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Volcanic Ash Deposition and Its Implications for Soil Biological Fertility: Insights from the Slopes of Mount Semeru, Indonesia

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Abstract: Volcanic ash from Mount Semeru can alter soil characteristics, including the biological properties. Microorganisms respond rapidly to changing environmental conditions, leading to the general consideration as sensitive indicators of soil health. In general, biological fertility status can be determined based on the Biological Fertility Index (BFI). Therefore, this study aims to assess the BFI and total population of soil microorganisms following the Mount Semeru eruption across four differently managed land-use systems, including monoculture and intercropping patterns. Field studies were conducted on the slopes of Mount Semeru, specifically in Pronojiwo Village, Lumajang Regency, at an elevation of 400-800 meters above sea level. The classification of the BFI was carried out through laboratory analysis of Soil Organic Matter (SOM), Microbial Biomass Carbon (MBC) by the fumigation extraction technique, Basal Soil Respiration (BSR), and Cumulative Soil Respiration (CSR) over a 25-day observation period, along with the total microbial population assessed using the agar plate method. The mineralization quotient (qCO_2) and metabolic quotient (qM) were also calculated based on parameter measured. The results showed that BFI scores of 16.28 and 18.19 were obtained for monoculture and polyculture systems with volcanic ash cover exceeding 10 cm, showing an “intermediate” fertility status. In contrast, monoculture and polyculture land covered with volcanic ash <2 cm had BFI scores of 20.03 and 21.03, respectively, in the "Good" category. The total microbial count ranged from a medium of 4.8×10^5 cfu g^{-1} in the monoculture sugarcane, to significantly higher levels in intercropping leeks and chili at 5.4×10^7 cfu g^{-1}.

Keywords: Intercropping; Microbial Biomass Carbon; Modified Biological Fertility Index; Monoculture

Introduction

Natural disturbances vary in intensity, magnitude, and frequency, influencing population dynamics and ecosystem processes. For example, large-scale disturbances can significantly affect biogeochemical cycles, altering nutrient pools, biomass, and soil communities. These include hurricanes, volcanic eruptions, fires, frosts, and pest or pathogen outbreaks. Disturbances at the landscape scale are reflected in ecosystem processes depending on the intrinsic characteristics of the ecosystem and the interactions with abiotic factors. However, limited knowledge exists on how these large-scale disturbances influence below-ground communities, which play a crucial role in maintaining soil function and nutrient cycling (Wardle et al., 2004).

Volcanic eruptions represent one of the most frequent natural disasters in Indonesia, particularly in East Java Province. A prominent example is Mount

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Semeru, the highest mountain on the island of Java, standing at approximately 3.67 m above sea level. Classified as an active type-A volcano, Mount Semeru is capable of erupting at any time (Hasanuddin et al., 2004). Significant eruptions occurred in December 2021 and December 2022, followed by several smaller eruptions of varying intensity and volume. These eruptions released various materials, including volcanic ash, which has a profound effect on the environment, soil, water, and air. The distribution of volcanic ash is largely determined by wind speed and direction, which control the spatial extent of ash fall.

The presence of volcanic ash on the soil surface exerts both negative and positive impacts on soil properties. According to (Simbolon et al., 2018), volcanic ash deposition affects various soil characteristics, particularly biological properties. The activity, population, and diversity of soil microorganisms are strongly influenced by the extent of ash cover. Microbial activity is frequently enhanced immediately following volcanic eruptions, as microorganisms possess a significant ability to react to volcanic disruptions (Berenstecher et al., 2017). While initial flushes of activity may occur due to nutrient release, the long-term physical impact of ash deposition often leads to decrease soil microorganism activity. One of the most affected microbial processes is soil respiration. As the thickness of volcanic ash on the surface increases, the soil tends to become more compact due to ash weathering, resulting in reduced aeration. Greater soil compaction decreases pore size, which in turn limits air circulation and reduces oxygen availability for soil microorganisms, ultimately disrupting microbial activity (Simbolon et al., 2018).

Aside from negative effects, volcanic ash provides beneficial impacts by supplying essential elements to the soil and plants. However, excessive concentrations of these elements can be toxic and adversely affect plant growth (Azarbad et al., 2016). The recent eruptions of Mount Semeru have caused significant changes in soil fertility, particularly in the biological fertility, which is highly sensitive to the deposition of volcanic materials. Therefore, evaluating the Biological Fertility Index (BFI) is essential to determine the condition of soil fertility after volcanic ash deposition. Renzi et al. (2017) stated that BFI level serves as an effective tool for assessing and monitoring soil biological fertility, preventing further degradation, and guiding proper management strategies to maintain biological health.

Currently, various indicators have been developed to assess soil fertility, both general and specific, to support land use and management for particular crops (Antisari et al., 2021). These indicators persist in their evolution to enhance efficiency in land management. Methods for assessing soil fertility encompass the Soil Fertility Index (SFI), Soil Evaluation Factor (SEF), Soil Nutrient Index (SNI), and Synthetic Soil Fertility Index (SSFI) (Tomczyk et al., 2024).

Although these composite indicators integrate physical and chemical soil properties effectively, soil management also requires sensitive biological indicators, which can provide early signals of soil degradation and resilience. BFI, introduced by Renzi et al. (2017), provides a comprehensive assessment based on biochemical parameters of soil, reflecting both microbial activity and nutrient cycling efficiency.

Empirical studies have shown that BFI values typically range between 15 and 35 in undisturbed fertile soil, while values below 20 indicate biologically stressed or degraded soil (Renzi et al., 2017; Zhao et al., 2023). For instance, in volcanic ash-affected soil of southern Italy, Renzi et al. (2017) reported a BFI value of 18.4 ± 2.1, compared to 32.7 ± 3.6 in nearby unaffected agricultural soil, showing a reduction of nearly 45% in microbial activity and carbon turnover efficiency. Similarly, post-eruption soil in the Andes (Berenstecher et al., 2017) showed MBC values dropping from 410 $\mu g\ C\ g^{-1}$ to 230 $\mu g\ C\ g^{-1}$, consistent with a sharp decline in BFI class from "moderate" to "low biological fertility." These results suggest that BFI effectively captures biological degradation following volcanic ash deposition and serves as a sensitive indicator of early soil recovery.

Cropping systems play a crucial role in determining the structure and function of soil microbial communities. More diverse planting systems, such as polyculture or intercropping, generally support higher microbial biomass and activity than monoculture systems. Studies have shown that increased plant diversity enhances rhizosphere carbon inputs and residue deposition, thereby improving microhabitat and substrate availability for microorganisms. Consequently, microbial biomass carbon (MBC), basal respiration, and enzymatic activities tend to increase under diverse cropping systems. For instance, crop diversification through rotation or intercropping can raise MBC by approximately 20–30% compared to monoculture and increase basal respiration by 15–25%, reflecting enhanced soil biological fertility (Liu et al., 2020). Moreover, intercropping systems tend to stabilize microbial networks and increase resilience to abiotic disturbances, including volcanic ash deposition. In post-eruption conditions, polyculture-managed soil tends to recover microbial functions more rapidly than monoculture systems, which typically provide greater homogeneous organic inputs and susceptible to biological fertility decline.

Given the sensitivity of soil biological processes to volcanic ash deposition, assessing the BFI provides an effective approach for evaluating post-eruption soil recovery (Amanda et al., 2024). Determining BFI classes across different land uses and ash-covered conditions can help identify the extent of soil biological degradation and guide strategies for sustainable soil management. This research's novelty lies in its focus on comparing the biological fertility status between monoculture and polyculture systems in volcanic ash-affected soil. Therefore, this study aims to compare the biological fertility status between monoculture and polyculture systems on volcanic ash-affected soil, to understand how crop diversity influences microbial activity and soil recovery potential after volcanic disturbances.

Method

Study area

This study was conducted on the southern slopes of Mount Semeru, Lumajang Regency, East Java, Indonesia (Figure 1). The soil at this location is classified as Andosol according to the USDA soil taxonomy system. The area covers the districts of Candipuro and Pronojiwo, precisely in the villages of Curah Kobo'an, Sumber Mujur, and Sumber Wuluh, geographically located between S -8.168909°E 113.004683° and S -8.154254°E 113.023495°. Moreover, the study location used monoculture and intercropping planting patterns with soil conditions covered by volcanic ash with a thickness of <2cm (A3), <2cm (A4), 15cm (A2), and>30cm (A1). The distance from Mount Semeru ranges from 15 to 21 km with an altitude of 450-800 meters above sea level (masl).

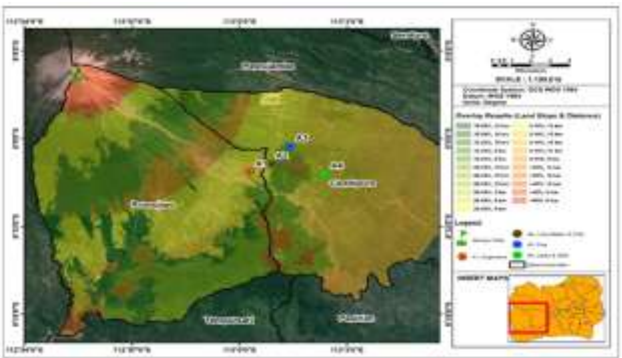

Figure 1. The area located at slopes of Semeru Mountain, East Java, Indonesia

Soil sampling

Three composite soil samples were randomly obtained from the topsoil layer (0-20 cm in depth) for each land use category. Sampling was conducted at a depth of 0–20 cm, as the highest microbial biomass is concentrated in the upper soil horizons (Soleimani et al. 2019) and microbial activity is responsive to alterations in land use (Ahmed et al. 2019) or obscured by volcanic ash deposits. The proportion that passed through a 2 mm sieve was transferred at 4°C in a refrigerated storage container.

Climate

The study area, located on the slopes of Mount Semeru, received an average annual rainfall of approximately 2,085.97 mm, with annual precipitation ranging from 1,677.8 mm to 2,365.64 mm over the five years (2020–2024). Rainfall predominantly occurred between November and April, reaching peak intensity in December. The dry season typically extends for about six months (May–October). The annual temperatures ranged from 21°C to 31°C, with an overall minimum temperature of 17°C and a maximum temperature of 36°C (figure 2). Relative humidity varied seasonally, averaging 80–88% during the rainy season and dropping to below 70% during the dry season. The study area lies at an elevation of 450–800 m above sea level and is classified as a "wet" (B) climatic zone according to the Schmidt and Ferguson classification system. The local climate type is further influenced by the geomorphological position of the site on Mount Semeru slopes and periodic volcanic activity, which modify both microclimatic and rainfall patterns.

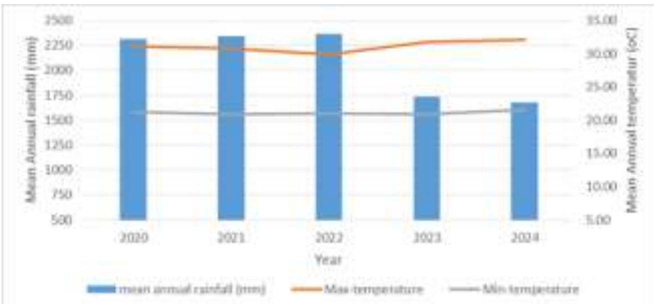

Figure 2. Mean annual distribution of rainfall and maximum and minimum temperature of the study area from 2020 to 2024 (Source: NASA POWER, Data Aces Viewer (DAV). https://power.larc.nasa.gov/data-access-viewer/)

Soil Analysis Measurements

Soil pH was measured using a pH meter (AZ86555) in a 1:2.5 soil-to-water suspension. The total soil organic carbon (SOC) content was determined using the Walkley and Black dichromate oxidation method. A 0.500 g subsample of air-dried soil (<0.5 mm particle size) was placed in a 100 mL volumetric flask, followed by the addition of 5 mL of 1 N $K_2Cr_2O_7$ and thorough shaking. Subsequently, 7.5 mL of concentrated H_2SO_4 was added, and the mixture was allowed to stand for 30 minutes to complete oxidation. After cooling, the sample was diluted with deionized water and left overnight for sedimentation. The absorbance of the clear supernatant was measured at 561 nm using a spectrophotometer. Calibration standards (0 and 250 ppm) were prepared by pipetting 0 and 5 mL of a 5,000 ppm stock solution into

100 mL volumetric flasks. The soil organic matter (SOM) content was derived using the van Bemmelen conversion factor (1.724) according to the following equation.

$$SOM=SOC\times1.724 \quad (1)$$

Table 1. Location and type cultivation

Location	Coordinate	Cultivation type	Status
Curah kobo'an village 12 km from eruption source 800 msl code A_1	S -8.168909° E 113.004683°	 Sugarcane (Monoculture)	 Covered in volcanic ash >30cm
Curah kobo'an village 12 km from eruption source 650 msl code A_2	S -8.164375° E 113.014167°	 Chilli and long beans (intercropping)	 Covered in volcanic ash 10-15 cm
Sumber mujur village 15 km from eruption source 550 msl code A_3	S -8.154254° E 113.023495°	 Chilli and leeks (intercropping)	 Covered in volcanic ash < 2cm
Sumber wuluh village 21 km from eruption source 450 msl code A_4	S -8.169948° 113.039723	 Pine (Monoculture)	 Covered in volcanic ash < 2cm

Soil Microbial Biomass

MBC was quantified using the chloroform fumigation–extraction method. Soil samples from refrigerated (4°C) were pre-incubated at 30°C for five days at field capacity in open glass jars. Three replicates of each sample (10 g) were fumigated with ethanol-free chloroform for 24 h in a vacuum desiccator under dark conditions, while three non-fumigated replicates served as controls. Both fumigated and non-fumigated soil were extracted with 50 mL of 0.5 M K_2SO_4 for 30 minutes and filtered through Whatman No. 42 paper. The potassium dichromate oxidation method was used to determine the carbon concentration in the extracts, and MBC was calculated from the difference between fumigated and non-fumigated samples.

Microbial Respiration

Soil microbial respiration was measured following the method of Isermeyer (1951). About 100 grams of moist soil were incubated in sealed glass jars at 30°C under dark conditions and at field capacity. Carbon dioxide (CO_2) evolved during incubation was trapped in 10 mL of 0.2 N NaOH, containing two drops of phenolphthalein indicator, and the remaining alkali was titrated with 0.2 N HCl. Control jars without soil were used to account for background CO_2 absorption.

The amount of CO_2–C evolved was calculated from the titration difference between samples and blanks. Cumulative soil respiration (CSR) was expressed as the total CO_2–C released over a 25-day incubation period (mg CO_2–C kg^{-1} soil), while Basal soil respiration (BSR) corresponded to the respiration rate on day 25 (mg CO_2–C kg^{-1} soil d^{-1}).

The metabolic quotient (qCO_2), representing microbial maintenance energy, was calculated as the ratio of BSR to MBC (mg CO_2–C 10^{-2} h^{-1} mg^{-1} MBC). The mineralization quotient (qM), expressed as a percentage, was derived from the ratio of CSR to SOC, showing the efficiency of soil microflora in decomposing organic carbon. The carbon use efficiency (CUE) of microorganisms was calculated as the ratio of MBC to SOC, reflecting the microbial capacity to convert organic carbon into biomass.

Soil Microbial Population

Soil samples were collected from a depth of 0–15 cm across four different land-use types. For each land use, samples were taken from three randomly selected sites and placed into sterile, labeled containers showing location, land-use type, and collection date. The samples were transported under refrigerated conditions to the laboratory for microbiological analysis. The entire microbial population was assessed by the serial dilution and spread plate technique, with colony-forming units (CFU) enumerated following incubation on nutrient agar media.

BFI

It is calculated as the sum of scores assigned to six variables:

$$BFI=BSR+CSR+MBC+SOM+qCO_2+qM \quad (2)$$

where:

BSR (%) is basal respiration at the last day of incubation;
CSR (%) is cumulative respiration during the incubation period;
MBC (μg C g^{-1} soil) is microbial biomass carbon;
SOM (%) is soil organic matter;
qCO_2 (mg CO_2–C 10^{-2} h^{-1} mg MBC^{-1}) is the metabolic quotient; and
qM is the mineralization quotient (CSR × SOC^{-1} × 100).

Table 2. Scores of the intervals of values for the different parameters

Parameters	Score				
	1	**2**	**3**	**4**	5
Soil organic matter , (SOM) (%)	<1.0	≥1.0 ≤1.5	>1.5 ≤2.0	>2.0 ≤3.0	>3.0
Microbial biomass carbon , (MBC) (μg C g^{-1}soil)	<100	≥100 ≤200	>200 ≤300	>300 ≤400	>400
Basal soil respiration (BSR) (mg CO_2–C kg^{-1} soil d^{-1})	<5	≥5 ≤10	>10 ≤15	>15 ≤20	>20
Cumulative soil respiration(CSR) (mg CO_2–C kg^{-1}soil)	<100	≥100 ≤200	>200 ≤300	>300 ≤400	>400
Metabolic quotient, (qCO_2 (mg CO_2–C 10^{-2} h^{-1} mg MBC^{-1})	>0.4	≥0.4 ≤0.3	<0.3 ≥0.2	<0.2 ≥0,1	<0.1
Mineralization quotient,(qM) (%)	<1.0	≥1 ≤2	>2 ≤3	>3 ≤4	>4
Classes of the Biological Fertility Index (BFI)					
Fertility class	I stress	II Pre-stress	III Medium	IV Good	V High
BFI scores sum	6	7-12	13-18	19-24	25-30
BFI scores sum**	< 9	9 < BFI < 12	13< BFI<18	1 19<BFI< 24	24
	Soil with very low	pre-stress soils	soils with intermediate	good fertility soils	soils with very high

Parameters	Score				
	1	**2**	**3**	**4**	5
	fertility		fertility		fertility

(source :** Renzi et al. (2017))

Table 3. Summarize the variable and the analyzed method

Variable	Methods
Microbial biomass carbon, MBC (µg C g−1 soil)	Fumigation & Extraction Methods
Basal Soil Respiration (BSR)	Isermeyer method (total respiration on day 25)
Cumulative Soil Respiration (CSR)	Isermeyer method (total respiration from day 1 to day 25)
Soil Microbial Population	Dilution methods
Soil Organic Matter (SOM)	Walkey and black
Metabolic Quotient , (qCO_2)	The amount of soil basal respiration produced by each unit of soil microbial carbon biomass $\frac{BSR}{MBC}$
Mineralization Quotient, (qM)	The ratio of cumulative respiration to soil organic carbon $\frac{CSR}{SOC}$
microbial carbon use efficiency (CUE)*	$CUE = \frac{MBC}{SOC}$

*efficiency of microbes to decompose organic carbon Modified formula from Yu et al. (2025).

BFI serves as a composite indicator integrating six biological variables, including SOM, BSR, CSR, MBC, qCO_2, and qM. Each parameter was assigned a score from 1 to 5, corresponding to increasing levels of soil biological fertility (Table 2). The scoring thresholds were adapted from previously established empirical ranges in the literature. The total BFI score was obtained by summing the individual parameter scores, which were subsequently classified into five fertility categories ranging from very low to very high biological fertility (Table 2).

Result and Discussion

Characteristics of Volcanic Ash

Based on volcanic ash sand fractionation, fine sand and very fine sand categories were identified, representing the fractions that dominate the volcanic ash covering the soil surface. Very fine sand (50-100µm) accounted for 31.74%, and fine sand (100-250µm) accounted for 56.01%. The remainder consisted of medium- to coarse-sand fractions, accounting for 12.25% (Figure 3).

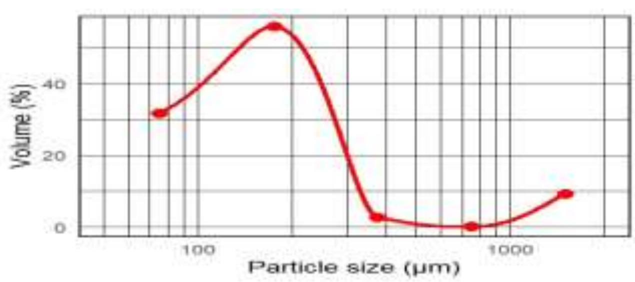

Figure 3. Percentage of volcanic ash particle size

The amount of pore space can change after a volcanic eruption due to pore blockage. Fine ash particles can easily penetrate the soil macropores in a highly variable manner, depending on soil texture, ash particle size, and rainfall characteristics. Based on the data, the greater the number of fine particles, the lower the drainage, infiltration, and aeration of the soil. A previous study by Sanyoto, S and A.P. Rahardjo (2020) showed that volcanic ash cover from the eruption of Mount Merapi, with varying thicknesses, affected infiltration rates. The infiltration rate decreased as the thickness of the volcanic ash layer increased.

In line with the study by Setiawati et al. (2024), the scanning electron microscope characteristics of Mount Semeru volcanic ash show that the structure of the erupted volcanic ash was in the form of prismatic and angular blocks of diverse sizes, ranging from 40µm–44µm, according to observations made at 1,000x magnification (Figure 4). The small size will fill soil pore space and affect soil physical properties.

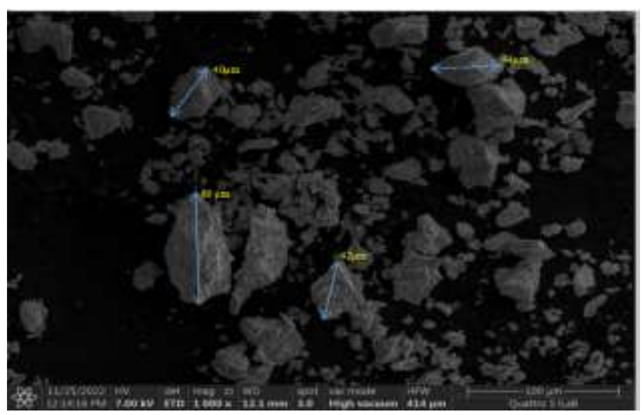

Figure 4. Characteristics of volcanic ash from the eruption of Mount Semeru (Setiawati et al., 2024)

Effects of A Volcanic Ash Deposition on Soil pH and Organic Material

The addition of volcanic ash generally lowered the soil pH before the eruption from 6.35-7.0 to 5.22-5.77. Volcanic ash deposition initially increased soil acidity due to the release of soluble oxides and acidic anions (e.g., SiO_2, Al_2O_3, Fe_2O_3) during weathering (Antisari et al., 2021; Witham et al., 2005). Soil with a sufficiently thick layer of volcanic ash tends to have a higher pH compared to volcanic ash cover of <2cm (Table 4). In monoculture sugarcane land use and intercropping long beans and chili, the pH was 5.77 and 5.66, while in land use covered with volcanic ash <2 cm, the pH was 5.22 and 5.25.

Table 4. Soil organic matter and physical parameters under different land use

Parameter	Unit	Land Use			
		Monoculture (sugarcane)	Intercropping (long beans and chilli	Monoculture (Pine)	Intercropping (leeks and chilli)
Volcanic ash thickness	cm	>30	10-15	< 2	< 2
Soil pH		5.77	5.66	5.22	5.25
Soil texture		Sandy Clay Loam		Loamy Sand	
Soil bulk density	(g/cm^3)	1.36		1.72	
SOC	%	1.61	1.66	1.52	1.79
SOM	%	2.78	2.86	2.62	3.08

SOC: total organic carbon, SOM: total organic matter

When volcanic ash is freshly deposited on the soil surface, it primarily consists of amorphous aluminosilicate minerals such as SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, and K_2O. Initial investigation of volcanic ash from Mount Semeru found a SiO_2 content of 37.48%. Aside from Si, elements such as Ca, Fe, and Al were detected at relatively high concentrations of 8.60%, 7.75%, and 5.79%, respectively (Setiawati et al., 2024). When in contact with water (rainfall or soil moisture), hydrolysis and oxidation processes occur, releasing H^+ ions and increasing soil acidity by the following mechanisms:

Hydrolysis of aluminosilicates**:**

$$\text{Aluminosilicates} + H_2O \rightarrow Al(OH)_3 + H_4SiO_4 + H^+$$

Aluminum hydroxide ($Al(OH)_3$) subsequently hydrolyzes: $Al(OH)_3 \rightleftharpoons Al^{3+} + 3OH^-$

However, Al^{3+} can further react with H_2O to produce H^+: $Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$

The organic carbon content in the soil with different monoculture and polyculture cropping patterns did not differ significantly. The organic carbon levels ranged from 1.52% to 1.79%, while organic matter levels were between 2.62% and 3.08%. The organic matter content decreased compared to the soil unaffected by volcanic ash, which ranged from 3.14% to 3.3%. The general decrease in organic matter content in soil covered by a sufficiently thick layer of volcanic ash can be attributed to conditions that limited aeration, as the small size of the volcanic ash closed soil pores, resulting in disrupted initial microorganism activity (Fiantis et al., 2019) and the temporary accumulation of undecomposed organic matter.

Effects of Ash Deposition on Soil Microorganisms

Microorganisms, which are sensitive indicators of the status of an ecosystem, can lose resilience to ecosystem disturbances and become unable to perform nutrient cycling functions. The importance of microorganisms in ecosystem functioning has led to an increased interest in determining soil microbial populations. Some studies have investigated the effects of volcanic eruptions on soil microorganisms. The microbial activity is stimulated after volcanic eruptions, and the microbes have a substantial capacity to respond to the volcanic disturbances (Berenstecher et al., 2017). The thicker the volcanic ash that covers the surface of the soil, the more it can affect the biological conditions of the soil (Qadaryanty et al., 2020).

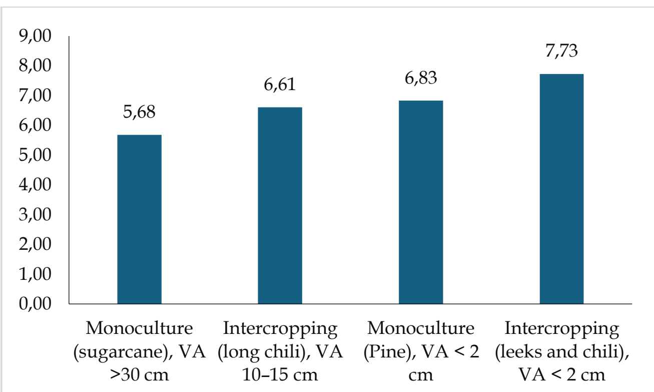

Figure 5. Microbial population in soil

The total microbial count ranged from a low of 4.8 x 10^5 cfu g^{-1} in the monoculture sugarcane, to significantly higher numbers in intercropping leeks and chili at 5.4 x 10^7 cfu g^{-1} compared to other land use types (Figure 5). This suggested that microbial population variation might be attributed to the effect of thin layers of volcanic ash covering, aside from higher organic matter content. The high population of microorganisms in the soil will have a positive relationship with the level of soil fertility.

According to Pakolo et al. (2018), the closer a site is to the eruption center, the thicker the volcanic ash on the ground, and the lower the total microbial population, because volcanic ash deposits on the ground cause a decrease in groundwater levels, pH, microbial biomass, and organic matter (Berenstecher et al., 2017). Soil microorganisms fulfill several functions, including nutrient provision, organic matter decomposition, enhancement of plant growth, and regulation of plant pests and diseases. The number of microbe populations present can determine soil fertility, as a high number of microorganisms suggests the presence of sufficient organic matter, adequate water supply, ideal temperature, and soil ecological conditions. Additionally, zones of intense microbial activity are created in the till layer by soil churning and the breakdown of organic compounds.

Suntoro et al. (2014) stated that the presence of volcanic ash affects the physical properties of the soil. This is because the accumulation of volcanic ash that starts to compact on the soil surface reduces the infiltration rate. The compaction of volcanic ash on the soil surface also affects soil aeration, thereby reducing the oxygen supply (Sinaga et al., 2015). Volcanic ash on the soil surface also affects chemical properties such as pH and increases heavy metal content. According to Salomo et al. (2018), volcanic ash contains silica (SiO), lead (Pb), and other heavy metals such as Ag, Mg, Ni, and Fe. The high content of heavy metals can disrupt the activity of microorganisms in the soil. Added that heavy metals in the soil may cause biotoxicity, thereby affecting the structure and activity of microorganisms. (Ustiatik et al., 2023) also mentioned that the distance from the center of the eruption and the thickness of volcanic ash in a land area are the main factors influencing the survival of microorganisms in the soil, specifically phosphate-solubilizing bacteria. According to research by Hernandez et al. (2020) the amount of rRNA 16S bacteria in soil that was exposed to vulcanic from various age was 10^8 copies per gram of soil.

Effects of Ash Deposition on microbial metabolism

Apart from influencing the total abundance of microbes, environmental disturbances have important effects on microbial metabolism (Hadland et al., 2024). The soil processes and properties are affected by climate change or any disturbance (mount eruption, earthquake), which causes changes in SOM and MBC.

The microbial biomass is the living component of SOM, and it typically comprises 1–5% of total organic matter content, generally about 2-3% of total organic carbon (C-org), and represents a major labile pool of nutrients. Due to the high turnover rate, microbial biomass C content can respond rapidly to changes in soil management practice. It is influenced by SOM content, temperature, moisture content, pH, substrate availability, as well as seasons and soil depth.

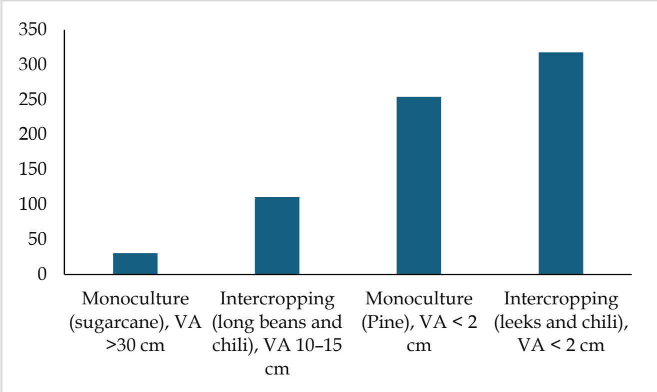

Figure 6. microbial biomass carbon (MBC) on monoculture and polyculture covered by volcanic ash (<2 cm and > 10 cm)

The results showed that MBC in the study area was 30.5 to 317.8 μg C g^{-1} soil (Figure 6). The higher MBC in land with volcanic ash cover <2 cm in Intercropping and monoculture cultivation than land with thick volcanic ash cover (>10 cm) shows more microorganism activity in the soil. The effect of the eruption, which covered the soil surface >10cm, showed a lower soil microorganism population, namely 4.8×10^5 cfu.g^{-1} and 4.1×10^6 cfu.g^{-1} (Figure 5). Similarly, Lepcha & Devi (2020) reported the influence of different land uses, seasons, and soil depth on MBC and several soil properties. Prajuli et al. (2025) found that the MBC concentration in the topsoil layer (0-10 cm) of an irrigated agroecosystem was greater than in the 20-30 cm layer. The higher SMBC in the top soil layer is attributed to greater soil nutrient availability and differences in soil properties. The ratio of MBC to total organic carbon (MBC/SOC = CUE) in soil may serve as a quantitative indicator of soil carbon. This ratio has been useful as an index of changes in SOM resulting from land management changes. It reflects the activity and efficiency of the soil microbial community in using the available organic carbon. Higher MBC/SOC ratios show effective microbial activity and healthy soil.

Allocating the absorbed carbon to growth and respiration is the responsibility of microbial CUE. Microbes' partitioning of organic carbon is seen in the positive correlation between microbial CUE and SOC. SOC buildup results from a high CUE because it allocates more resources to biomass and byproducts. Conversely, a low CUE value indicates that more carbon is being allocated to cellular respiration, which causes SOC loss (Tao et al. 2023).

The CUE value for intercropped leeks and chili, covered with volcanic ash <2 cm, was higher compared to soil covered with volcanic ash > 10 cm, or monoculture pine soil. An elevated microbial CUE signifies an enhanced capacity for the sequestration of soil organic carbon (SOC), a phenomenon contingent upon increased biomass synthesis, which is in turn influenced by various environmental factors. According to the results derived from soil temperature assessments conducted within the leek and chili intercropping system, the recorded temperature was 38°C, which is higher than the temperature at other locations. Previous study by Allison et al. (2010) identified temperature as a significant factor affecting CUE. This attenuation response may stem from alterations in the physiological characteristics of microbial populations with increased temperatures, manifesting as a reduction in the proportion of assimilated carbon directed towards growth. An investigation into this mechanism, using an enzyme-microbe model to simulate soil carbon responses to an increase of 5 °C, demonstrated that declines in microbial biomass and degradative enzyme activity could elucidate the observed mitigation of soil carbon releases in response to warming. In particular, the reduction in CUE constrains microbial decomposer biomass and alleviates the loss of soil carbon. The CUE value is also modulated by microbial population dynamics and metabolic activities, which are quantified through respiration measurements. Based on the outcomes of the comprehensive microbial analysis, the population density within intercropped leeks and chili exceeded that of other land-use practices (Figure 5). This result corresponds with the total CO_2 emissions recorded (Figure 8).

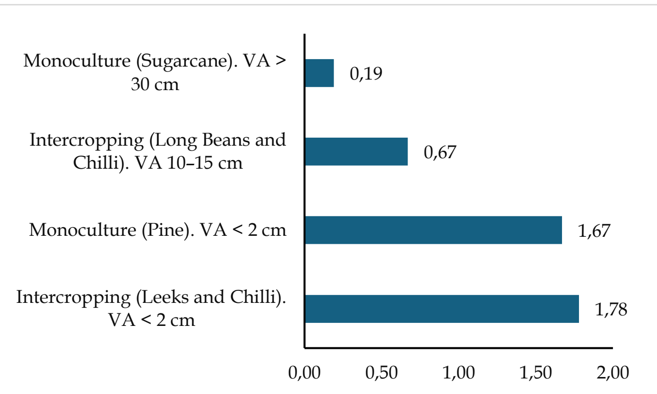

Figure 7. Ratio microbial biomass carbon (MBC) to soil organic carbon (SOC) on monoculture and polyculture covered by volcanic ash (<2 cm and > 10 cm).

Effects of Ash Deposition on Soil Activities

During the mineralization of organic materials by soil micro- and mesofauna, organic compounds experience oxidation to produce carbon dioxide and water, while aerobic microorganisms simultaneously use oxygen, thereby facilitating soil respiration. The ecological roles of soil micro- and mesofauna maintain equilibrium in natural, undisturbed soil that has not been augmented with nutrients or organic amendments. In soil disturbed by the influence of volcanic eruptions, changes in temperature, physical properties, and the addition of mineral materials that may contain toxic elements occur, thereby affecting the activity, biodiversity, and population of microorganisms (Aini & Hanudin, 2016).

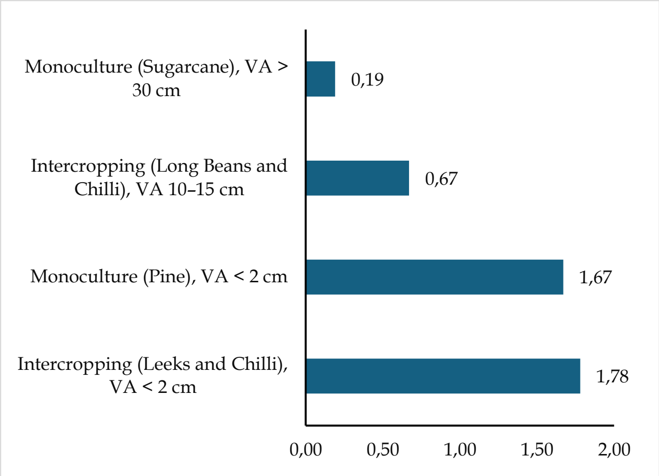

Figure 8. Basal soil respiration (BSR) and cumulative soil respiration (CSR)

The existence of a substantial stratum of volcanic ash facilitates the manifestation of pollution, attributable to the presence of heavy metals and rare earth elements. Based on the analysis results, the volcanic ash originating from Mount Semeru was characterized by the presence of various heavy metals, specifically Pb, Rb, and Ba, along with rare earth elements Nb, Y, Eu, (Setiawati et al., 2024), which possess the potential to induce alterations in the chemical, biological, and physical attributes of the soil. Modifications in enzyme arylsulphatase (ASA), alkaline phosphatase (APA), and urease (UA) activity consequent to heavy metal contamination by Pb, Cr, Ni, Cd, Fe, Mn, Cu, and Zn alongside a reduction in BSR.

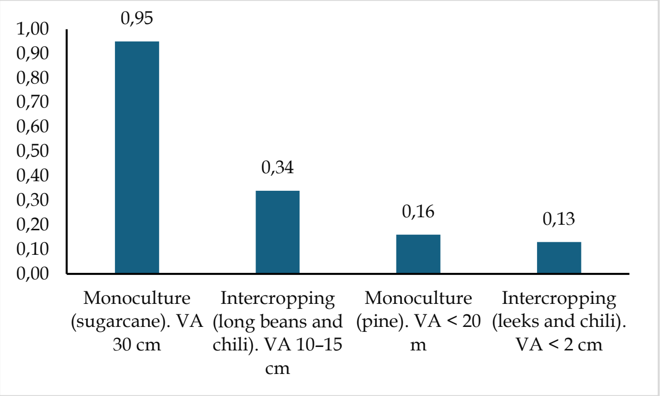

Figure 9. The qCO_2 on monoculture and polyculture covered by volcanic ash (<2 cm and > 10 cm)

Metabolic Quotient (qCO_2) refers to the amount of soil basal respiration produced by each unit of soil microbial carbon biomass (respiration-to-biomass ratio). The qCO_2 is defined as soil respiration per unit soil MBC (CO_2/SMBC) per unit time and is expressed in milligrams of CO_2–C per gram of MBC per hour. Sugarcane monoculture covered with volcanic ash >10cm had the highest qCO_2 value of 0.95 mg CO_2–C 10^{-2} h^{-1} mg MBC^{-1} compared to other land uses (Figure 9). A high qCO_2 value shows significant microbial activity through respiration and does not result in the formation of soil carbon biomass, as evidenced by lower MBC values (Figure 6). It further shows that the volcanic ash cover caused the microbes to be in a state of stress or depression, leading to expenditure of more energy on survival than on production. A larger proportion of the C from microbial biomass is used only for respiration (maintenance energy), not for growth or the formation of new biomass. Bakhshandeh et al. (2019) reported that the qCO_2 value in natural forests was lower compared to arable land, showing more favourable conditions for microorganisms in comparison to stressful conditions. In pine monoculture land with volcanic ash cover <2 cm, the qCO_2 value was 0.16, and in intercropped land with cover <2 cm, the qCO_2 value was 0.13 (Figure 9), showing no significant disturbance causing stress to the microorganisms (de Lima et al., 2021). According to Wardle & Ghani (1995), the qCO_2 value alone does not show soil disturbance due to less sensitivity and ecosystem development. It also does not differentiate between the impacts of disturbance and microbial stress.

Soil MBC and qCO_2 are the most important parameters for determining soil carbon stability and microbial CUE. An increase or decrease in qCO_2 is related to shifts in microbial metabolism. Low qCO_2 values (high microbial CUE) show better growth and less carbon dioxide (CO_2) released into the atmosphere. In contrast, higher qCO_2 (low microbial CUE) is relatively associated with greater C loss, either through soil respiration or exudation, which in turn results in less C being converted into microbial biomass, ultimately reducing the potential for long-term C sequestration (Ashraf et al., 2022).

Determinant of Soil Biology Fertility Index

Based on the calculation results, the BFI scores sum (Figure 10) ranged from 16.28 to 21.03, showing variation between land with little volcanic ash cover (<2 cm), which had a "Good" fertility index, and land with thick volcanic ash cover (>10 cm), having a "Medium" BFI class (Figure 10).

Monoculture and polyculture cultivation with different canopy cover did not affect biological fertility status, but the thickness of the volcanic ash cover had a greater impact. This result is consistent with the study by Saputra et al. (2022), in which the thickness of volcanic ash after the eruption of Mount Kelud varied between land use systems and was more influenced by the slope position of the plot, rather than the amount of canopy cover. The thickness of the volcanic ash will reduce soil porosity, thereby decreasing the concentration of oxygen entering the soil and ultimately the activity of soil microorganisms. BSR was 10.2, and CSR was 84.3, compared to other lands where it was >100 mg CO_2–C kg^{-1} soil d^{-1}.

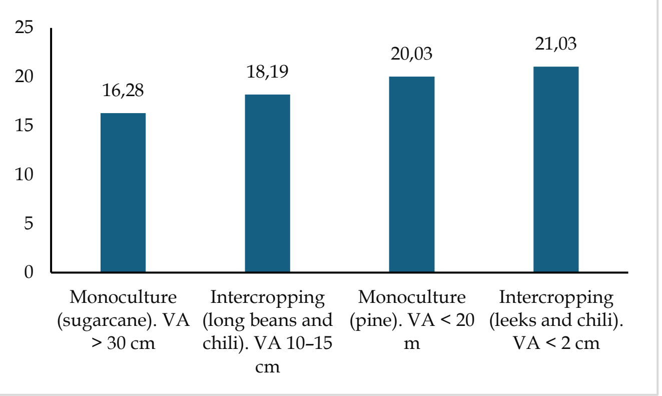

Figure 10. The simplified biological fertility index (BFIs) scores and corresponding fertility classes calculated in four type land use.

The resilience of ecosystems to volcanic eruptions plays a significant role in determining the recovery of BFI scores over time. Understanding ecosystem resilience is crucial for predicting the long-term effects of eruptions on land fertility. In general, ecosystem resilience is influenced by factors such as soil type, vegetation, and microbial communities.

Conclusion

This study emphasizes that the thickness of volcanic ash is the main factor affecting the biological fertility of soil in post-eruption environments. Thick ash deposits

(>10 cm) significantly inhibit microbial abundance and activity, leading to “medium” BFI values (16.28–18.19). In contrast, thinner ash layers (<2 cm) preserve more conducive conditions for microbial function, resulting in elevated BFI values (20.03–21.03) in “Good” category. Microbial responses to environmental stress fundamentally regulate soil biological fertility, as evidenced by the strong relationship between microbial populations and BFI. Thick ash conditions limit the positive effects of intercropping systems on microbial populations, indicating that volcanic disturbances can override cropping practices. Therefore, microbial indicators, particularly microbial populations and metabolic activity, provide a reliable basis for assessing soil recovery and biological fertility after volcanic ash deposition.

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Author Contributions
The “Conceptualization, T.C.S and R.P.V; methodology and field sampling: R.P.V, B and S.M; validation: T.C.S, S.E and B; writing—original draft preparation, all author; writing—review T.C.S , B.H and L.S; editing: R.P.V. All authors have read and agreed to the published version of the manuscript.”

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Conflicts of Interest
The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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