JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2023, 24(10), 360–368
https://doi.org/10.12911/22998993/170860
ISSN 2299–8993, License CC-BY 4.0

Received: 2023.07.04
Accepted: 2023.08.08
Published: 2023.08.24

Volcanic Deposits Thickness and Distance from Mt Semeru Crater Strongly Affected Phosphate Solubilizing Bacteria Population and Soil Organic Carbon

Reni Ustiatik[1], Ayu Putri Ariska[2], Qo'id Luqmanul Hakim[3],
Kurniawan Sigit Wicaksono[1], Sri Rahayu Utami[1*]

[1] Soil Science Department, Faculty of Agriculture, Brawijaya University, Jl Veteran, Malang, 65145, Indonesia

[2] Study Program of Agroecotechnology, Faculty of Agriculture, Brawijaya University, Jl Veteran, Malang, 65145, Indonesia

[3] Master Program of Soil and Water Management, Faculty of Agriculture, Brawijaya University, Jl Veteran, Malang, 65145, Indonesia

* Corresponding author's e-mail: srirahayu.fp@ub.ac.id

ABSTRACT

Volcanic eruptions cause large-scale damage and leave piles of volcanic material that destroy plants, agricultural lands, animals, and soil microorganisms, decreasing soil fertility. Therefore, it is necessary to accelerate soil fertility recovery in post-volcanic eruption areas to resume agricultural activities. This study aims to elucidate the effect of volcanic deposits on soil fertility as well as explore tolerant plants and bacteria after Mt Semeru eruption. Soil, volcanic ash, and plant samples were collected from Pronojiwo Sub-regency, Lumajang Regency, East Java, Indonesia. Soil and volcanic ash chemical properties were analyzed (pH, available and total phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca) content). Bacteria were isolated and enumerated, then tested for P solubilization (PSB). The result showed that 3 months after Mt Semeru's eruption, the first succession was fern, moss, and fungi. Some local plants (banana and coconut) emerge new shoots and recover. A high total P (137.32 mg/kg) with neutral pH 6.8 was found in the volcanic ash. Total P and available P were higher at the closest distance from the crater, and soil pH controlled P availability in the soil covered with volcanic deposits. Also, the thickness and distance from the crater strongly affect organic C, which reduces the PSB population from 10^3 to 10^4 CFU/g, compared to unaffected areas. The bacteria exhibited P solubilization activities even under harsh environmental conditions. Thus, accelerating soil fertility restoration by adding organic materials and inoculating beneficial bacteria (such as PSB) in the post-eruption area is essential as the bacteria benefit both soil fertility recovery and agriculture sustainability in degraded lands (e.g., post-eruption).

Keywords: beneficial bacteria, degraded lands, pyroclastic materials, soil fertility, soil restoration.

INTRODUCTION

Indonesia lies in the Pacific Ring of Fire, which causes frequent earthquakes and many active volcanoes (Masum & Akbar 2019). From December 2021 to February 2023, Mt Semeru frequently released volcano-pyroclastic flow and ash after long dormant. Volcanic eruptions affect nearby agricultural lands, due to the damage caused by the accumulation of volcanic ash and floods (Detikcom 2021). When a volcano erupts, tons of volcanic materials (rock and ash) are released into the atmosphere, then deposited on the land surfaces leading to soil compaction, which is one of the limiting factors for plant growth (Fiantis et al. 2019).

The eruption of Mt Semeru spewed pyroclastic materials within 1–5 km that contain dangerous compounds such as hydrogen sulfide (H_2S), sulfur dioxide (SO_2), and nitrogen dioxide (Voi.id 2021). Also, volcanic ash contains toxic trace elements such as arsenic (As), cadmium (Cd), copper (Cu), cobalt (Co), chromium (Cr), and zinc

(Zn) (Lestiani et al. 2018). Besides the negative impact, pyroclastic material of volcanic eruptions is beneficial for soil fertility in the future (Fiantis et al. 2019; Smithsonian Institution 2022).

Deposited volcanic ash in the soil decreases soil quality because the accumulation of volcanic materials reduces soil water content, soil pH, organic matter, microbial biomass, and enzymatic activity, such as β-glucosidase, glycine aminopeptidase, and acid phosphatase (Berenstecher et al. 2017). Previous studies reported that the addition of fresh or decomposed organic materials accelerates post-eruption land rehabilitation because organic materials increase soil electrical conductivity (EC), organic carbon (C), total nitrogen (N), and available phosphorus (P), and maintain soil chemical properties (Utami et al. 2017; Utami et al. 2019; Ferreiro et al. 2020).

Volcanic deposits originally contained no organic C and the rapid soil organic carbon (SOC) accumulation is from lichens and tolerant vascular plants (Fiantis et al. 2019), such as pine tree (Conifer) and grass (Poaceae). The tolerant plants have been reported to be associated with plant growth-promoting microorganisms that support the plants in a new deposit, which lack soil moisture and available nutrients (Shirouzu et al. 2014; Guo et al. 2021). The association contributes to plants' adaptation and proliferation in areas close to an active volcano. Moreover, the beneficial microorganism can be used as biofertilizers to promote plant growth in degraded areas, e.g., post-volcanic eruption and heavy metals contamination more efficiently due to the microorganisms survive under unfavorable environments (Rincón-Molina et al. 2020; Ustiatik et al. 2022a).

The beneficial microorganisms exhibit particular traits related to the production of plant growth-promoting substances, such as ammonium from free N_2 in the air (free-living diazotrophic), indole acetic acid, and siderophores (Ustiatik et al. 2021a; Ustiatik et al. 2022b). After disturbances, microorganism abundance (bacteria and fungi) is higher in the rhizosphere area of pioneers (indigenous) plants in order to survive under unfavorable environments (Ustiatik et al., 2021b; Ustiatik et al., 2022a). Microorganisms require metabolite products from plants, such as polysaccharides from root exudates. In return, microorganisms provide soil nutrients for plants (Jacoby et al. 2017). The association between plant growth-promoting microorganisms and pioneer plants can accelerate soil fertility recovery after a volcanic eruption. This study aims: 1) to elucidate the effect of volcanic deposit thickness and the distance from Mt Semeru crater on soil fertility; 2) to isolate and screen tolerant plants and bacteria with P solubilizing trait after Mt Semeru eruption. Furthermore, the tolerant bacteria and plants will be beneficial for land rehabilitation after volcanic eruptions in the future.

MATERIALS AND METHODS

Study site and design

The study was conducted from March to December 2022 (3–9 months after Mt Semeru's eruption in December 2021). Soil and volcanic ash sampling were carried out in agricultural areas affected by Mt Semeru eruption, concentrated in Supiturang Village, Pronojiwo Sub-Regency, Lumajang Regency, East Java, Indonesia (Figure 1). Sampling points were determined using purposive random sampling.

The study was designed using a completely randomized factorial design with 2 factors. Factor (1) consisted of 3 distances from the crater (namely 6.5 km (J1), 8 km (J2), and 9.5 km (J3)) and factor (2) consisted of 2 thickness of volcanic ash (<20 cm (T1) and >20 cm (T2)) with 3 replications. Three sampling points were collected from unaffected areas as control (T0). At each sampling point, samples were taken from 3 different points, then composited into one sample (total 21 samples).

Soil and volcanic ash analysis

Soil and volcanic ash were analyzed for chemical properties that consisted of organic C (Walkey and Black), pH (Electrometry), available and total P (Bray I and HCl 25% extraction), calcium (Ca) and magnesium (Mg) (extracted by 1 M NH_4OAc pH 7, measured using Atomic Absorbance Spectrophotometry, Thermo-Fisher, USA).

Total and P-solubilizing bacteria enumeration and characterization

Five grams of samples (soil mixed with volcanic ash) were mixed with 45 mL of sodium chloride (NaCl) solution 0.9% (v/v). The suspensions were transferred into test tubes for serial dilution at a ratio of 1:9 (1 mL of sample suspension and 9 mL of 0.9% NaCl solution). Serial dilution was made up to 10^{-7}. An aliquot (0.1 mL) of each serial dilution (10^{-1}, 10^{-3}, 10^{-5}, and 10^{-7}) was cultured onto nutrient agar (NA: 15 g/L agar, 5 g/L NaCl, 5 g/L peptone, 2 g/L yeast extract, and 1 g/L beef extract) for total bacterial enumeration. P-solubilizing bacteria were tested using Pikovskaya medium (yeast extract 0.5 g/L, dextrose 10 g/L, $Ca_3(PO_4)_2$ 5 g/L, $(NH_4)_2SO_4$ 0.5 g/L, KCl 0.2 g/L, $MgSO_4.7H_2O$ 0.1 g/L, $MnSO_2.H_2O$ 0.0001 g/L, $FeSO_4$ 0.0001 g/L, and agar 15 g/L). Each treatment was made in triplicates. Positive results were indicated by a clear zone around the bacteria colonies. Bacteria population were enumerated according to standard plate count method (Cappuccino & Welsh 2017).

Data analysis

Statistical analysis was conducted using GenStat 12th Edition. The obtained data were subjected to a data normality test using Shapiro Wilk's test. Abnormal distribution data were subsequently transformed using square root (Sqrt) or logarithm (Log10), and then statistically analyzed using a one-way analysis of variance (ANOVA). The difference between treatment means was tested using Tukey Test at 5% significance level. Principal Component Analysis (PCA) was run to determine the principal parameters among tested soil fertility parameters strongly affected by volcanic eruption.

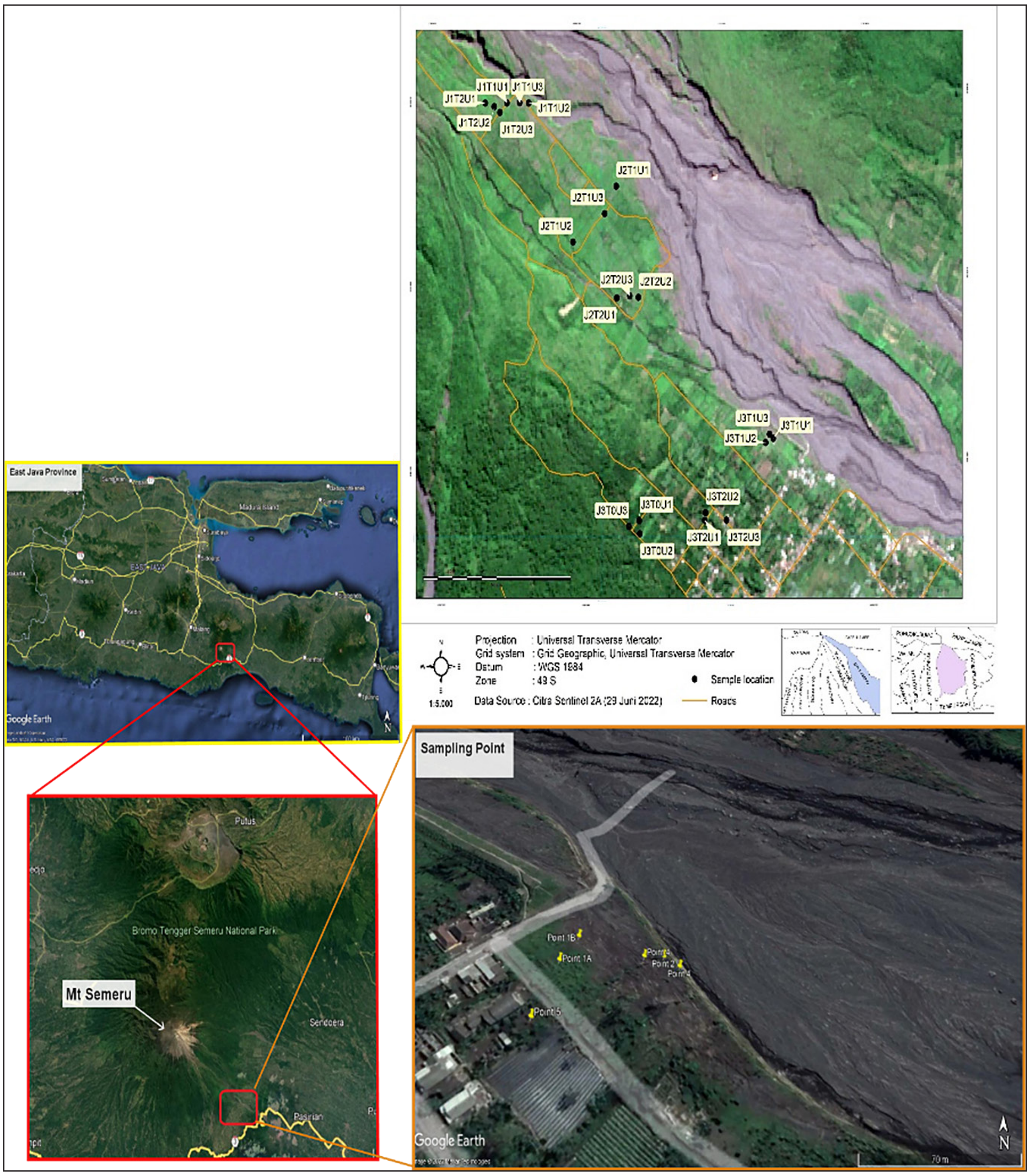


Figure 1. Soil and volcanic ash sampling site

RESULTS

Study site condition after 3 months of eruption

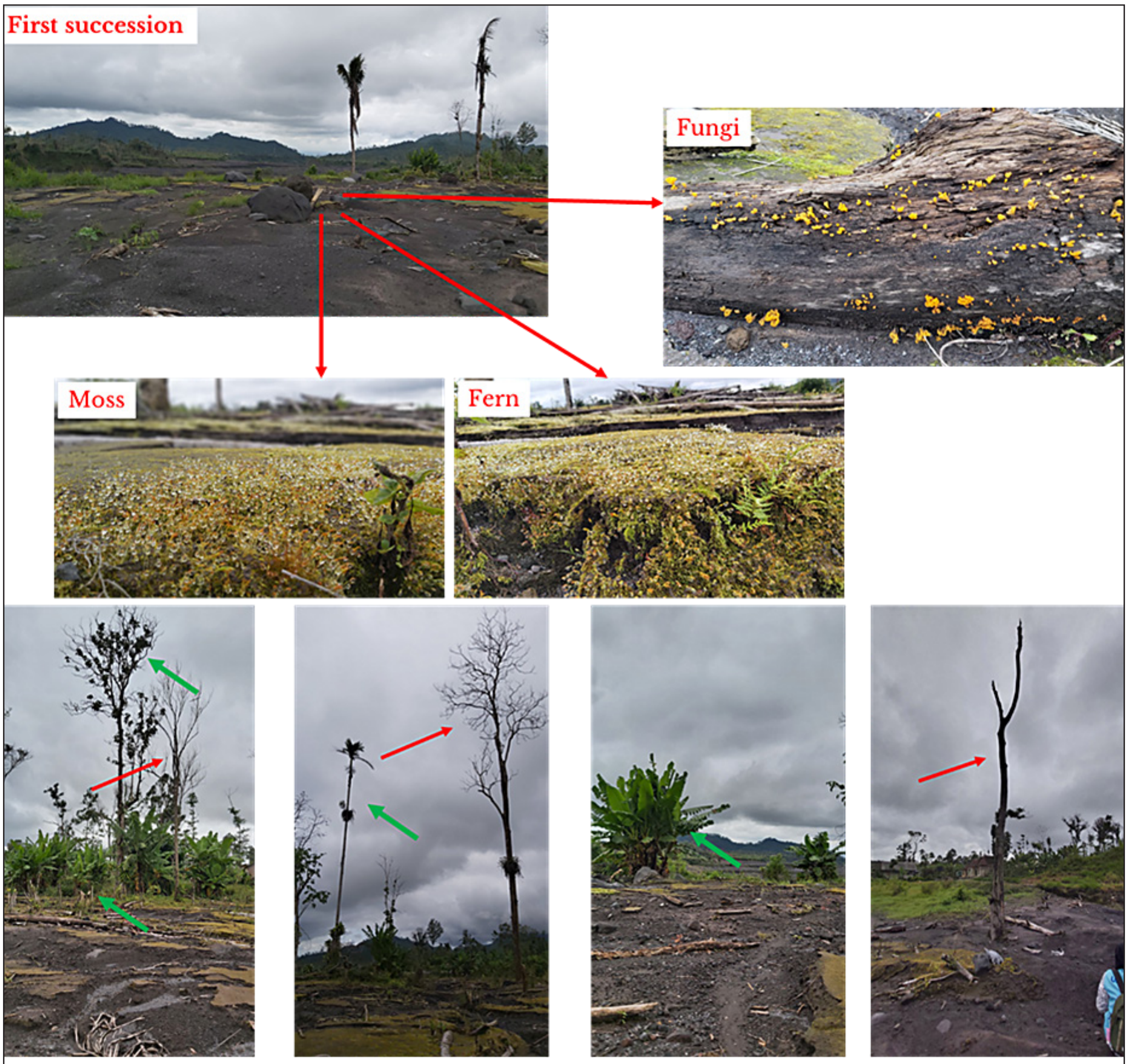
Three months after the eruption of Mt Semeru in December 2021, the first succession that grew on the study site covered with pyroclastic materials were fern, moss, and fungi that inhabited the death trees (Figure 2). Some local plants can recover, namely taro, banana, and other big trees (e.g, coconut, jack fruit, and bitter bean), by emerging new shoots and branches (Figure 2). However, some others could not survive after the volcanic eruption. The survival plants were recorded as tolerant plants. The chemical properties of the volcanic ash were high in P content with neutral pH. As per other essential macronutrients, exchangeable K, Ca, and Mg concentrations were low (Table 1).

Soil chemical properties at three different distances from Mt Semeru Crater

The chemical analysis result showed that distances from Mt Semeru crater and volcanic ash thickness significantly affected soil pH, organic C, total P, and available P ($p<0.05$) (Figures 3a-d). However, there was no significant difference in

Table 1. Chemical properties of volcanic ash

Parameters	Units	Results
pH H_2O	-	6.80
pH KCl	-	6.10
Total P	mg/kg	137.32
Exchangeable K	me/100g	0.06
Exchangeable Ca	me/100g	3.71
Exchangeable Mg	me/100g	0.30



Remarks:
Red arrow: Death plant that can not recover after the volcanic eruption
Green arrow: Plant species that can recover after the volcanic eruption

Figure 2. Primary succession and tolerant plants after Mt Semeru eruption

the total P ($p>0.05$) (Figure 3c), even though a significant difference was found in the soil available P ($p<0.05$) (Figure 3d). Soil pH after volcanic ash deposit ranged from neutral to slightly acidic. The highest total P and available P content were at the distance of 6.5 km from the crater (the closest distance in this study) and a thickness of less than 20 cm, 627.79 mg/kg and 20.61 mg/kg, respectively. The highest available P in the affected area is similar to the available P in the unaffected area (control). Also, the highest concentration of organic C was at <20 cm of the farther distance from Mt Semeru crater (9.5 km), similar to the unaffected area.

Bacteria enumeration and characterization

After the volcanic eruption, total bacteria population was significantly affected by deposits of volcanic materials. The bacteria population in the study site was in the range of 10^3–10^4 CFU/g (Figure 4). The distance from Mt Semeru crater and volcanic ash thickness significantly affected the total bacteria population ($p<0.05$), which was higher in the farther area (9.5 km) than in the closer area from Mt Semeru crater (6.5 km). Moreover, in the thicker area covered by volcanic ash, the total bacteria population was also low. However, this study highlighted that the distance

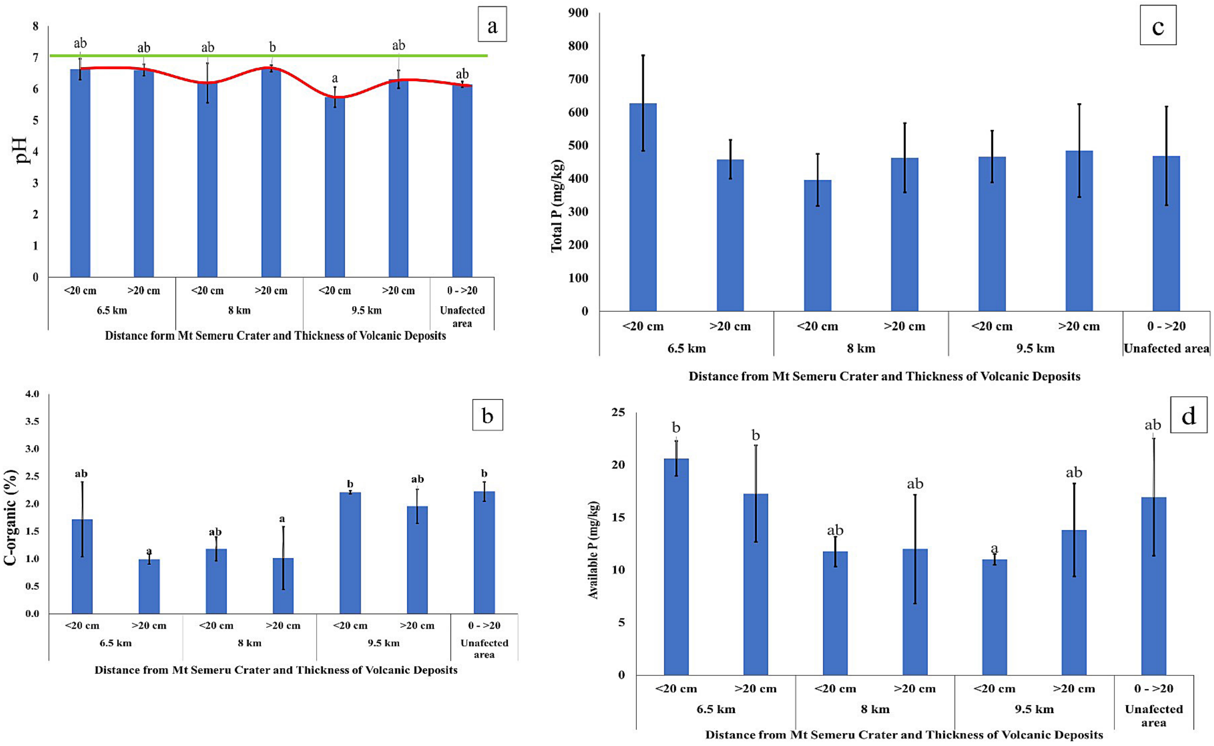


Figure 3. Soil pH (a), C-organic (b), total P (c), and available P (d) of the post-volcanic areas at three different distances from Mt Semeru crater (6.5, 8, and 9.5 km) and volcanic deposit thickness (0, <20, and >20 cm). Means with different letters are significantly different ($p<0.05$), as determined by Tukey's test

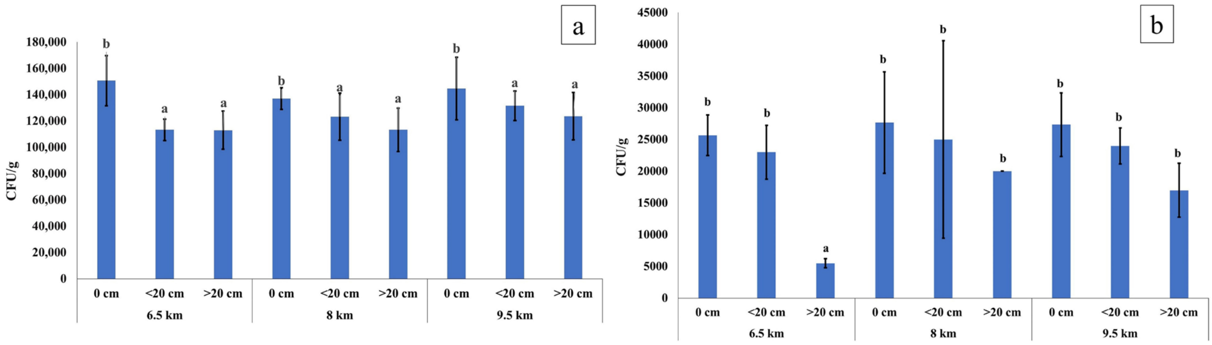


Figure 4. Enumeration of total (a) and P solubilizing bacteria (b) of the post-volcanic areas at three different distances from Mt Semeru crater (6.5, 8, and 9.5 km) and volcanic deposit thickness (0, <20, and >20 cm). Means with different letters are significantly different ($p<0.05$), as determined by Tukey's test

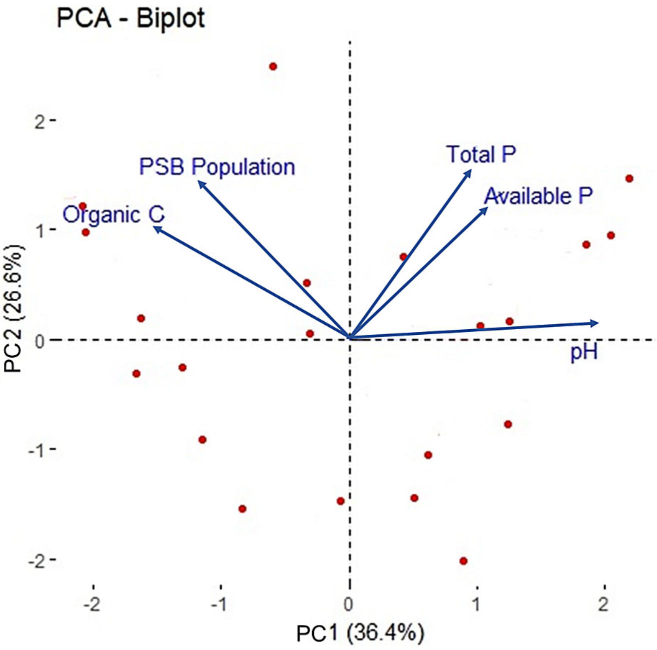


Figure 5. Biplot of principal component analysis

from Mt Semeru crater and volcanic ash thickness did not significantly affect P-solubilizing bacteria population, which the highest population found at <20 cm in a distance of 8 km (2.56×10^4 CFU/g).

Effects of distance from the crater and volcanic ash thickness on soil fertility after Mt Semeru eruption

PCA analysis showed that among measured parameters (Figure 5), P solubilizing bacteria (PSB) population and organic C were strongly affected by the thickness of volcanic deposits and the crater distance (PC2). However, soil pH was the opposite of both parameters, as the pH was lower at topsoil than subsoil at distances 8 and 9.5 km from the crater. Soil organic C was higher on topsoil than subsoil, followed by the PSB population that was in line with organic C at 3 distances from the crater. Also, total P was in line with available P as available P was higher on subsoil than topsoil at 8 and 9.5 km from the crater, but it was the opposite for the closet distance (6.5 km). Both available P and total P parameters were strongly correlated with pH (PC1). Moreover, total P, available P, and PSB population were in line at 2 distances, 8 and 9.5 km, respectively.

DISCUSSION

Three months after Mt Semeru's eruption, some pioneer plants grew and started to colonize areas covered with pyroclastic material (e.g., moss, fungi, and fern). Also, some local species recovered (e.g., banana and coconut). Bananas re-emerged through their rhizomes buried with volcanic ash and coconut trees re-grew by emerging new shoots after all the leaves were burned with hot volcanic ash. Several plants were tolerant after a volcanic eruption, such as Conifer (pine tree) and Poaceae (grass, e.g., *Miscanthus condensatus* and *Andropogon glomeratus*) that are associated with plant growth-promoting bacteria to support the plants in a new deposit which lacks available soil nutrients (Shirouzu et al. 2014; Guo et al. 2021). Fern from Pteridiceae family (*Cheilantes aemula*) is one of pioneer plants that colonized a recent deposit of pyroclastic materials (Rincón-Molina et al. 2022) and tolerate extreme environmental conditions because plant growth-promoting bacteria colonization (Rincón-Molina et al. 2020; Rincón-Molina et al. 2022). Also, the first succession on a newly exposed volcanic deposit after 3 years of Mt Merapi eruption was covered by mosses that were also colonized by Oxalobacteraceae, moss-associated bacteria (Lathifah et al. 2019). This indicates that in unfavorable environments, plants are symbiotic with microorganisms. This study found yellow fan-shaped fungi on dead trees (Figure 2). The fungus is a decomposing fungus from Dacrymycetaceae family that inhabits dead trees and litterfall (Lung & Hoang 2017). The fungus is an efficient wood decayer (Shirouzu et al. 2014). Thus, this study suggested that the fungus colonialization might accelerate organic materials decomposition to supply soil nutrients for the new ecosystem in the post-eruption areas.

After Mt Semeru eruption, the closest area to the crater was covered with thicker pyroclastic materials, mainly volcanic ash, that affected soil fertility. Soil chemical properties were strongly affected after being covered with volcanic deposits, specifically soil organic C and total P. Compared to unaffected areas, soil total P was higher and aligned with available P. The available P was strongly influenced by pH and total P from parent materials as the source of P, which was in line with volcanic ash thickness as the volcanic ash contains high P (137.32 mg/kg). However, soil pH at the unaffected and affected areas were neutral as the characteristics of the volcatic deposits is neutral. Soil pH affects P availability as pH influences the activity of phosphatases, which are enzymes that break down P-containing compounds in the soil. Phosphatases are more active in alkaline soils than in acidic soils (Margalef et al. 2017; Sun et al. 2020). This study predicted that high P content in the study area is essential for soil fertility in the future, specifically when parent materials (e.g., volcanic ash) are weathered, as P is an essential macronutrient and one of its primary sources is from parent materials (Fiantis et al. 2019).

This study highlighted that the PSB population and organic C decreased as the volcanic deposit thickened. Organic C in the affected areas was lower than in unaffected areas, low organic C was found at >20 cm due to organic materials accumulated in the topsoil before the volcanic eruption, then buried with volcanic deposits. Pristine volcanic deposits initially contain no organic carbon, then C content increase within 100 years due to organic matter accumulation in the surface horizons, up to 10% in the topsoil (Fiantis et al. 2019). In line with organic C, a low abundance of PSB was found at >20 cm as C content of soil organic matter increases soil microbes' productivity (Widdig et al. 2019; Djuuna et al. 2022). Thus, this study suggested that adding organic material in the post volcanic eruption areas is crucial as the organic material strongly influences soil properties, mainly microbial activity, in supporting soil fertility recovery.

The isolated bacteria solubilized $Ca_3(PO_4)_2$ (one of P sources) for plant growth and energy source, as P is an essential nutrient (Crowe et al., 2018). Inoculation of PSB will be beneficial for not only soil fertility recovery but also agriculture sustainability in degraded lands (e.g., post-mining and post-eruption) (Alori et al., 2017; Bai et al., 2022). Thus, the isolated bacteria are practical for accelerating soil fertility recovery in the study site. However, further studies are required to elucidate the effectiveness of these bacteria in improving soil physical, chemical, and biological properties in the field. Also, using the bioindicator method to analyze the effect of soil degradation from either natural disasters or man-made on soil properties is crucial.

CONCLUSION

Three months after Mt Semeru's eruption, fern, moss, and fungi were the first succession. Some local plants (banana and coconut) can recover by emerging new shoots. The volcanic ash contained high P (total P was 137.32 mg/kg) with neutral pH 6.8. The highest total P, in line with available P were found at the closest site to Mt Semeru's crater (6.5 km) and P availability was controlled by soil pH. The thickness and distance from the crater strongly affected organic C, which reduced PSB population. The bacteria population ranged from 10^3 to 10^4 CFU/g. The isolated bacteria exhibited P solubilization activity. These bacteria are beneficial bacteria that can survive under harsh environments and have been widely used as producers of plant growth-promoting substances and control plant pathogens. Thus, inoculating these bacteria in the post-eruption area is practical for accelerating soil fertility recovery. Also, adding organic material is crucial for faster soil fertility recovery in post-volcanic eruption areas.

Acknowledgments

The authors thank Beauty Laras Setia Pertiwi for student assistant, laboratory assistants at Brawijaya University, and field assistants at Lumajang Regency, East Java, Indonesia. This study was funded by Faculty of Agriculture, Brawijaya University, through Professor Grant Number 3454.5/UN10.F04/PN/2022.

REFERENCES

1. Alori E.T., Glick B.R. and Babalola O.O. 2017. Microbial phosphorus solubilization and its potential for use in sustainable agriculture. Frontiers in Microbiology, 8(JUN), 1–8.

2. Bai L., Yang Y., Shi Z., Zou Y., Zhou H. and Jia J. 2022. Improvement of low-fertility soils from a coal mining subsidence area by immobilized nitrogen-fixing bacteria. Processes, 10(6).
3. Berenstecher P., Gangi D., González-Arzac A., Martínez M.L., Chaves E.J., Mondino E.A. and Austin, A.T. 2017. Litter microbial and soil faunal communities stimulated in the wake of a volcanic eruption in a semi-arid woodland in Patagonia, Argentina. Functional Ecology, 31(1), 245–259.
4. Biedendieck R., Knuuti T., Moore, S.J. and Jahn, D. 2021. The "beauty in the beast"— the multiple uses of Priestia megaterium in biotechnology. 5719–5737.
5. Blake C., Christensen M.N. and Kov T. 2021. Molecular aspects of plant growth promotion and protection by *Bacillus subtilis*. 34(1), 15–25.
6. Cappuccino, J.G. and Welsh C. 2017. Microbiology: A Laboratory Manual.
7. Castro R.O., Cantero, E.V. Bucio J.L. 2008. Plant growth promotion by *Bacillus megaterium* involves cytokinin signaling. April, 263–265.
8. Crowe S.A., Antoniewicz M.R., Hinrichs K. and Maresca J.A. 2018. Diverse Sources of Phosphorus. 18(2), 656–667.
9. Detikcom. 2021. Peristiwa Pilu Erupsi Gunung Semeru di Penghujung Tahun 2021. 1–5. https://news.detik.com/berita-jawa-timur/d-5877972/peristiwa-pilu-erupsi-gunung-semeru-di-penghujung-tahun-2021/2 (in Indonesian)
10. Djuuna I .A. F., Prabawardani S. and Massora M. 2022. Population distribution of phosphate-solubilizing microorganisms in agricultural soil. Microbes and Environments, 37(1), 1–8.
11. Fiantis D., Ginting F.I., Gusnidar N.M. and Minasny B. 2019. Volcanic Ash, insecurity for the people but securing fertile soil for the future. Sustainability (Switzerland), 11(11).
12. Guo Y., Nishizawa T., Sakagami N., Fujimura R., Kamijo T. and Ohta, H. 2021. Root bacteriome of a pioneer grass Miscanthus condensatus along restored vegetation on recent Miyake-jima volcanic deposits. Rhizosphere, 19(August), 100422.
13. Hashem A., Tabassum B. and Fathi A.E. 2019. *Bacillus subtilis*: A plant-growth promoting rhizobacterium that also impacts biotic stress. Saudi Journal of Biological Sciences, 26(6), 1291–1297.
14. Jacoby R., Peukert M., Succurro A., Koprivova A. and Kopriva, S. 2017. The role of soil microorganisms in plant mineral nutrition—current knowledge and future directions. Frontiers in Plant Science, 8(September), 1–19.
15. Lathifah A.N., Guo Y., Sakagami N., Suda W., Higuchi M., Nishizawa T., Prijambada I.D. and Ohta H. 2019. Comparative characterization of bacterial communities in moss-covered and unvegetated volcanic deposits of mount Merapi, Indonesia. Microbes and Environments, 34(3), 268–277.
16. Lestiani D.D., Apryani R., Lestari L., Santoso M., Hadisantoso E.P. and Kurniawati S. 2018. Characteristics of trace elements in volcanic ash of kelud eruption in East Java, Indonesia. Indonesian Journal of Chemistry, 18(3), 457–463.
17. Lung W. and Hoang N. 2017. Survey the composition and distribution of fungi species in the natural reserve Wetland Lung Ngoc Hoang, Vietnam. Journal of Advances in Technology and Engineering Research, 3(1), 19–26.
18. Margalef O., Sardans J., Fernández-Martínez M., Molowny-Horas R., Janssens I.A., Ciais P., Goll D., Richter A., Obersteiner M., Asensio D. and Peñuelas J. 2017. Global patterns of phosphatase activity in natural soils. Scientific Reports, 7(1), 1–13.
19. Masum M. and Ali A.M. 2019. The pacific ring of fire is working as a home country of geothermal resources in the World. IOP Conference Series: Earth and Environmental Science, 249(1).
20. Rincón-Molina, Clara I., Martínez-Romero, E., Ruiz-Valdiviezo, V. M., Velázquez, E., Ruiz-Lau, N., Rogel-Hernández, M. A., Villalobos-Maldonado, J. J., & Rincón-Rosales, R. 2020. Plant growth-promoting potential of bacteria associated to pioneer plants from an active volcanic site of Chiapas (Mexico). Applied Soil Ecology, 146(October 2019), 103390. https://doi.org/10.1016/j.apsoil.2019.103390
21. Rincón-Molina C.I., Martínez-Romero E., Aguirre-Noyola J.L., Manzano-Gómez L.A., Zenteno-Rojas A., Rogel M.A., Rincón-Molina F.A., Ruíz-Valdiviezo V.M. and Rincón-Rosales R. 2022. Bacterial community with plant growth-promoting potential associated to pioneer plants from an active mexican volcanic complex. Microorganisms, 10(8).
22. Shirouzu T., Osono T. and Hirose D. 2014. Resource utilization of wood decomposers: Mycelium nuclear phases and host tree species affect wood decomposition by Dacrymycetes. Fungal Ecology, 9(1), 11–16.
23. Smithsonian Institution. 2022. Semeru. Global Volcanism Program. https://volcano.si.edu/volcano.cfm?vn=263300
24. Sun Y., Goll D.S., Ciais P., Peng S., Margalef O., Asensio D., Sardans J. and Peñuelas J. 2020. Spatial pattern and environmental drivers of acid phosphatase activity in Europe. Frontiers in Big Data, 2(January), 1–13.
25. Utami, S.R., Agustina C., Wicaksono K.S., Prasojo, B.D. and 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.

26. Ustiatik R., Nuraini Y., Suharjono and Handayanto E. 2021a. Isolation of mercury-resistant endophytic and rhizosphere microorganisms from grasses in abandoned gold mining area. Jurnal Agronomi Indonesia (Indonesian Journal of Agronomy), 49(1), 97–104.
27. Ustiatik R., Nuraini Y., Suharjono and Handayanto E. 2021b. Siderophore Production of the Hg-Resistant Endophytic Bacteria Isolated from Local Grass in the Hg-Contaminated Soil. Journal of Ecological Engineering, 22(5), 129–138. https://doi.org/10.12911/22998993/135861
28. Ustiatik R., Nuraini Y., Suharjono S., Jeyakumar P., Anderson C.W.N. and Handayanto E. 2022a. Endophytic bacteria promote biomass production and mercury-bioaccumulation of Bermuda grass and Indian goosegrass. International Journal of Phytoremediation, 24(11), 1184–1192. https://doi.org/10.1080/15226514.2021.2023461
29. Ustiatik R., Nuraini Y., Suharjono S., Jeyakumar P., Anderson C.W.N. and Handayanto E. 2022b. Mercury resistance and plant growth promoting traits of endophytic bacteria isolated from mercury-contaminated soil. Bioremediation Journal, 26(3), 208–227.
30. Utami S.R., Suntari R., Agustina C. and Kusumarini N. 2019. Improving nutrient availability in pyroclastic materials from Mount Kelud using organic and inorganic amendments. J. Degrade. Min. Land Manage, 7(1), 1987–1993.
31. Voi.id. 2021. Know the Dangers of Volcanic Materials when Mount Semeru Erupts. 9–12.
32. Widdig M., Schleuss P.M., Weig A.R., Guhr A., Biederman L.A., Borer E.T., Crawley M.J., Kirkman K.P., Seabloom E.W., Wragg P.D. and Spohn M. 2019. Nitrogen and phosphorus additions alter the abundance of phosphorus-solubilizing bacteria and phosphatase activity in grassland soils. Frontiers in Environmental Science, 7(Nov.), 1–15.