote sensing-derived index commonly utilized to quantify vegetation density and assess land cover

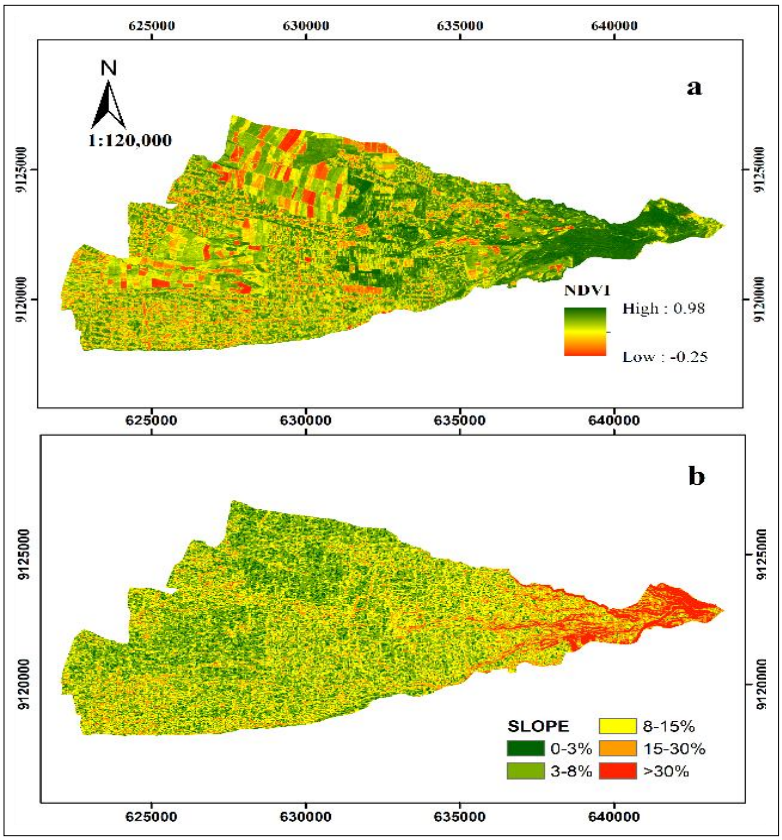


Fig 5: Map of NDVI (a) and slope (b) distribution.

conditions (Sholikah *et al*., 2023). NDVI in this location ranges from about -0.25 to 0.98 (Fig 5a). NDVI is often used as a proxy for soil health (r = 0.56), suggesting that plant greenness can be a reliable indicator for rapid post-eruption soil health monitoring based on remote sensing data. High vegetation density post-eruption influences the spatial patterns associated with patches that exhibit revegetation patterns and the restoration of soil nutrient distribution and moisture retention (Végh and Tsuyuzaki, 2021). The connectivity of these patches is vital in post-eruption landscapes, where soils are highly heterogeneous, as it promotes the colonization of beneficial microorganisms that further accelerate organic matter decomposition and nutrient cycling.

The correlation matrix strongly illustrates the intricate relationships between soil health and land characteristics, including physical, chemical and biological properties, slope and NDVI (Fig 6). One viable commodity that aligns with the soil health characteristics after the eruption is pineapple. This fruit can yield substantial harvests on the post-eruption land of Mount Kelud and has become emblematic of the area. Soil health, often synonymous with soil quality, refers to the soil's ability to function biologically, chemically and physically, supporting plant and microbial life while preserving environmental quality. Grasping the connections between soil characteristics and health indicators is crucial for fostering sustainable agricultural methods (Maroeto *et al*., 2025; Van Binh *et al*., 2025).

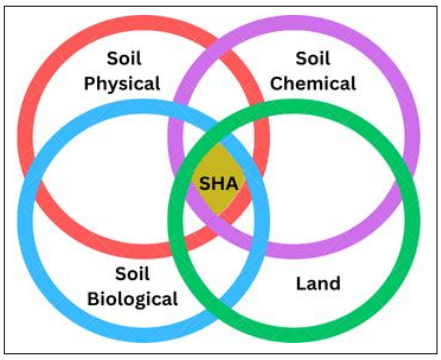


Fig 6: Interrelationship of soil health assessment indicators.

Spatial distribution of soil health assessment

Differences in soil health assessment distribution were analysed using the IDW interpolation method based on soil health status. The study site's post-eruption soil health assessment distribution (Fig 7) revealed moderately healthy (3709.01 ha, 36.70%) and healthy (6398.53 ha, 63.70%) classifications. The results of this SHA distribution form the basis for determining land management strategies for superior commodities, such as pineapple crops, on Mount Kelud (Maroeto *et al*., 2024). Land classified as moderately healthy (yellow) requires increased land management efforts, including the addition of organic matter to sandy soils. Additionally, land with undulating topography (8-15%) or steep slopes (>30%) requires a combination of terracing techniques. This cultivation system can increase the diversity of soil organisms and vegetation density. There is land that is dominantly included in the healthy class (green), enough to maintain its actual condition.

Spatial recommendations for superior commodities in volcanic-affected areas

Restoring agricultural productivity in post-eruption landscapes requires selecting crop species that are tolerant to sandy textures and low nutrient availability. Legumes and certain grains, known for their deep-rooting systems, contribute to soil structure improvement and nutrient cycling. Enhancement of organic matter through cover cropping has been shown to improve soil quality, water infiltration and overall crop resilience (Islam *et al*., 2024).

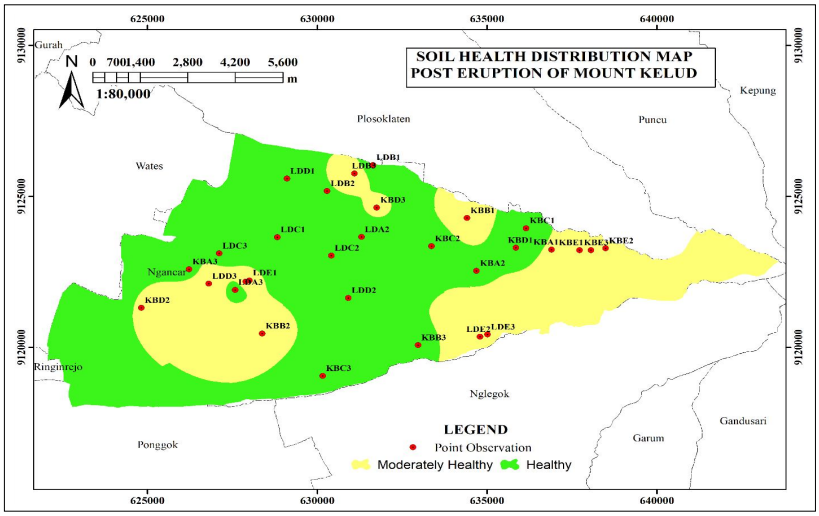


Fig 7: Spatial distribution of soil health assessment post-eruption.

Agronomic adaptation strategies should be integrated with land-based conservation measures, including slope stabilization (Wei *et al*., 2021), increasing vegetation density (Lai *et al*., 2022) and cultivation practices tailored to specific land characteristics, utilizing a landform-based approach (Sholikah *et al*., 2025). Agroforestry is recommended as a suitable system for steep slopes, combining existing tree species such as Falcataria moluccana (sengon) with pineapple cultivation to support ecological recovery and enhance productivity in eruption-affected regions, including Mount Kelud.

CONCLUSION

The soil health index of sandy soil after Mount Kelud's eruption, considering soil properties such as physical, chemical and biological aspects, alongside land features like slope and vegetation density (NDVI), falls within the moderately healthy to healthy range. The combination of land parameters can promote soil health recovery post-eruption, especially given the area's varied topography and predominance of agricultural land. GIS and remote sensing emerge as effective and practical tools for monitoring land condition at the landscape scale, supporting sustainable environmental management.

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Disclaimers

The interpretations and conclusions articulated herein represent the authors' independent scholarly perspectives. While internally coherent, these viewpoints underscore the need for collaborative, sustained efforts among stakeholders to address the multifaceted demands of sustainable agricultural development effectively. Although rigorous measures have been undertaken to ensure the validity and comprehensiveness of the presented data and analyses, the authors disclaim liability for any direct or indirect outcomes resulting from the application or misapplication of this information.

Informed consent

This article uses a plant as a research object, so it doesn't use informed consent.

Conflict of interest

The authors affirm that no conflicts of interest are associated with this publication. They further confirm the absence of any financial or personal affiliations that may have influenced the outcomes or interpretation of the research. This study did not involve human participants or animal subjects.

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