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Post-Reclamation of Mount Semeru Pyroclastic Materials using Adaptive Vegetation and Indigenous Microbes: Increasing Main Macronutrients to Enhance Red Chili (*Capsicum annuum* L.) Yield

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Abstract

Mount Semeru's frequent eruptions produce pyroclastic materials that are initially infertile and structurally unstable, creating major constraints for ecosystem recovery and agricultural productivity. The integration of adaptive vegetation and the indigenous microbial consortium was attempted to improve the fertility of pyroclastic materials for red chili cultivation. A randomized complete block design was applied with 2 factors: adaptive vegetation species (Napier grass, Vetiver grass, *Centrosema* sp., and *Indigofera* sp.) and microbial consortium (*Bacillus subtilis* and *Bacillus megaterium*). In 1 year, the vegetation was pruned quarterly, and its biomass was returned to the pyroclastic materials. After one-year reclamation, red chili was planted, and the main macronutrients (C, N, P, K), plant uptake, and yield were measured. One-year reclamation significantly improved these macronutrients, with organic C and total N increasing from 0.12 to 0.15–0.60% and from 0.001 to 0.02–0.05%, respectively. However, the organic C and total N remained very low. Available P increased from 11.80 to 36.51–133.28 mg kg^{-1}, while exchangeable K showed an irregular pattern (0.66 to 0.17–0.59 cmol kg^{-1}). This improvement was likely due to vegetation rather than microbes. Red chili in the Napier grass showed the highest nutrient uptake (N = 606.88; P = 1,386.36; K = 463.17 mg plant^{-1}), dry biomass (92.91 g plant^{-1}), and yield (13.14 to 13.45 tons ha^{-1}). *Centrosema* sp. treatments showed limited fertility improvement and the lowest yield (4.06 to 5.15 tons ha^{-1}). This bioreclamation strategy represents a sustainable framework for restoring nutrient-depleted pyroclastic materials and enhancing agricultural recovery on post-eruption land. Persistently low total N indicates that sustained organic matter inputs remain necessary to overcome N limitation in subsequent cropping seasons.

Keywords: bioreclamation; crop production; nutrient uptake; soil fertility; volcanic materials

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INTRODUCTION

The December 2021 eruption of Mount Semeru, located in East Java, Indonesia, produced extensive pyroclastic materials that blanketed surrounding landscapes, altering soil physical and chemical properties, with Supiturang Village, Lumajang Regency, among the areas most

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severely affected (Ustiatik et al., 2023; Setiawati et al., 2024; Albarki et al., 2025a). These events have caused significant agricultural disruption across the volcanic areas of East Java. For example, the eruption of Mount Sinabung caused losses in the agricultural sector. Red chilis were the most affected (47.91%), followed by tomatoes (18.33%) and potatoes (11.63%) (Tampubolon et al., 2017). A similar pattern of decline was seen following the 2010 eruption of Mount Merapi, where red chili pepper productivity in the affected area dropped to 3.44 tons ha^{-1} (Rahayu and Febriani, 2021). This condition frequently results in a complete cessation of agricultural activities, while local communities rely on natural land recovery processes. This decline in agronomic productivity is largely driven by the physical and chemical limitations of fresh pyroclastic material.

Despite these agronomic challenges, pyroclastic deposits have been shown to be a source of new soil formation in volcanic areas (Khumaeni et al., 2025; Romadhan et al., 2025). This material contains various primary minerals that serve as nutrient sources (Setiawati et al., 2024; Suhendro et al., 2025). However, despite the potential nutrient reserves of fresh pyroclastic material, the nutrient availability and organic matter levels of such material are characteristically very low. This directly limits soil fertility in the early phases of soil development (Muñoz et al., 2021). These limitations are further influenced by the material's dominance of coarse-textured particles, an unstable structure, and a low cation exchange capacity (CEC) (Utami et al., 2019a). In conditions of a substrate dominated by coarse particles and low negative charge, the capacity of the soil to retain water and nutrients is determined by the accumulation of organic matter.

The organic C content of fresh pyroclastic material should be increased. However, this process is very slow. For example, fresh tephra from Mount Talang in West Sumatra initially had a very low organic C content (0.19%) and reached only 1.75% after being left for 2 years naturally (Fiantis et al., 2016). In contrast, intervention in the form of applying local organic matter to Mount Kelud deposits was shown to significantly increase organic C from 0.35 to 0.68% in just 2 months (Utami et al., 2019a). This highlights the importance of human intervention in enhancing the process of organic matter formation in pyroclastic material.

Moreover, the stability of this organic matter accumulation is dependent on the land-cover system. The recovery of soil organic carbon (SOC) has been observed to occur at a steady rate in forest and agroforestry areas over a period of 3 to 6 years. However, on intensive agricultural land, recovery was slower, increasing by approximately 0.32% per year in the first three years after the Mount Kelud eruption, then declining again in the sixth year (Saputra et al., 2022). Chemically, the enhancement of SOC has been demonstrated to play a key role in the improvement of other soil properties, particularly in increasing the dependent CEC (Utami et al., 2019b). Nevertheless, incubation experiments demonstrated that the addition of ex-situ organic matter improved pH, CEC, organic C, and base cations within the first 90 days (Utami et al., 2017). However, these effects were only temporary. Consequently, reliance on ex-situ organic matter supplies will have limited capacity to ensure long-term nutrient retention, and there is a risk of degradation of soil quality at broader landscapes.

To overcome the limitations of ex-situ organic matter amendment, the adoption of in-situ organic matter provision through vegetation is essential. It is important to emphasize that vegetation is the driving force behind land rehabilitation (Muñoz et al., 2021). It is well documented that plants, through their root systems and the organic matter produced by their litter or pruning, can contribute to soil fertility over time (Hirzel et al., 2025). The supply of organic matter has been demonstrated to stimulate microbial activity, accelerate mineral weathering, and ultimately release nutrients that were previously unavailable (Hayes and Roulia, 2025). Over time, these natural biological processes contribute to the restructuring of the soil structure, resulting in generally improved soil quality. The soil will be able to enhance its capacity to store carbon and water, leading to an increase in total porosity (Štrbac et al., 2025).

Various studies confirm that supplying fresh and decomposed organic matter accelerates the recovery of volcanic areas by increasing the availability of C, N, and P (Utami et al., 2017; 2019b). Nevertheless, the capacity of different vegetation types to recover from such conditions is a key factor in determining the speed of the process (Dou et al., 2024). Therefore, the selection of vegetation species that are able to demonstrate adaptability to post-eruption conditions plays a substantial role in the initiation of agricultural rehabilitation.

Following the eruption of Mount Semeru, previous research has combined several adaptive vegetation species with indigenous microbes to initiate the rehabilitation. The vegetation selected for study includes Napier grass (*Pennisetum purpureum*), Vetiver grass (*Vetiveria zizanioides*), *Centrosema* sp., and *Indigofera* sp. (Albarki et al., 2025a; 2025b). The selection of these 4 species was determined by their complementary natural functions. The grass group (*Gramineae*) has extensive and deep fibrous roots that can grip and improve the physical structure of volcanic ash, while the legume group (*Leguminosae*) is naturally capable of fixing nitrogen. To optimize the intervention, a consortium of indigenous bacteria, consisting of *Bacillus megaterium* and *Bacillus subtilis*, was also applied. These bacteria were selected because they originated from the pyroclastic material of Mount Semeru and for their ability to fix nitrogen and dissolve phosphate (Ustiatik et al., 2023). The interaction between vegetation and bacteria offers a potential approach for addressing nutrient limitations in fresh pyroclastic materials. As demonstrated by the findings of Albarki et al. (2025a; 2025b), this intervention increased organic C, improved water availability, and reduced bulk density over one year of testing.

Despite these documented improvements in physical properties and vegetation biomass C production, 2 critical questions remain unanswered. First, Albarki et al. (2025a; 2025b) have not conducted a post-reclamation evaluation of the chemical fertility dynamics and actual agronomic productivity of the same system. Second, other studies (Ishaq et al., 2020a; 2020b) have separately focused on the growth rates of adaptive species in their natural habitats rather than on the reclaimed material. Consequently, the agronomic suitability of this volcanic substrate for supporting economically valuable horticultural crops has not been thoroughly evaluated.

Therefore, it is necessary to determine whether a one-year reclamation cycle is sufficient to restore the nutrient availability required by a sensitive indicator plant commonly cultivated in volcanic areas, such as red chili (Panjaitan et al., 2018; Purnomo et al., 2020). This study is the initial investigation to specifically evaluate the chemical fertility dynamics and agronomic productivity gains of such a reclamation system. Therefore, it can be considered a biological assay for evaluating productivity within reclaimed pyroclastic deposits (Renwick et al., 2025). This study provides empirical evidence of the "legacy effect" of bioreclamation, as demonstrated by an assessment of nutrient uptake and crop yield.

The central question of this study was whether a one-year bioreclamation of fresh pyroclastic material from Mount Semeru could achieve sufficient fertility levels to support viable crop production. It was hypothesized that the legacy effect of adaptive vegetation, enhanced by an indigenous microbial consortium, would significantly increase nutrient availability and red chili yield compared to individual treatments. The findings of this study will provide valuable insights into the early development of fertility, with implications for practical, community-based guidance for developing sustainable reclamation strategies in post-eruption areas.

MATERIALS AND METHOD

Study area

This study focused on the possibility of using pyroclastic materials for crop cultivation. The area of Supiturang Village, Lumajang Regency, East Java (112°59'7.64" E, 8°10'3.35" S; 750 to 850 m above sea level/masl) was identified as one of the regions most severely impacted by the December 4, 2021, major eruption of Mount Semeru (Figure 1). This area is commonly covered by pyroclastic materials approximately 20 cm in thickness (Ustiatik et al., 2023). The eruption was initiated by a lava dome collapse within Jonggring-Seloko crater, a process further intensified by significant erosion resulting from heavy rainfall (555 mm) throughout November (McGowan et al., 2026). During the eruption, temperatures fluctuated significantly, reaching a maximum of 42.4 °C and a minimum of 14.0 °C (Chandra et al., 2025).

The mineralogical and chemical composition of Mount Semeru pyroclastic material has been characterized in prior work, which reported a dominance of primary minerals typical of fresh tephra (Setiawati et al., 2024; Suhendro et al., 2025). Consistent with this baseline, the materials used in the present study exhibited low fertility and unstable physical properties before the reclamation phase, characteristics typical of fresh volcanic deposits (Albarki et al., 2025a; 2025b). The eruption is still ongoing; hence, the deposition of pyroclastic materials repeats regularly, hindering the in-situ experiment. Therefore, it was necessary to conduct the experiment outside the impacted eruption area.

Junrejo Village, Batu City, East Java (112°33' E, 7°54' S; 650 to 700 masl), which has similar climatic conditions (Figure 2), was selected. The site is characterized by a humid tropical highland

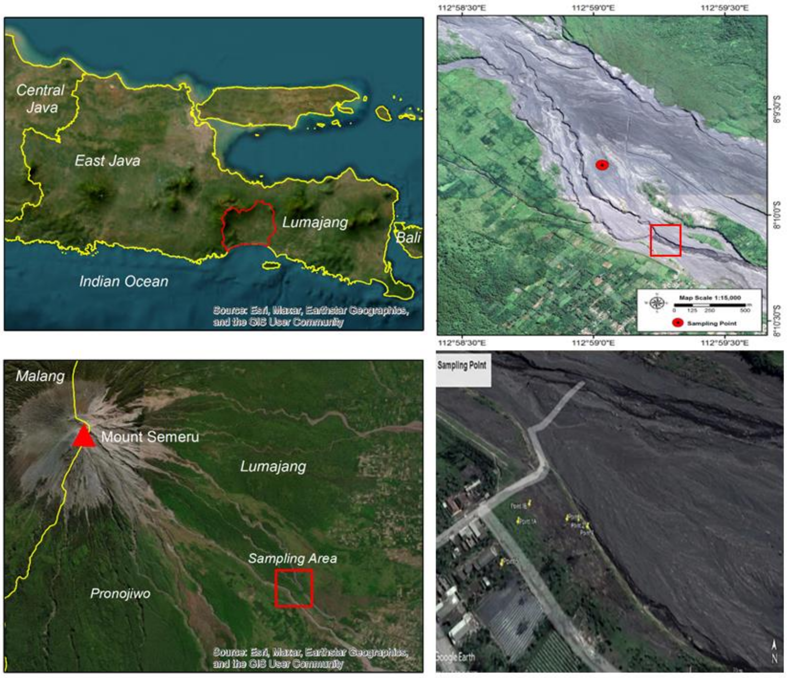

Figure 1. Sampling site of the pyroclastic materials

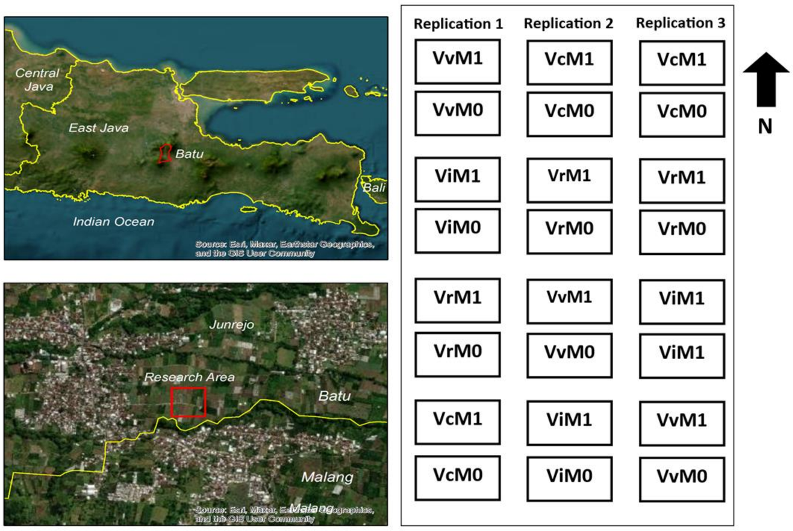

Figure 2. Experimental site

climate, with an average annual rainfall of 2,000 to 2,500 mm (predominantly from November to March), a mean annual temperature of 22 to 25 °C, and an average relative humidity of 80 to 85%. A field experiment was conducted to simulate a 20-cm-thick layer of pyroclastic materials over the original soil for red chili cultivation.

Reclamation phase

Prior to red chili cultivation (December 2022 to March 2024), adaptive vegetation and indigenous microbes were applied for one year to improve the condition of pyroclastic materials for crop growth. A randomized complete block design (RCBD) with 2 factors (vegetation type and microbial inoculation) was used with 3 replicates (Figure 2).

The first factor was the type of adaptive vegetation (V) used during the reclamation phase, such as Napier grass (Vn), Vetiver grass (Vv), *Centrosema* sp. (Vc), and *Indigofera* sp. (Vi). These 4 species were selected for their complementary functional traits for soil rehabilitation. The 2 grass species (Napier and Vetiver grass) possess extensive and deep fibrous root systems that can bind and physically stabilize loose pyroclastic material. The 2 legume species (*Centrosema* sp. and *Indigofera* sp.) contribute N fixation, addressing the N limitation characteristic of fresh pyroclastic materials. All species are additionally recognized as locally adapted and fast-establishing colonizers.

The second factor was the microbial treatment (M), consisting of 2 levels: without microbial inoculation (M0) and with the indigenous microbial consortium inoculation (M1). The microbial consortium consists of *B. subtilis* and *B. megaterium*, which were isolated from the local post-eruption environment of Mount Semeru. Indigenous microbes were selected based on demonstrated nitrogen-fixing and phosphate-solubilizing capacity (Ustiatik et al., 2023). The application of the microbial consortium was intended to optimize compatibility between the inoculant and the pyroclastic materials, rather than relying on generic commercial microbial strains.

This one-year phase focused on the biophysical restructuring of the pyroclastic materials. Before treatment, the pyroclastic material was left in its original state (Albarki et al., 2025a; 2025b). The material was not mechanically processed, and no pre-existing topsoil was added. These baseline conditions were maintained across the entire plot before treatment to ensure that any differences appearing between them after treatment could be related to the effects of the vegetation and microbial treatments rather than to pre-existing material heterogeneity.

Pyroclastic materials were placed in experimental plots measuring 2 m × 1 m with a depth of 20 cm, reflecting the average deposit thickness observed in the post-eruption landscape of Mount Semeru (Ustiatik et al., 2023; Albarki et al., 2025a; 2025b). Vegetation was planted at a spacing of 20 cm × 20 cm. The microbial consortium was applied to the soil using a spraying method with a concentration of 10^8 CFU ml^{-1} at 7, 14, and 21 days after planting adaptive vegetation, using a dosage of 20 ml of consortium diluted in 50 ml of distilled water per m^2. Throughout this phase, vegetation was pruned every 3 months, and the biomass was incorporated into the materials to facilitate organic matter accumulation and nutrient cycling. This process improves material stability and N fixation, optimizing nutrient availability for the next cultivation phase (Albarki et al., 2025a; 2025b).

Red chili cultivation phase

Following the one-year reclamation phase, the experimental plots were redesigned to grow productive crops, *Capsicum annuum* L. var. BAJA MJ F1 (April to September 2024). To align with standard agronomic practices, each plot was divided into 2 ridges to ensure optimal drainage and root-zone aeration, thereby modifying the pyroclastic materials from 20 to 30–40 cm thick above the original soil. This practice is similar to that used by local farmers. The planting distance was maintained at 30 cm × 40 cm to accommodate 5 crops per ridge (Figure 3).

All plots received a standardized basal application of inorganic fertilizers: Urea (150 kg ha^{-1}), SP-36 (150 kg ha^{-1}), and KCl (200 kg ha^{-1}), following the Indonesian Ministry of Agriculture guidelines. The fertilizers were applied in 2 split applications at 7 and 30 days

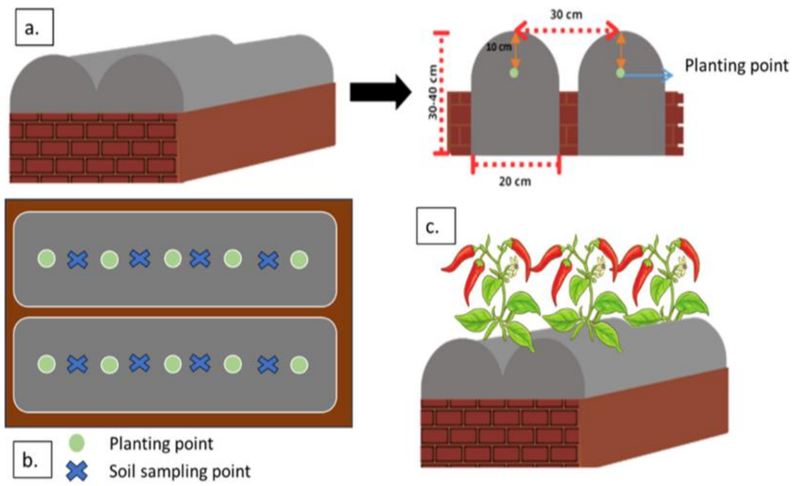

Figure 3. Plot design for reclamation. a) Pyroclastic materials were 30–40 cm thick above the original soil; b) Two rows of ridges and 10 plants per observation plot; c) Raised bed for red chili cultivation

Table 1. Laboratory analysis methods of pyroclastic materials

Parameter	Unit	Method	Frequency
Organic C	%	Walkey and Black	Before reclamation, one-year reclamation, 6 WAP, 14 WAP
Total N	%	Kjeldahl	Before reclamation, one-year reclamation, 6 WAP, 14 WAP
Available P	mg kg^{-1}	P-Olsen	Before reclamation, one-year reclamation, 6 WAP, 14 WAP
Exchangeable K	cmol kg^{-1}	NH_4O_{AC} 1 N	Before reclamation, one-year reclamation, 6 WAP, 14 WAP

Note: WAP = Weeks after red chili planting

Table 2. Laboratory analysis method of plant parameters

Parameter	Unit	Method	Frequency (WAP)
Dry biomass weight	g plant^{-1}	Oven-dried at 70 °C	14
Estimated plant C assimilation in dry biomass	g plant^{-1}	0.46 × total dry weight biomass (Hairiah et al., 2011)	6 and 14
N uptake	mg plant^{-1}	Kjeldahl	6 and 14
P uptake	mg plant^{-1}	Dry ashing	6 and 14
K uptake	mg plant^{-1}	Dry ashing	6 and 14

Note: WAP = Weeks after red chili planting

after planting red chili. By maintaining a uniform basal nutrient input from fertilizers, it was ensured that differences in crop growth, nutrient uptake, and yield were driven by the one-year reclamation treatments rather than external fertilizer supply. However, the nutrient content measured in the pyroclastic materials is the result of reclamation and fertilization; therefore, this study does not distinguish the proportional contributions of each source.

Measurement of nutrient content in the reclaimed pyroclastic materials

The chemical characteristics of pyroclastic material following one year of reclamation are critical for determining its potential as a source of nutrients for crop growth. Reclaimed pyroclastic material can enhance soil fertility and support the development of productive agricultural systems. To evaluate its effect on crop growth, nutrient content in pyroclastic materials was analyzed before and after one-year reclamation, as well as at the maximum vegetative and harvest period (Table 1).

Nutrient uptake measurement

Plant biomass was sampled and weighed at the maximum vegetative and generative phases. The entire plant was uprooted, washed, and separated into roots, stems, leaves, and fruits. Three plants per plot were sampled, weighed for fresh biomass, and oven-dried at 70 °C to obtain the dry weight. Dried samples were then ground to a uniform size. These subsamples were then analyzed to determine total C and nutrient uptake of N, P, and K (Table 2).

Crop yield measurement

Red chili was harvested periodically when the fruits had turned completely red, and the harvested fruits were accumulated at the end of the harvest period (14 WAP). The fruits in every plot were weighed and converted to ton ha^{-1}.

Data analysis

The collected data were organized using Microsoft Excel and statistically analyzed using RStudio version 4.6.0. The Shapiro–Wilk test was used to assess the normality of the data. Analysis of variance (ANOVA) was conducted to determine the effects of treatments. If significant differences were identified (F prob $\leq$ 0.05), a post hoc comparison was carried out using the least significant difference (LSD) test to evaluate differences among treatment means. Principal component analysis (PCA) was conducted to evaluate the multivariate relationships among the chemical properties of pyroclastic materials after one year of reclamation and 6 WAP, plant nutrient uptake during vegetative and generative phases, and red chili yield.

RESULTS AND DISCUSSION

Fertility improvement of pyroclastic materials

The nutrient composition of pyroclastic materials exhibited significant variation across treatments and growth phases (F prob ≤ 0.05; Tables 3 to 6). The combination of adaptive vegetation biomass and an indigenous microbial consortium (M1) notably influenced nutrient partitioning within red chili and enhanced nutrient enrichment processes in reclaimed materials. Returning vegetation residues to pyroclastic materials triggers a cascade of biogeochemical reactions that improve the availability of the main macronutrients, C, N, P, and K, therefore accelerating the development of functional soil fertility in post-eruption areas.

Organic C

The organic C in pyroclastic materials improved from 0.12 to 0.15–0.60% after a one-year reclamation (Table 3), representing a 1.25- to 5-fold increase compared to the pre-reclamation condition. However, this is still considered very low status (Eviati et al., 2023), as expected, as pyroclastic materials are naturally poor in organic matter following an eruption. The result indicated that organic C content in the materials cannot be improved in a short time, although it might be statistically increased by the number. Before planting, the organic C content reflected the inherently low organic matter of fresh pyroclastic materials. The highest organic C content was recorded under ViM0 (*Indigofera* sp. without microbes), suggesting leguminous biomass residues contribute to soil organic matter accumulation. Microbial treatment (M1) insignificantly increased organic C, likely because of limited decomposable substrates for microbial metabolism.

Table 3. Organic C in the pyroclastic materials

	Organic C (%)		
Before reclamation	0.12		
One-year reclamation	M0	M1	Average (V)
Vn	0.37^{bc}	0.22^{bcd}	0.29^{a}
Vv	0.19^{cd}	0.34^{bc}	0.26^{b}
Vc	0.15^{d}	0.40^{b}	0.27^{b}
Vi	0.60^{a}	0.27^{bcd}	0.44^{b}
Average (M)	0.32	0.31	
F prob			
Vegetation (V)			0.04706*
Microbes (M)			0.64399
Interaction (V × M)			0.00116**
Maximum vegetative period (6 WAP)	M0	M1	Average (V)
Vn	0.43	0.32	0.38^{ab}
Vv	0.25	0.23	0.24^{c}
Vc	0.32	0.26	0.29^{bc}
Vi	0.48	0.46	0.47^{a}
Average (M)	0.37	0.31	
F prob			
Vegetation (V)			0.00653**
Microbes (M)			0.21739
Interaction (V × M)			0.84774
Harvest period (14 WAP)	M0	M1	Average (V)
Vn	0.53^{a}	0.36^{b}	0.45^{a}
Vv	0.29^{bc}	0.49^{a}	0.39^{a}
Vc	0.11^{d}	0.22^{cd}	0.16^{c}
Vi	0.20^{cd}	0.37^{b}	0.29^{b}
Average (M)	0.29^{b}	0.36^{a}	
F prob			
Vegetation (V)			1.32×10^{-05}**
Microbes (M)			0.013443**
Interaction (V × M)			0.000759**

Note: Vn = Napier grass, Vv = Vetiver grass, Vc = *Centrosema* sp., Vi = *Indigofera* sp., M0 = Without indigenous microbes, M1 = With indigenous microbes. The average with different letters shows significant differences with the LSD post hoc test; * = Statistically significant (F prob ≤ 0.05), ** = Highly statistically significant (F prob ≤ 0.01)

At the maximum vegetative period (6 WAP), organic C content ranged from 0.23 to 0.48%. Significant variations were driven by the vegetation types (F prob ≤ 0.05), with *Indigofera* sp. (Vi) and Napier grass (Vn) showing higher values. At the harvest period (14 WAP), organic C content ranged from 0.11 to 0.53%. Unlike the previous period, microbial treatment (M1) significantly increased overall organic C content (F prob ≤ 0.01), with an average of 0.36% compared to the uninoculated treatments. Furthermore, the interaction between the vegetation and microbes was significant at this period (F prob ≤ 0.05), with the VnM0 and VvM1 treatments maintaining the highest values (0.53% and 0.49%, respectively).

The observed increase in organic C content reflects the development of biological activity in reclaimed pyroclastic materials. This pattern is similar to that reported by Utami et al. (2017), incubation with *Tithonia diversifolia* biomass and 100% fertilizer in pyroclastic materials from Mount Kelud increased the organic C content from 0.35 to 0.68% after 60 days of incubation. This long-term organic C accumulation aligns with Fiantis et al. (2016), who observed an 8-fold (0.19 to 1.75%) increase in total C for Mount Talang tephra over 46 months. Fresh volcanic material from Mount Semeru is initially sterile and completely free of organic matter (Setiawati et al., 2024). Carbon accumulation only begins once pioneer plants, such as grasses and shrubs, start to grow. This natural process mirrors observations at Mount Talang, where vegetation began establishing itself 2 years after the eruption (Fiantis et al., 2016).

Biomass return enhances microbial growth and enzymatic activity, leading to greater decomposition and nutrient cycling efficiencies (Luo et al., 2020; Saputra et al., 2022). Microbial decomposition of organic residues releases dissolved organic C, which is associated with enzymatic processes that mediate C, N, P, and K turnover. This coupling between biomass input and microbial activity accelerates the formation of stable organic matter (Soong et al., 2018; Błońska et al., 2021). In addition, root exudates released during organic matter decomposition play a role in modifying the soil structure. Utami et al. (2017) reported that the bulk density of pyroclastic materials from Mount Kelud declined as soil organic C content increased, a process linked to the incorporation of organic inputs and the establishment of natural vegetation.

Total N

After one-year reclamation, total N content significantly improved from 0.001 to 0.02–0.05% (Table 4), representing a 20- to 50-fold increase compared to the pre-reclamation condition. However, this is still considered very low status (Eviati et al., 2023), as expected for N-deficient pyroclastic materials. The result indicated that total N content in materials with low organic status cannot be improved in a short time, although it might be statistically increased in number. The significant increase in total N content was primarily driven by the vegetation type (F prob ≤ 0.05), with *Indigofera* sp. (Vi) recording the highest average (0.041%), reflecting the contribution of leguminous residues. Interestingly, treatments without indigenous microbes (M0) maintained significantly higher total N content (0.035%) (F prob ≤ 0.05), compared to the microbial treatments (M1) at this early period.

At 6 WAP, total N content ranged from 0.03 to 0.06%. Significant variations were driven solely by the vegetation type (F prob ≤ 0.01), with Napier grass (Vn) recording the highest value (0.055%), while microbial treatments (M1) showed no significant differences. This suggests early stimulation of N mineralization driven by specific vegetation residues rather than added microbes. Although the base dose of urea used was uniform, significant variations in total N content among the treatments indicate that legacy effects from the reclamation may influence N retention, therefore causing differences in the performance of each vegetation type and microbial inoculation under the same basal fertilization conditions.

At 14 WAP, total N content increased from 0.06 to 0.09%. At this period, only microbial treatments significantly increased overall total N content (F prob ≤ 0.01), with M1 treatments maintaining the highest values (0.073%). However, the interaction between vegetation and microbial treatments showed no significant difference. Nitrogen released by decomposing residues and supplied through microbial immobilization is important to soil fertility in pyroclastic soils (Nira, 2023; Zhu et al., 2025). *Indigofera* sp. enhances soil N and microbial activity, which indirectly increases P availability through enzyme interactions (Zhu et al., 2025). This demonstrates the importance of biological N from vegetation and microbes in restoring soil fertility.

Table 4. Total N in the pyroclastic materials

	Total N (%)		
Before reclamation	0.001		
One-year reclamation	M0	M1	Average (V)
Vn	0.03	0.02	0.026[b]
Vv	0.02	0.03	0.025[b]
Vc	0.04	0.03	0.033[ab]
Vi	0.05	0.04	0.041[a]
Average (M)	0.04[a]	0.03[b]	
F prob			
Vegetation (V)			0.00763**
Microbes (M)			0.02985*
Interaction (V × M)			0.30983
Maximum vegetative period (6 WAP)	M0	M1	Average (V)
Vn	0.05	0.06	0.055[a]
Vv	0.03	0.03	0.031[b]
Vc	0.03	0.04	0.035[b]
Vi	0.03	0.04	0.031[b]
Average (M)	0.04	0.04	
F prob			
Vegetation (V)			0.000269**
Microbes (M)			0.100927
Interaction (V × M)			0.713458
Harvest period (14 WAP)	M0	M1	Average (V)
Vn	0.06	0.07	0.065
Vv	0.06	0.07	0.065
Vc	0.06	0.06	0.060
Vi	0.06	0.09	0.075
Average (M)	0.06[b]	0.07[a]	
F prob			
Vegetation (V)			0.068303
Microbes (M)			0.000485**
Interaction (V × M)			0.125734

Note: Vn = Napier grass, Vv = Vetiver grass, Vc = *Centrosema* sp., Vi = *Indigofera* sp., M0 = Without indigenous microbes, M1 = With indigenous microbes. The average with different letters shows significant differences with the LSD post hoc test; * = Statistically significant (F prob ≤ 0.05), ** = Highly statistically significant (F prob ≤ 0.01)

Available P

Table 5 shows that fresh pyroclastic materials contained a moderate status of available P (11.80 mg kg^{-1}). However, after one-year reclamation, the available P content increased to 36.51–133.28 mg kg^{-1}, raising its fertility status from moderate to very high (Eviati et al., 2023). The interaction between vegetation and microbes was significant at this period (F prob ≤ 0.05), with ViM1 (133.28 mg kg^{-1}) and VnM0 (133.07 mg kg^{-1}) recording the highest values. This reflects P mineralization driven by specific vegetation-microbe combinations. At 6 WAP, available P content ranged from 47.80 to 75.09 mg kg^{-1}. Significant differences were driven solely by vegetation type, with Napier grass (Vn) maintaining the highest available P content (70.06 mg kg^{-1}), while microbial treatments showed insignificant effect.

At the harvest 14 WAP, the available P content slightly declined. Similar to 6 WAP, only the vegetation type was significant (F prob ≤ 0.05), with Vn continuing to record the highest available P content (64.99 mg kg^{-1}). However, microbial treatments (M1) showed no significant differences. Despite the uniform application of SP-36, significant variations in available P content among treatments suggest that legacy effects from the reclamation may influence P availability, therefore causing differences in the performance of each vegetation type and microbial inoculation under the same basal fertilization conditions. This overall reduction is a physiological consequence of substantial

Table 5. Available P in the pyroclastic materials

	Available P (mg kg^{-1})		
Before reclamation	11.80		
One-year reclamation	M0	M1	Average (V)
Vn	133.07^{a}	55.73^{b}	94.40^{a}
Vv	53.76^{b}	53.76^{b}	53.76^{c}
Vc	41.11^{d}	36.51^{e}	38.81^{d}
Vi	47.31^{c}	133.28^{a}	90.29^{b}
Average (M)	68.81	69.82	
F prob			
Vegetation (V)			1.57×10^{-15}**
Microbes (M)			0.344
Interaction (V × M)			2×10^{-16}**
Maximum vegetative period (6 WAP)	M0	M1	Average (V)
Vn	65.04	75.09	70.06^{a}
Vv	62.52	60.75	61.63^{b}
Vc	50.42	48.18	49.30^{c}
Vi	50.70	47.80	49.25^{c}
Average (M)	57.17	57.95	
F prob			
Vegetation (V)			6.36×10^{-05}**
Microbes (M)			0.756
Interaction (V × M)			0.242
Harvest period (14 WAP)	M0	M1	Average (V)
Vn	56.21	73.77	64.99^{a}
Vv	45.89	45.82	45.86^{b}
Vc	44.38	49.46	46.92^{b}
Vi	47.87	46.76	47.32^{b}
Average (M)	48.59	53.95	
F prob			
Vegetation (V)			0.0141*
Microbes (M)			0.2097
Interaction (V × M)			0.3809

Note: Vn = Napier grass, Vv = Vetiver grass, Vc = *Centrosema* sp., Vi = *Indigofera* sp., M0 = Without indigenous microbes, M1 = With indigenous microbes. The average with different letters shows significant differences with the LSD post hoc test; * = Statistically significant (F prob ≤ 0.05), ** = Highly statistically significant (F prob ≤ 0.01)

P uptake, functioning as a sink during the generative and fruiting period. Vegetative biomass turnover functions as the primary driver of organic P inputs, thereby releasing labile P, which is essential for the successful establishment of early crops in marginal substrates (Katayama et al., 2021). Furthermore, the incorporation of residue has been shown to elicit robust stimulation of indigenous microbes and phosphatase activity, thereby accelerating the mineralization of P from both organic fractions and previously fixed mineral pools (Miao et al., 2024).

Exchangeable K (K_{exch})

Fresh pyroclastic materials initially contained a high status of K_{exch} (0.66 cmol kg^{-1}). After a one-year reclamation, K_{exch} ranged between 0.17 and 0.59 cmol kg^{-1} (Table 6), reflecting a shift in fertility status to a range from low to high (Eviati et al., 2023). The interaction between vegetation and microbes was significant (F prob ≤ 0.05), with the uninoculated Napier grass treatment (VnM0) recording the highest K_{exch} (0.59 cmol kg^{-1}), suggesting that Napier grass residues could maintain K retention. Conversely, the overall decrease across all treatments was associated with K leaching, which was inhibited by the physical instability of pyroclastic material under high annual rainfall.

At 6 WAP, the interaction effect showed that red chili cultivated in the uninoculated Napier grass legacy (VnM0) recorded higher K_{exch} (1.52 cmol kg^{-1}), outperforming all other treatments (0.19 to 0.37 cmol kg^{-1}). This transient surge was attributed to the combined effects of rapid K^{+}

Table 6. Exchangeable K in the pyroclastic materials

	Exchangeable K (cmol kg^{-1})		
Before reclamation	0.66		
One-year reclamation	M0	M1	Average (V)
Vn	0.59^a	0.44^b	0.51^a
Vv	0.20^c	0.20^c	0.20^b
Vc	0.18^c	0.17^c	0.17^b
Vi	0.17^c	0.20^c	0.18^b
Average (M)	0.28^a	0.25^b	
F prob			
Vegetation (V)			3.1×10^{-12}**
Microbes (M)			0.005396**
Interaction (V × M)			0.000152**
Maximum vegetative period (6 WAP)	M0	M1	Average (V)
Vn	1.52^a	0.19^b	0.85
Vv	0.36^b	0.33^b	0.35
Vc	0.22^b	0.25^b	0.23
Vi	0.26^b	0.37^b	0.32
Average (M)	0.59	0.28	
F prob			
Vegetation (V)			0.0769
Microbes (M)			0.0882
Interaction (V × M)			0.0254*
Harvest period (14 WAP)	M0	M1	Average (V)
Vn	0.50^a	0.54^a	0.52^a
Vv	0.27^b	0.21^{bc}	0.24^c
Vc	0.16^{bc}	0.14^c	0.15^d
Vi	0.21^{bc}	0.47^a	0.34^b
Average (M)	0.29	0.34	
F prob			
Vegetation (V)			6.39×10^{-07}**
Microbes (M)			0.06451
Interaction (V × M)			0.00208**

Note: Vn = Napier grass, Vv = Vetiver grass, Vc = *Centrosema* sp., Vi = *Indigofera* sp., M0 = Without indigenous microbes, M1 = With indigenous microbes. The average with different letters shows significant differences with the LSD post hoc test; * = Statistically significant (F prob ≤ 0.05), ** = Highly statistically significant (F prob ≤ 0.01)

release from uniform basal KCl application and decomposing Napier grass residues. At 14 WAP, K_{exch} generally declined, ranging from 0.14 to 0.54 cmol kg^{-1}. This decline is a consequence of K uptake, as red chili functions as a major sink for K during the generative and fruit-development phases, alongside the progressive leaching of unbound K^+ from the unstable pyroclastic materials. Significant interactions (F prob ≤ 0.05) showed that treatments VnM1 (0.54 cmol kg^{-1}), VnM0 (0.50 cmol kg^{-1}), and ViM1 (0.47 cmol kg^{-1}) maintained the K_{exch}.

Vegetation residues returned to the pyroclastic materials might increase organic matter content. An increase in organic matter is expected to increase CEC, thereby increasing K retention (Paramisparam et al., 2021; Cruz et al., 2023). This increase can reduce K leaching from the pyroclastic materials, although the effectiveness of organic amendments in mitigating leaching can vary depending on the material's mineralogical composition (Escudey et al., 2015; Yakovleva et al., 2020). The transient surge observed at 6 WAP may be attributed to the solubilization of K from high-biomass grass residues, which, when combined with the uniform basal KCl application, produces a temporary elevation of K_{exch} (Andrews et al., 2021).

Although the base dose of KCl was uniform, significant variations in K_{exch} among the treatments indicate that legacy effects from the reclamation may influence K retention, therefore causing differences in the performance of each vegetation type and microbial inoculation under the same basal fertilization conditions. However, considering the low weatherability of K-bearing minerals (Setiawati et al., 2024), the total amount of K_{exch} released from the pyroclastic materials would decrease, as the K supply from the fertilizer cannot compensate for plant uptake, particularly given that red chili functions as a major sink for K during the generative and fruit-development period (Sheetal et al., 2024).

Furthermore, adaptive vegetation residue and indigenous microbes drive soil aggregation in coarse pyroclastic materials, enhancing water retention and root penetrability (Saputra et al., 2022). According to Albarki et al. (2025a), the combination of Napier grass and indigenous microbes significantly reduced the bulk density of Mount Semeru pyroclastic materials from 1.7 to 1.2 g cm^{-3} within 12 months, accompanied by increased total porosity, available water content, and permeability.

Nutrient uptake by red chili

Nutrient uptake by red chili varied significantly among the treatments and growth period (F prob ≤ 0.05; Tables 7 to 10). Treatments combining adaptive vegetation residues and indigenous microbial inoculants (M1) generally displayed greater nutrient accumulation than the non-inoculated (M0).

Estimated C assimilation in biomass partitioning

At 6 WAP, estimated plant C assimilation ranged from 0.59 to 1.33 g $plant^{-1}$. Significant variations were driven independently by the vegetation type (F prob ≤ 0.01) and microbial treatments (F prob ≤ 0.01), while the interaction between the vegetation and microbes was

Table 7. Estimated plant C content

	Estimated plant C content (g $plant^{-1}$)		
Maximum vegetative period (6 WAP): stems-leaves-roots	M0	M1	Average (V)
Vn	0.66	1.33	1.00^{a}
Vv	0.66	1.07	0.86^{ab}
Vc	0.83	0.77	0.80^{ab}
Vi	0.59	0.85	0.72^{b}
Average (M)	0.69^{b}	1.00^{a}	
F prob			
Vegetation (V)			2.78×10^{-06}**
Microbes (M)			0.00643**
Interaction (V × M)			0.13508
Harvest period (14 WAP): stems-leaves-roots	M0	M1	Average (V)
Vn	16.93	16.63	16.78^{a}
Vv	7.79	10.46	9.13^{b}
Vc	4.16	7.03	5.60^{c}
Vi	6.93	12.63	9.78^{b}
Average (M)	8.95	11.69	
F prob			
Vegetation (V)			0.000263**
Microbes (M)			0.093937
Interaction (V × M)			0.058030
Harvest period (14 WAP): fruits	M0	M1	Average (V)
Vn	5.54^{a}	5.00^{a}	5.27^{a}
Vv	1.66^{b}	2.32^{b}	1.99^{c}
Vc	1.81^{b}	1.53^{b}	1.67^{c}
Vi	2.36^{b}	5.05^{a}	3.70^{b}
Average (M)	2.84^{b}	3.48^{a}	
F prob			
Vegetation (V)			1.29×10^{-07}**
Microbes (M)			0.01926*
Interaction (V × M)			0.00133**

Note: Vn = Napier grass, Vv = Vetiver grass, Vc = *Centrosema* sp., Vi = *Indigofera* sp., M0 = Without indigenous microbes, M1 = With indigenous microbes. The average with different letters shows significant differences with the LSD post hoc test; * = Statistically significant (F prob ≤ 0.05), ** = Highly statistically significant (F prob ≤ 0.01)

insignificant (Table 7). For the vegetation factor, Napier grass (Vn) recorded the highest average C assimilation (1.00 g plant^{-1}). Meanwhile, microbial treatments (M1) significantly enhanced average C assimilation (1.00 g plant^{-1}) compared to treatments without microbes (M0, 0.69 g plant^{-1}).

At 14 WAP, total C assimilation in stems, leaves, and roots increased substantially, ranging from 4.16 to 16.93 g plant^{-1}. At this period, the significant increase was driven solely by the vegetation type (F prob $\leq$ 0.01), with Napier grass (Vn) recording the highest average (16.78 g plant^{-1}). Microbial treatments (M1) and the interaction were insignificant, indicating that C assimilation during this period relied heavily on the specific vegetation residues rather than the added microbes. Furthermore, in the chili fruits, estimated C assimilation ranged from 1.53 to 5.54 g plant^{-1}. The accumulation was significantly driven by the interaction between vegetation and microbes (F prob $\leq$ 0.01), alongside both main factors. Specifically, the interaction effect showed that VnM0 (5.54 g plant^{-1}), ViM1 (5.05 g plant^{-1}), and VnM1 (5.00 g plant^{-1}) treatments recorded the highest C assimilation.

This increase reflects the C allocated to the vegetative parts (leaves and stems) to support photosynthetic capacity before fruit set. However, it is important to note that plant C content in this study was estimated using a standard conversion factor (0.46 × dry biomass). Even with this estimation approach, these accumulation patterns suggest that Napier grass residue turnover helps improve the biophysical conditions of the rhizosphere. By reducing bulk density and increasing porosity, the organic residues facilitated extensive root growth and sustained nutrient uptake. This biophysical improvement aligns with established pedological principles, which indicate that the incorporation of organic matter into physically constrained pyroclastic materials is a key factor in enhancing photosynthetic efficiency and biomass productivity (Soong et al., 2018; Saputra et al., 2022).

N uptake

At 6 WAP, average N uptake showed no significant differences among the vegetation types, suggesting that the early N-fixing advantage of legumes (*Centrosema* sp. and *Indigofera* sp.) provided no immediate benefit to early crop growth (Table 8). In contrast, at 14 WAP, N uptake in stems, leaves, and roots increased substantially, ranging from 69.29 to 374.38 mg plant^{-1}. At this period, the significant variation was driven solely by the vegetation type (F prob $\leq$ 0.01), while the microbial treatments and their interaction were insignificant. The Napier grass legacy (Vn) recorded the highest average N uptake (351.21 mg plant^{-1}). This suggests that the decomposition of Napier grass residues offers a more synchronized N supply than legume-derived inputs.

Furthermore, N uptake in chili fruit ranged from 44.13 to 232.50 mg plant^{-1}. Harvest data showed that N uptake was significantly driven by both independent main factors, vegetation type (F prob $\leq$ 0.01) and microbial inoculation (F prob $\leq$ 0.05), while their interaction remained insignificant. For the vegetation factor, Napier grass (Vn) maintained the highest average N uptake (225.25 mg plant^{-1}), while *Centrosema* sp. (Vc) recorded the lowest average (60.11 mg plant^{-1}). Overall microbial inoculation (M1) significantly improved average N uptake (155.28 mg plant^{-1}) compared to the uninoculated treatment (M0, 107.40 mg plant^{-1}). This indicates that microbial treatments play a role in facilitating N transformations in physically constrained reclamation contexts (Zhao et al., 2019; Nira, 2023).

P uptake

At 6 WAP, P uptake ranged from 4.26 to 24.89 mg plant^{-1}. Statistical analysis revealed that the variation was driven solely by the vegetation type (F prob $\leq$ 0.05), while microbial inoculation and its interaction showed no significant differences (Table 9). The Napier grass legacy (Vn) recorded the highest average P uptake (20.79 mg plant^{-1}). At 14 WAP, P uptake increased substantially, ranging from 274.76 to 1,079.21 mg plant^{-1}. Similar to the 6 WAP, the significant increase was driven independently by the vegetation type (F prob $\leq$ 0.01). The Napier grass legacy (Vn) maintained the highest average uptake (999.71 mg plant^{-1}). Microbial treatments and their interaction remained insignificant. This suggests that biomass residue turnover in Napier grass produces organic acids, helping release P from the pyroclastic materials.

Furthermore, at 14 WAP, P uptake in chili fruits ranged from 97.21 to 585.74 mg plant^{-1}. Once again, the significant variation was driven by the vegetation type (F prob $\leq$ 0.01). Napier grass (Vn) consistently recorded the highest average P uptake (525.95 mg plant^{-1}), while *Centrosema* sp. (Vc) recorded the lowest average (124.28 mg plant^{-1}). Microbial treatments and the interaction effect showed no significant

Table 8. Nutrient uptake of N during the chili plant growth phase

	N uptake (mg plant^{-1})		
Maximum vegetative period (6 WAP): stems-leaves-roots	M0	M1	Average (V)
Vn	3.44	2.59	3.01
Vv	1.40	2.23	1.81
Vc	3.21	2.25	2.73
Vi	3.69	3.08	3.38
Average (M)	2.93	2.54	
F prob			
Vegetation (V)			0.224
Microbes (M)			0.458
Interaction (V × M)			0.606
Harvest period (14 WAP): stems-leaves-roots	M0	M1	Average (V)
Vn	328.04	374.38	351.21^{a}
Vv	120.43	108.15	114.29^{b}
Vc	70.00	78.18	74.09^{b}
Vi	69.29	163.20	116.25^{b}
Average (M)	146.94	180.98	
F prob			
Vegetation (V)			4.59×10^{-06}**
Microbes (M)			0.185
Interaction (V × M)			0.458
Harvest period (14 WAP): fruits	M0	M1	Average (V)
Vn	217.99	232.50	225.25^{a}
Vv	92.85	138.60	115.73^{bc}
Vc	44.13	76.10	60.11^{c}
Vi	74.60	173.91	124.25^{b}
Average (M)	107.40^{b}	155.28^{a}	
F prob			
Vegetation (V)			0.000275**
Microbes (M)			0.026251*
Interaction (V × M)			0.465300

Note: Vn = Napier grass, Vv = Vetiver grass, Vc = *Centrosema* sp., Vi = *Indigofera* sp., M0 = Without indigenous microbes, M1 = With indigenous microbes. The average with different letters shows significant differences with the LSD post hoc test; * = Statistically significant (F prob ≤ 0.05), ** = Highly statistically significant (F prob ≤ 0.01)

differences at the harvest period, indicating that long-term P mobilization in this reclamation relied primarily on the specific traits of the adaptive vegetation residues rather than on microbial inoculation. This process is important for plants to get the nutrients they need when growing on pyroclastic materials (Katayama et al., 2021; Miao et al., 2024).

K uptake

At 6 WAP, K uptake ranged from 2.74 to 8.31 mg plant^{-1}. Statistical analysis revealed that the variation was driven solely by the vegetation type (F prob ≤ 0.01), while microbial inoculation and its interaction showed no significant differences (Table 10). The Napier grass legacy (Vn) recorded the highest average K uptake (7.70 mg plant^{-1}). At 14 WAP, K uptake in stems, leaves, and roots increased substantially, ranging from 66.32 to 309.63 mg plant^{-1}. Similar to the 6 WAP, the significant increase was driven independently by the vegetation type (F prob ≤ 0.01). The Napier grass legacy (Vn) maintained the highest average uptake (296.22 mg plant^{-1}).

Furthermore, K uptake in chili fruits ranged from 24.97 to 153.54 mg plant^{-1}. Once again, the significant variation was driven by the vegetation type (F prob ≤ 0.01), with Napier grass (Vn) consistently recording the highest average K uptake (144.15 mg plant^{-1}). This suggests that root exudates and biomass residue turnover from Napier grass effectively accelerate the weathering of K minerals and improve root nutrient uptake. Incorporating organic residues from adaptive vegetation biomass improves soil physicochemical conditions for plant growth,

Table 9. Nutrient uptake P in the chili plant growth phase

	P uptake (mg plant^{-1})		
Maximum vegetative period (6 WAP): stems-leaves-roots	M0	M1	Average (V)
Vn	24.89	16.70	20.79[a]
Vv	4.26	15.77	10.01[b]
Vc	12.70	12.16	12.43[b]
Vi	8.60	13.08	10.84[b]
Average (M)	12.61	14.42	
F prob			
Vegetation (V)			0.0353*
Microbes (M)			0.4884
Interaction (V × M)			0.0891
Harvest period (14 WAP): stems-leaves-roots	M0	M1	Average (V)
Vn	1,079.21	920.20	999.71[a]
Vv	638.20	560.24	599.22[b]
Vc	274.76	308.10	291.42[c]
Vi	352.60	728.77	540.68[b]
Average (M)	586.19	629.32	
F prob			
Vegetation (V)			0.000227**
Microbes (M)			0.601441
Interaction (V × M)			0.142163
Harvest period (14 WAP): fruits	M0	M1	Average (V)
Vn	585.74	466.16	525.95[a]
Vv	196.28	281.02	238.65[b]
Vc	097.21	151.35	124.28[b]
Vi	154.13	273.44	213.70[b]
Average (M)	258.34	292.99	
F prob			
Vegetation (V)			0.00487**
Microbes (M)			0.61340
Interaction (V × M)			0.60935

Note: Vn = Napier grass, Vv = Vetiver grass, Vc = *Centrosema* sp., Vi = *Indigofera* sp., M0 = Without indigenous microbes, M1 = With indigenous microbes. The average with different letters shows significant differences with the LSD post hoc test; * = Statistically significant (F prob ≤ 0.05), ** = Highly statistically significant (F prob ≤ 0.01)

leading to greater root nutrient uptake (Paramisparam et al., 2021; Cruz et al., 2023).

To summarize, macronutrient uptake dynamics indicate that reclamation efficacy is largely determined by the synchrony between plant residue mineralization and crop nutrient demand. Napier grass and indigenous microbes (VnM1) facilitated optimal synchrony through 3 key mechanisms: (i) substantial biomass that serves as a slow-release substrate; (ii) root-driven physical amelioration of the compacted matrix; and (iii) microbial-mediated nutrient solubilization. Furthermore, indigenous microbes support this synchronous coupling of pyroclastic materials and crops, acting as an important factor in improving crop yield. Conversely, leguminous treatments, particularly *Centrosema* sp. (Vc), exhibited an asynchrony, where the rapid decomposition of its relatively low biomass resulted in early nutrient release prior to the crop's peak physiological needs.

Total biomass and crop yield enhancement

Plant biomass

For total dry weight biomass, values ranged from 29.55 to 92.91 g plant^{-1}. Statistical analysis revealed that the variations were driven independently by vegetation type (F prob ≤ 0.01) and microbial inoculation (F prob ≤ 0.05), while their interaction was not significant (Table 11). The Napier grass legacy (Vn) recorded the highest average total biomass (88.57 g plant^{-1}). Furthermore, overall microbial inoculation (M1) significantly increased total biomass (63.13 g plant^{-1}) compared to the uninoculated treatments (M0, 50.88 g plant^{-1}). Similarly,

Table 10. Nutrient uptake of K in the chili plant growth phase

	K uptake (mg plant^{-1})		
Maximum vegetative period (6 WAP): stems-leaves-roots	M0	M1	Average (V)
Vn	8.31	7.09	7.70^{a}
Vv	2.74	3.44	3.10^{b}
Vc	4.66	4.50	4.58^{b}
Vi	2.87	4.63	3.75^{b}
Average (M)	4.67	4.92	
F prob			
Vegetation (V)			0.00789**
Microbes (M)			0.75303
Interaction (V × M)			0.64162
Harvest period (14 WAP): stems-leaves-roots	M0	M1	Average (V)
Vn	282.81	309.63	296.22^{a}
Vv	165.15	131.28	148.22^{b}
Vc	70.51	66.32	68.41^{c}
Vi	89.38	172.72	131.05^{bc}
Average (M)	151.96	169.99	
F prob			
Vegetation (V)			8.91×10^{-05}**
Microbes (M)			0.4695
Interaction (V × M)			0.3944
Harvest period (14 WAP): fruits	M0	M1	Average (V)
Vn	134.76	153.54	144.15^{a}
Vv	60.25	79.37	69.81^{b}
Vc	24.97	37.51	31.24^{b}
Vi	46.83	74.82	60.82^{b}
Average (M)	66.71	86.31	
F prob			
Vegetation (V)			0.000446**
Microbes (M)			0.187131
Interaction (V × M)			0.984370

Note: Vn = Napier grass, Vv = Vetiver grass, Vc = *Centrosema* sp., Vi = *Indigofera* sp., M0 = Without indigenous microbes, M1 = With indigenous microbes. The average with different letters shows significant differences with the LSD post hoc test; * = Statistically significant (F prob ≤ 0.05), ** = Highly statistically significant (F prob ≤ 0.01)

for stems and leaves (ranging from 8.17 to 32.11 g plant^{-1}), significant variations were driven independently by vegetation type (F prob ≤ 0.01) and microbial treatments (F prob ≤ 0.01) without any interaction effect.

Meanwhile, root biomass was driven solely by vegetation type (F prob ≤ 0.001), with Vn recording the highest average (4.95 g plant^{-1}). This suggests that the residual fertility and improved physical stability under Napier grass supported comprehensive crop growth. The underlying mechanism is similar to Albarki et al. (2025b), who demonstrated that Napier grass exhibits an exceptional crop growth rate (67 g m^{-2} day^{-1}) and C storage potential (2.7 kg m^{-2}) on Mount Semeru pyroclastic materials. Adding organic matter improves soil nutrient availability.

In terms of chili fruits, values ranged from 3.33 to 12.03 g plant^{-1}. Unlike the other biomass parameters, fruit accumulation was significantly driven by the interaction between vegetation and microbes (F prob ≤ 0.01). The interaction effect showed that the Napier grass treatments recorded the highest fruit dry weight (VnM0 at 12.03 g plant^{-1} and VnM1 at 10.90 g plant^{-1}). Interestingly, *Indigofera* sp. combined with microbial inoculation (ViM1) significantly improved fruit dry weight (10.97 g plant^{-1}), which was statistically comparable to the Napier grass treatments.

Overall, the continuous decomposition of high biomass from adaptive vegetation helps establish a supportive biophysical environment. This is important because pyroclastic materials

Table 11. Dry weight biomass

	Dry weight biomass (g plant^{-1})		
Stems and leaves (A)	M0	M1	Average (V)
Vn	32.11	30.95	31.53[a]
Vv	12.85	19.81	16.33[b]
Vc	8.17	12.98	10.57[c]
Vi	12.97	23.35	18.16[b]
Average (M)	16.52[b]	21.77[a]	
F prob			
Vegetation (V)			2.78×10^{-06}**
Microbes (M)			0.00643**
Interaction (V × M)			0.13508
Roots (B)	M0	M1	Average (V)
Vn	4.70	5.20	4.95[a]
Vv	4.08	2.94	3.51[b]
Vc	0.88	2.30	1.59[c]
Vi	2.11	4.10	3.11[b]
Average (M)	2.94	3.64	
F prob			
Vegetation (V)			0.000263**
Microbes (M)			0.093937
Interaction (V × M)			0.058030
Fruits (C)	M0	M1	Average (V)
Vn	12.03[a]	10.90[a]	11.47[a]
Vv	3.60[b]	5.04[b]	4.32[c]
Vc	3.93[b]	3.33[b]	3.66[c]
Vi	5.13[b]	10.97[a]	8.05[b]
Average (M)	6.17[b]	7.56[a]	
F prob			
Vegetation (V)			1.29×10^{-07}**
Microbes (M)			0.01926*
Interaction (V × M)			0.00133**
Total Biomass (A+B+C)	M0	M1	Average (V)
Vn	84.23	92.91	88.57[a]
Vv	51.33	52.49	51.91[b]
Vc	29.55	34.99	32.27[c]
Vi	38.42	72.13	55.28[b]
Average (M)	50.88[b]	63.13[a]	
F Prob			
Vegetation (V)			5.45×10^{-06}**
Microbes (M)			0.01926*
Interaction (V × M)			0.0968

Note: Vn = Napier grass, Vv = Vetiver grass, Vc = *Centrosema* sp., Vi = *Indigofera* sp., M0 = Without indigenous microbes, M1 = With indigenous microbes. The average with different letters shows significant differences with the LSD post hoc test; * = Statistically significant (F prob ≤ 0.05), ** = Highly statistically significant (F prob ≤ 0.01)

inherently lack the capacity to sustain long-term biomass accumulation on their own (Panjaitan et al., 2018; Imran et al., 2022). This gradual release of main macronutrients supports continuous vegetative and reproductive development throughout the growing season. Decomposition of Napier grass residues, in particular, provided a gradual and sustained nutrient supply, which is crucial for maintaining fertility in nutrient-poor volcanic ash soils and sustaining long-term biomass accumulation (Zergaw et al., 2023).

Crop yield

Red chili productivity ranged from 4.06 to 13.45 tons ha^{-1}. Statistical analysis revealed that the variations were driven independently by both main factors, vegetation type (F prob ≤ 0.01) and microbial inoculation (F prob ≤ 0.05), while their interaction was not significant (Table 12). The Napier grass legacy achieved the highest red chili yields, specifically in the VnM0 (13.45 tons ha^{-1}) and VnM1 (13.14 tons ha^{-1}) treatments. This productivity directly reflects the earlier observed macronutrient uptake, with Napier grass treatments consistently driving the highest N, P, and K uptake throughout the maximum vegetative and harvest periods (Tables 8, 9, and 10). Conversely, leguminous species (*Centrosema* sp. and *Indigofera* sp.) had the lowest productivity, particularly in the absence of microbial inoculation (VcM0 at 4.06 tons ha^{-1} and ViM0 at 6.04 tons ha^{-1}). However, the overall microbial treatment (M1) significantly increased average crop productivity (9.43 tons ha^{-1}) compared to the non-inoculated plots (7.72 tons ha^{-1}). This suggests that microbial inoculation provides valuable benefits in increasing crop yields.

Overall, Napier grass provided significant biophysical improvements and appropriate nutrient synchronization, specifically continuous K mobilization and targeted P availability at the harvest period. Consequently, the red chili yield under these treatments (13.14 to 13.45 tons ha^{-1}) was substantially higher than typical Indonesian field productivity, which is commonly reported at about 6 to 8 tons ha^{-1} nationally or regionally, indicating strong agronomic potential under the tested management conditions (Maintang et al., 2021; Edi et al., 2023; Winarto et al., 2024). These findings underscore that effective pyroclastic material reclamation relies heavily on fast-growing and extensive-rooting grass species capable of positive biophysical feedback loops. Notably, this biophysical amelioration conceptually mirrors the stabilization mechanisms achieved through organic amendments, such as compost and biochar. These amendments are widely documented to resolve both immediate fertility bottlenecks and long-term physical instability in degraded soils (Boni et al., 2022; Imran et al., 2022; Saputra et al., 2022).

Soil-plant nutrient coupling and yield determinants

The first 2 principal components (Dim1 and Dim2) collectively accounted for 64.2% of the total variance in the dataset (50.1% and 14.1%, respectively), thereby substantiating the efficacy of the model for data interpretation (Figure 4). The PCA biplot reveals a strong positive correlation between crop yield, dry biomass, and main macronutrients during the later phases of growth. The main macronutrients (N1, K1, P1) at the maximum vegetative period (6 WAP) and nutrient uptake during the harvest period (14 WAP) were the focal points of the study. The analysis revealed a robust correlation among the variables, with a notable positive loading on PC1. This suggests that the availability and subsequent uptake of main macronutrients during the critical transition to the harvest period are the primary drivers of red chili yield in one-year reclaimed pyroclastic materials. Initial K_{exch} (K0) exhibited a closer alignment with the yield vector, suggesting that early K reserves played a consistent role throughout the plant's life cycle.

The Pearson correlation (Figure 5) provides definitive quantitative evidence of the temporal nutrient shifts required for optimizing crop yield in pyroclastic materials. A significant positive correlation was identified between crop yield

Table 12. Crop yield

	Productivity (tons ha^{-1})		
	M0	M1	Average (V)
Vn	13.45	13.14	13.30^{a}
Vv	7.36	10.04	8.70^{b}
Vc	4.06	5.15	4.60^{c}
Vi	6.04	9.38	7.71^{b}
Average (M)	7.72^{b}	9.43^{a}	
F prob			
Vegetation (V)			7.21×10^{-06}**
Microbes (M)			0.0333*
Interaction (V × M)			0.3165

Note: Vn = Napier grass, Vv = Vetiver grass, Vc = *Centrosema* sp., Vi = *Indigofera* sp., M0 = Without indigenous microbes, M1 = With indigenous microbes. The average with different letters shows significant differences with the LSD post hoc test; * = Statistically significant (F prob ≤ 0.05), ** = Highly statistically significant (F prob ≤ 0.01)

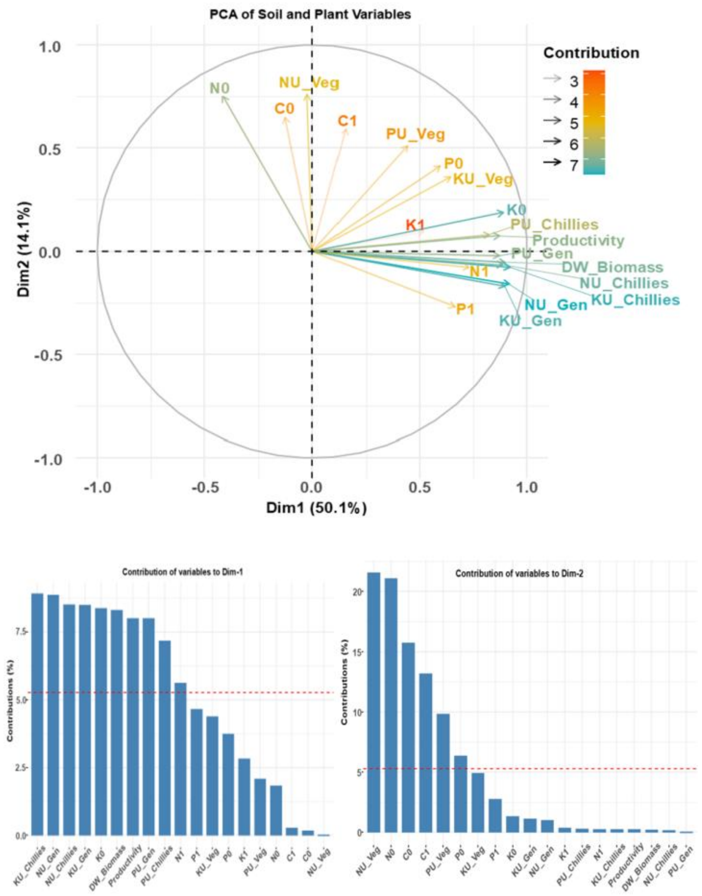

Figure 4. Principal component analysis

Note: NU = N uptake (g plant^{-1}), KU = K uptake (g plant^{-1}), PU = P uptake (g plant^{-1}), N = Total N (%), P = Available P (ppm), K = Exchangeable K (cmol kg^{-1}), DW = Dry weight (g plant^{-1}), Productivity = Crop yield (tons ha^{-1}), Veg = Maximum vegetative period at 6 WAP, Gen = Harvest period at 14 WAP

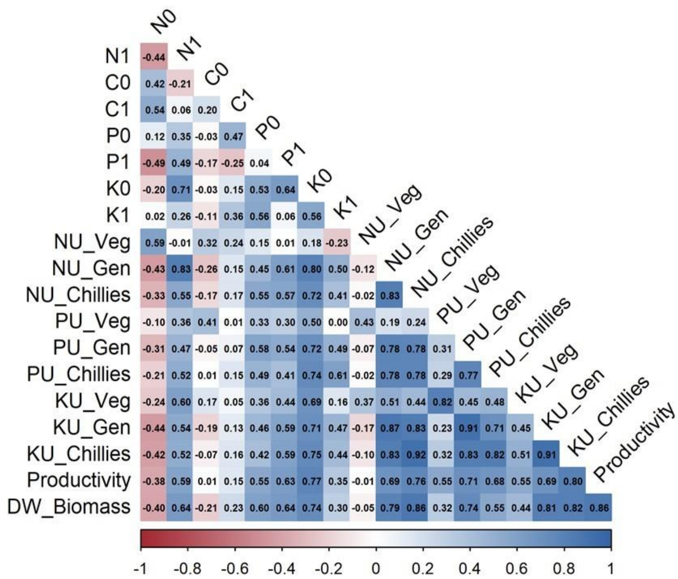

Figure 5. Pearson correlation

Note: NU = N uptake (g plant^{-1}), KU = K uptake (g plant^{-1}), PU = P uptake (g plant^{-1}), N = Total N (%), P = Available P (ppm), K = Exchangeable K (cmol kg^{-1}), DW = Dry weight (g plant^{-1}), Productivity = Crop yield (tons ha^{-1}), Veg = Maximum vegetative period at 6 WAP, Gen = Harvest period at 14 WAP and the availability of main macronutrients in pyroclastic materials at 6 WAP, particularly available P (P1, r = 0.63) and total N (N1, r = 0.59). This phenomenon is primarily driven by the crop physiological shift, as evidenced by the significant correlation between crop yield and key physiological parameters, particularly at the harvest period of K uptake (KU_Chili, r = 0.80) and N (NU_Chili, r = 0.76).

Conceptual framework of bio-reclamation of pyroclastic materials

The interactions driving post-eruption land rehabilitation are synthesized in the conceptual framework (Figure 6). A one-year reclamation process transformed the initially infertile Mount Semeru pyroclastic materials into a functional agronomic substrate. The combined use of adaptive vegetation and indigenous microbes resulted in a substantial increase in baseline fertility. Organic C increased from 0.12 to 0.15–0.60% and total N from 0.001 to 0.02–0.05%. However, the organic C and total N remained very low. Available P increased from 11.80 to 36.51–133.28 mg kg^{-1}, while exchangeable K fluctuated (0.66 to 0.17-0.59 cmol kg^{-1}). Multivariate principal component analysis (PCA) and Pearson correlation analyses (Figure 4 and Figure 5) indicate that pre-planting elemental loading does not directly determine final crop productivity. Rather, the red chili yield is influenced by the synchronizing of nutrient release and the ecological legacy established by adaptive vegetation.

This pathway of fertility improvement optimizes nutrient uptake, which directly determines the final yield. The Napier grass with indigenous microbe treatments (VnM1) produced the highest cumulative nutrient uptake, calculated as the sum of uptake at harvest period in each organ, such as stems, leaves, roots, and fruits (N = 606.88; P = 1,386.36; K = 463.17 mg plant^{-1}) and cumulative dry biomass (92.91 g plant^{-1}). The correlation matrix supports this finding, red chili yield (4.06 to 13.45 tons ha^{-1}) is highly dependent on nutrient availability (N1, P1) at maximum vegetative period (6 WAP) and nutrient uptake (NU_Gen, PU_Gen) during the harvest period (r > 0.70). Furthermore, the stabilization of exchangeable K after one year of reclamation (K0, r = 0.77) provided continuous osmotic support, maximizing the translocation of photosynthates directly into the crop yield/productivity.

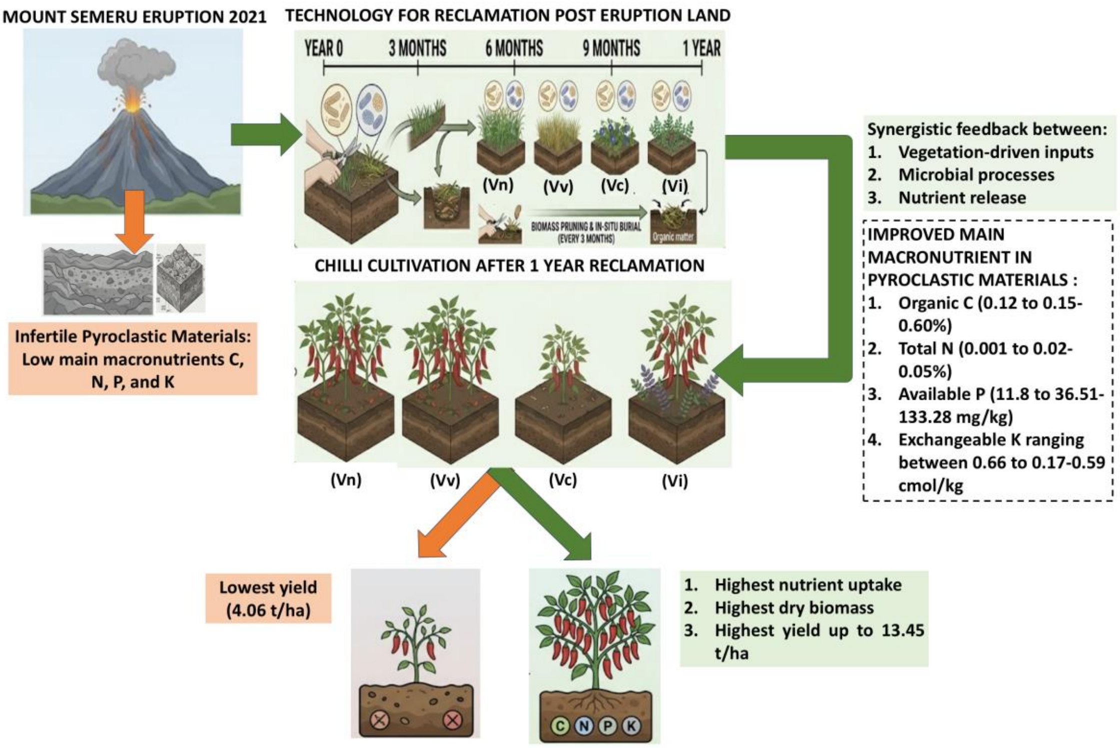

Figure 6. Conceptual framework of post-eruption land reclamation on Semeru pyroclastic materials, illustrating the bioreclamation process through vegetation-microbe synergy and its impact on macronutrient recovery and subsequent chili yield

Note: V = Napier grass, Vv = Vetiver grass, Vc = *Centrosema* sp., Vi = *Indigofera* sp., M0 = Without indigenous microbes, M1 = With indigenous microbes

The productivity of crops grown in reclaimed pyroclastic deposits is largely influenced by nutrient availability and absorption during the generative phase, which is crucial for fruit development. Initially, these soils often exhibit low fertility due to acidification, nutrient imbalances, and a lack of organic matter resulting from volcanic activity. While these conditions can hinder early growth, they do not entirely determine the potential yield (Tiimub et al., 2020; Marpaung et al., 2025). In the harvest period, it is crucial for plants to absorb nutrients, as they need sufficient amounts of N, P, K, and other essential nutrients to support the growth of their reproductive organ. Any nutrient shortages during this period are permanent and significantly affect the yield (Liu et al., 2023; Chen et al., 2025).

Instead of providing immediate but fleeting nutrient spikes, the continuous in-situ mineralization of pioneer biomass (particularly high-biomass grasses) steadily accelerates nutrient cycling and improves the physical stability of pyroclastic materials (Fiantis et al., 2019; Staudigel et al., 2025). Furthermore, studies have shown that organic amendments derived from native vegetation in reclamation phases improve soil nutrient retention, facilitating enhanced nutrient uptake during reproduction compared to initial soil conditions (Iacomino et al., 2022; Zhang et al., 2025). Therefore, soil fertility at the beginning establishes a baseline, and the synchronizing of nutrient availability and plant uptake during the maximum vegetative-to-harvest period is more decisive for crop yield in reclaimed pyroclastic materials.

CONCLUSIONS

Integrating adaptive vegetation and indigenous microbes generally improved the main macronutrients (C, N, P, and K) in the pyroclastic materials. However, despite these significant improvements, organic C (0.15 to 0.60%) and total N content (0.02 to 0.05%) across all treatments remained in a very low status. This indicates that organic C and total N content will remain a primary constraint in subsequent cropping seasons without sustained organic matter inputs. Overall, incorporating Napier grass biomass proved superior to other vegetation for enhancing chili yield (13.14 to 13.45 tons ha^{-1}). Notably, the addition of indigenous microbes provided insignificant yield advantage under the Napier grass legacy, suggesting that the high biomass input from Napier grass was sufficient to optimize the materials for chili production. *Indigofera* sp. produced the highest total N content in the pyroclastic materials and N plant uptake. On the contrary, *Centrosema* sp. exhibited the lowest agronomic performance, likely due to rapid biomass decomposition, leading to nutrient release that was unsynchronized with plant uptake. Furthermore, PCA analysis confirmed that macronutrient availability at the harvest period (14 WAP) was the primary driver of red chili yield. For post-eruption reclamation, researchers recommend prioritizing Napier grass as the primary species to accelerate the re-establishment of agricultural productivity and ensure the long-term resilience of volcanic landscapes.

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REFERENCES

Albarki, G. K., Sizilia, V. J., Kurniawan, S., Kusuma, Z., & Utami, S. R. (2025a). Temporarily degraded physical properties of pyroclastic materials from Mount Semeru: Can they be improved after reclamation with vegetation and indigenous microbes? *Journal of Degraded and Mining Lands Management*, *12*(5), 8865–8874. https://doi.org/10.15243/jdmlm.2025.125.8865

Albarki, G. K., Sizilia, V. J., Kurniawan, S., Ustiatik, R., & Utami, S. R. (2025b). Reclamation of volcanic deposits from Mt. Semeru using vegetation and indigenous microbes: Measuring vegetation growth rate and carbon increment. *IOP Conference Series: Earth and Environmental Science*, *1466*(1), 012006. https://doi.org/10.1088/1755-1315/1466/1/012006

Andrews, E. M., Kassama, S., Smith, E. E., Brown, P. H., & Khalsa, S. D. S. (2021). A review of potassium-rich crop residues used as organic matter amendments in tree crop agroecosystems. *Agriculture*, *11*(7), 580. https://doi.org/10.3390/agriculture11070580

Błońska, E., Piaszczyk, W., Staszel, K., & Lasota, J. (2021). Enzymatic activity of soils and soil organic matter stabilization as an effect of components released from the decomposition of litter. *Applied Soil Ecology*, *157*, 103723. https://doi.org/10.1016/j.apsoil.2020.103723

Boni, T., Pereira, E., Santos, A., Cassiolato, A., & Maltoni, K. (2022). Biomass residues improve soil chemical and biological properties reestablishing native species in an exposed subsoil in Brazilian Cerrado. *PLoS ONE*, *17*(6), e0270215. https://doi.org/10.1371/journal.pone.0270215

Chandra, Y. I. I., Maryanto, S., & Susilo, A. (2025). Monitoring Mount Semeru's 2021 eruption using NDVI and LST from sentinel satellite. *Jurnal Penelitian Pendidikan IPA*, *11*(4), 1203–1209. https://doi.org/10.29303/jppipa.v11i4.10605

Chen, Q., Li, X., Zhang, W., Xue, D., Sun, Q., Xing, H., ... & Wu, C. (2025). Impact of volcanic slag on cucumber yield, quality, and rhizosphere soil environment. *Plants*, *14*(9), 1328. https://doi.org/10.3390/plants14091328

Cruz, N., Avellan, A., Ruivo, L., Silva, F. C., Römkens, P. F. A. M., Tarelho, L. A. C., & Rodrigues, S. M. (2023). Biomass ash-based soil improvers: Impact of formulation and stabilization conditions on materials' properties. *Journal of Cleaner Production*, *391*, 136049. https://doi.org/10.1016/j.jclepro.2023.136049

Dou, Y., Tong, X., Horion, S., Feng, L., Fensholt, R., Shao, Q., & Tian, F. (2024). The success of ecological engineering projects on vegetation restoration in China strongly depends on climatic conditions. *Science of the Total Environment*, *915*, 170041. https://doi.org/10.1016/j.scitotenv.2024.170041

Edi, S., Syafri, Z. R., Nurhayati, N., & Meilin, A. (2023). Analysis of curly red chili farming at farmer-level in Kerinci Highland. *IOP Conference Series: Earth and Environmental Science*, *1287*(1), 012002. https://doi.org/10.1088/1755-1315/1287/1/012002

Escudey, M., Arancibia-Miranda, N., Pizarro, C., & Antilén, M. (2015). Effect of ash from forest fires on leaching in volcanic soils. *CATENA*, *135*, 383–392. https://doi.org/10.1016/j.catena.2014.08.006

Eviati, Sulaeman, Herawaty, L., Anggria, L., Usman, Tantika, H. E., … & Wuningrum, P. (2023). *Petunjuk teknis analisis kimia tanah, tanaman, air dan pupuk* (3rd ed.). Center for Soil and Fertilizer Instrument Standard Testing, Ministry of Agriculture. Retrieved from https://repository.pertanian.go.id/handle/123456789/24650

Fiantis, D., Ginting, F. I., Gusnidar, Nelson, M., & Minasny, B. (2019). Volcanic ash, insecurity for the people but securing fertile soil for the future. *Sustainability*, *11*(11), 3072. https://doi.org/10.3390/su11113072

Fiantis, D., Nelson, M., Shamshuddin, J., Goh, T. B., & Ranst, E. V. (2016). Initial carbon storage in new tephra layers of Mt. Talang in Sumatra as affected by pioneer plant. *Communications in Soil Science and Plant Analysis*, *47*(15), 1792–1812. https://doi.org/10.1080/00103624.2016.1208755

Hairiah, K., Dewi, S., Agus, F., Velarde, S., Ekadinata, A., Rahayu, S., & van Noordwijk, M. (2011). *Measuring carbon stocks across land use systems: A manual*. World Agroforestry Centre (ICRAF), SEA Regional Office. Retrieved from https://www.researchgate.net/publication/251236645_

Measuring_Carbon_stocks_across_land_use_systems_A_manual_Part_A

Hayes, M. H., & Roulia, M. (2025). Relevance of organic matter compositions, structures and associations to soil aggregates and to sustainable productivity. *Agronomy*, *15*(9), 2182. https://doi.org/10.3390/agronomy15092182

Hirzel, J., Undurraga, P., Vera, C., Matus, I., & Schoebitz, M. (2025). Chemical properties of a volcanic soil are influenced by eight years of crop rotations with different levels of residue incorporation. *Plants*, *14*(5), 764. https://doi.org/10.3390/plants14050764

Iacomino, G., Sarker, T. C., Ippolito, F., Bonanomi, G., Vinale, F., Staropoli, A., & Idbella, M. (2022). Biochar and compost application either alone or in combination affects vegetable yield in a volcanic mediterranean soil. *Agronomy*, *12*(9), 1996. https://doi.org/10.3390/agronomy12091996

Imran, A., Sardar, F., Khaliq, Z., Nawaz, M. S., Shehzad, A., Ahmad, M., ... & Mirza, M. S. (2022). Tailored bioactive compost from agri-waste improves the growth and yield of chili pepper and tomato. *Frontiers in Bioengineering and Biotechnology*, *9*, 787764. https://doi.org/10.3389/fbioe.2021.787764

Ishaq, R. M., Hairiah, K., Alfian, I., & van Noordwijk, M. (2020b). Natural regeneration after volcanic eruptions: Resilience of the non-legume nitrogen-fixing tree *Parasponia rigida*. *Frontiers in Forests and Global Change*, *3*, 562303. https://doi.org/10.3389/ffgc.2020.562303

Ishaq, R. M., Saputra, D. D., Sari, R. R., Suprayogo, D., Widianto, Prayogo, C., & Hairiah, K. (2020a). Turning volcanic ash into fertile soil: Farmers' options in coffee agroforestry after the 2014 Mount Kelud eruption. *AGRIVITA Journal of Agricultural Science*, *42*(1), 78–91. https://doi.org/10.17503/agrivita.v42i1.2494

Katayama, S., Omori, T., & Tateno, M. (2021). Fresh litter acts as a substantial phosphorus source of plant species appearing in primary succession on volcanic ash soil. *Scientific Reports*, *11*, 11497. https://doi.org/10.1038/s41598-021-91078-6

Khumaeni, A., Indriana, R. D., Jonathan, F., Fiantis, D., Ginting, F. I., Idris, N., & Kurniawan, H. (2025). Analysis of geochemical and mineral compositions of volcanic soil affected by Merapi eruption in Central Java Indonesia using laser-induced breakdown spectroscopy with calibration-free. *Talanta*, *295*, 128376. https://doi.org/10.1016/j.talanta.2025.128376

Liu, P., Zhang, T., Wang, G., Ju, J., Mao, W., & Zhao, H. (2023). Response of rice grain yield and soil fertility to fertilization management under three rice-based cropping systems in reclaimed Soil. *Agronomy*, *13*(7), 1840. https://doi.org/10.3390/agronomy13071840

Luo, S., Gao, Q., Wang, S., Tian, L., Zhou, Q., Li, X., & Tian, C. (2020). Long-term fertilization and residue return affect soil stoichiometry characteristics and labile soil organic matter fractions. *Pedosphere*, *30*(5), 703–713. https://doi.org/10.1016/s1002-0160(20)60031-5

Maintang, Ilyas, A., Nurlaila, & Nappu, M. B. (2021). Study of technology packages to support increasing production of chili pepper commodities in South Sulawesi. *IOP Conference Series: Earth and Environmental Science*, *807*(4), 042062. https://doi.org/10.1088/1755-1315/807/4/042062

Marpaung, I. S., Siagian, D. R., Napitupulu, D., Nainggolan, P., Sebayang, A., Simatupang, S., ... & Lumbantobing, S. P. (2025). Optimizing agronomic technology package for soil fertility and crop yield restoration on the affected area of Sinabung volcano eruption, Indonesia. *Landscape Online*, *100*, 1138. https://doi.org/10.3097/LO.2025.1138

McGowan, S., Procter, J., Kereszturi, G., Albino, F., & Suhendro, I. (2026). Analysis of the 4 December 2021 lahar on Mount Semeru using optical and SAR remote sensing. *International Journal of Applied Earth Observation and Geoinformation*, *146*, 105162. https://doi.org/10.1016/j.jag.2026.105162

Miao, Y., Zhou, F., Ding, S., Zhu, Z., Huo, Z., Chen, Q., & Liu, Z. (2024). Addition of high-quality plant residue alters microbial keystone taxa and network complexity and increases soil phosphorus (P) availability. *Agronomy*, *14*(12), 3036. https://doi.org/10.3390/agronomy14123036

Muñoz, G., Orlando, J., & Zuñiga-Feest, A. (2021). Plant colonizing volcanic deposits:

Root adaptations and effects on rhizosphere microorganisms. *Plant and Soil*, *461*(1), 265–279. https://doi.org/10.1007/s11104-020-04783-y

Nira, R. (2023). Gross and net nitrogen mineralization and their relationships with microbial biomass in a volcanic ash soil and alluvial soil after application of crop residues. *Communications in Soil Science and Plant Analysis*, *54*, 1459–1467. https://doi.org/10.1080/00103624.2022.2159038

Panjaitan, E., Napitupulu, N., & Afrianta, K. (2018). The effect of organic fertilizer and compost of volcanic ash on growth and yield of red chili (*Capsicum annum* L.). *IOP Conference Series: Earth and Environmental Science*, *215*(1), 012028. https://doi.org/10.1088/1755-1315/215/1/012028

Paramisparam, P., Ahmed, O. H., Omar, L., Ch'ng, H. Y., Johan, P. D., & Hamidi, N. H. (2021). Co-application of charcoal and wood ash to improve potassium availability in tropical mineral acid soils. *Agronomy*, *11*(10), 2081. https://doi.org/10.3390/agronomy11102081

Purnomo, S. (2020). Screening genetic resources of local accessions of Capsicum originated from East Java. *IOP Conference Series: Earth and Environmental Science*, *482*(1), 012047. https://doi.org/10.1088/1755-1315/482/1/012047

Rahayu, L., & Febriani, D. (2021). The efficiency of red chili farming in Merapi eruption area, Yogyakarta, Indonesia. *E3S Web of Conferences*, *232*, 01023. https://doi.org/10.1051/e3sconf/202123201023

Renwick, L. L. R., Celedón, A., Nájera, F., Fuentes Espoz, J.-P., Celedón, D., Arellano, C., & Salazar, O. (2025). Integrated crop-livestock farms have higher topsoil nitrogen and carbon than crop-only farms in Chilean Mediterranean climate volcanic soils. *Agricultural Systems*, *222*, 104172. https://doi.org/10.1016/j.agsy.2024.104172

Romadhan, P., Wisnubroto, M. P., Shodiq, M. S., & Amin, M. (2025). Comparative impact assessment of soil properties in rice fields by cold lava from Mount Marapi, West Sumatra. *Earth Systems and Environment*, *10*, 2491–2504. https://doi.org/10.1007/s41748-025-00770-4

Saputra, D., Sari, R. R., Hairiah, Widianto, Suprayogo, D., & Noordwijk, M. V. (2022). Recovery after volcanic ash deposition: Vegetation effects on soil organic carbon, soil structure and infiltration rates. *Plant and Soil*, *474*, 163–179. https://doi.org/10.1007/s11104-022-05322-7

Setiawati, T. C., Nurcholis, M., Basuki, B., Budiman, S. A., & Yudiantoro, D. F. (2024). Elemental composition and mineralogical characteristics of volcanic ash and soil affected by the eruption of Mount Semeru, East Java. *Journal of Degraded and Mining Lands Management*, *11*(3), 5741–5753. https://doi.org/10.15243/jdmlm.2024.113.5741

Sheetal, Sharma, K. C., Sharma, S., Sharma, N., Chaudhary, D. R., Manuja, S., & Sharma, A. (2024). Impact of different nutrient management strategies for nitrogen, phosphorous and potassium uptake and availability in chilli (*Capsicum annuum* var. *annuum* L.). *Asian Research Journal of Agriculture*, *17*(2), 123–133. https://doi.org/10.9734/arja/2024/v17i2430

Soong, J. L., Marañon-Jimenez, S., Cotrufo, M. F., Boeckx, P., Bodé, S., Guenet, B., ... & Janssens, I. A. (2018). Soil microbial CNP and respiration responses to organic matter and nutrient additions: Evidence from a tropical soil incubation. *Soil Biology and Biochemistry*, *122*, 141–149. https://doi.org/10.1016/j.soilbio.2018.04.011

Staudigel, H., Dahl, M. B., Tesfay, Y. B., Beil, I., Urich, T., & Kreyling, J. (2025). Tripled plant productivity and soil microbiome restructuring in a greenhouse volcanic ash fertilization experiment. *Ecosphere*, *16*(9), e70406. https://doi.org/10.1002/ecs2.70406

Štrbac, M., Manojlović, M., Ćirić, V., Đurić, S., Čabilovski, R., Petković, K., … & Vijuk, M. (2025). Fertility status and soil quality assessment of chernozem and stagnosol soils under organic farming practices. *Agronomy*, *15*(9), 2214. https://doi.org/10.3390/agronomy15092214

Suhendro, I., Gurusinga, M. A., Toramaru, A., Harijoko, A., Wibowo, H. E., Latief, G. A. E. Z., ... & Rahmawati, Z. Y. (2025). Magma ascent dynamics and transport process of the Mt. Semeru lava dome that collapsed on 4th December 2021 (East Java, Indonesia). *Journal of Volcanology and Geothermal*

Research, *467*, 108432. https://doi.org/10.1016/j.jvolgeores.2025.108432

Tampubolon, J., Nainggolan, H. L., Ginting, A., & Aritonang, J. (2017). Mount Sinabung eruption: Impact on local economy and smallholder farming in Karo Regency, North Sumatra. *IOP Conference Series: Earth and Environmental Science*, *178*(1), 012039. https://doi.org/10.1088/1755-1315/178/1/012039

Tiimub, B. M., Christophé, N., Atepre, B. A., Tiimob, R. W., Tiimob, G. L., Tiimob, E. N., ... & Agyenta, J. J. (2020). Crop production potential of reclaimed mine sites for sustainable livelihoods. *Journal of Applied Research Technology (JART)*, *1*(1), 1–15. https://doi.org/10.35912/jomaps.v1i1.1785

Ustiatik, R., Ariska, A. P., Hakim, Q. L., Wicaksono, K. S., & Utami, S. R. (2023). Volcanic deposits thickness and distance from Mt Semeru crater strongly affected phosphate solubilizing bacteria population and soil organic carbon. *Journal of Ecological Engineering*, *24*(10), 360–368. https://doi.org/10.12911/22998993/170860

Utami, S. R., Mees, F., Dumon, M., Qafoku, N. P., & Van Ranst, E. (2019b). Charge fingerprint in relation to mineralogical composition of Quaternary volcanic ash along a climatic gradient on Java Island, Indonesia. *CATENA*, *172*, 547–557. https://doi.org/10.1016/j.catena.2018.09.024

Utami, S. R., Suntari, R., Agustina, C., & Kusumarini, N. (2019a). Improving nutrient availability in pyroclastic materials from Mount Kelud using organic and inorganic amendment. *Journal of Degraded and Mining Lands Management*, *7*(1), 1987–1993. https://doi.org/10.15243/jdmlm.2019.071.1987

Utami, S. R., Agustina, C., Wicaksono, K. S., Prasojo, B. D., & Hanifa, H. (2017). Utilization of locally available organic matter to improve chemical properties of pyroclastic materials from Mt. Kelud of East Java. *Journal of Degraded and Mining Lands Management*, *4*(2), 717–721. https://doi.org/10.15243/jdmlm.2017.042.717

Winarto, B., Susila, A., Triastono, J., Pramono, J., Supriyo, A., Cempaka, I. G., … & Handayati, W. (2024). Chili growth-yield improvement under different experience-creativity farmer levels, agronomical components, and their partial economic analysis. *International Journal on Advanced Science, Engineering and Information Technology*, *14*(2), 691–698. https://doi.org/10.18517/ijaseit.14.2.18830

Yakovleva, L. V., Danilov, D., & Nikolaeva, E. A. (2020). Effect of mineral and organic fertilizers on potassium leaching in sandy loam soils. *IOP Conference Series: Materials Science and Engineering*, *828*(1), 012032. https://doi.org/10.1088/1757-899x/828/1/012032

Zergaw, Y., Kebede, T., & Berhe, D. T. (2023). Direct application of coffee pulp vermicompost produced from epigeic earthworms and its residual effect on vegetative and reproductive growth of hot pepper (*Capsicum annuum* L.). *The Scientific World Journal*, *2023*, 7366925. https://doi.org/10.1155/2023/7366925

Zhang, R., Meng, T., Sun, Z., & Liu, Z. (2025). Effects of applying different organic and inorganic soil amendments to improve the late stage of reclaimed soil from abandoned homesteads on soil nutrients and maize yield. *Frontiers in Sustainable Food Systems*, *9*, 1542710. https://doi.org/10.3389/fsufs.2025.1542710

Zhao, Y., Zhang, M., Yang, W., & Li, Y. (2019). Effects of microbial inoculants on phosphorus and potassium availability, bacterial community composition, and chili pepper growth in a calcareous soil: A greenhouse study. *Journal of Soils and Sediments*, *19*(11), 3597–3607. https://doi.org/10.1007/s11368-019-02319-1

Zhu, Y., Gao, Z., Liu, L., Li, J., Zhu, T., Ma, J., … & Duan, M. (2025). Nitrogen-fixing plants enhance soil phosphorus availability by promoting transformations among phosphorus fractions in a subtropical karst forest. *Forests*, *16*(2), 360. https://doi.org/10.3390/f16020360