Mineralogical properties of pyroclastic materials from Mount Merapi, Indonesia

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Abstract. Mount Merapi, located in Indonesia, is known as one of the most active volcanoes globally, often resulting in volcanic eruptions that produce pyroclastic materials. These materials from Mount Merapi's eruptions have the potential to influence soil fertility in areas affected by the volcanic activities. This study aims to analyze the mineralogical properties of pyroclastic materials from Mount Merapi. The methodology involves collecting pyroclastic material samples from the 2010 eruption of Mount Merapi, followed by analysis using various mineralogical techniques such as polarized microscopy, X-ray diffraction, petrographic analysis, and wet chemical analysis. The findings offer detailed insights into the mineral composition, types of clay minerals, overall elemental presence, and the rock types forming these minerals in the pyroclastic materials. Variations in mineral composition are observed in the pyroclastic materials from Mount Merapi. Predominant minerals, including the plagioclase, pyroxene, and hornblende groups, are distinctly identified. These minerals' presence suggests their susceptibility to weathering, categorized as easily weatherable minerals. This tendency for weathering is shown by the presence of elements like Na, Ca, and Mg in these minerals, which are crucial macro-nutrients for plant growth.

1 Introduction

Indonesia, with its 127 active volcanoes distributed across the islands of Sumatra, Java, Nusa Tenggara, Sulawesi, Maluku, and North Maluku, stands unique for its volcanic abundance. These volcanoes are part of the Pacific Ring of Fire, a global region noted for frequent major earthquakes and numerous volcanoes. Amongst these, Mount Merapi in Java Island is particularly noteworthy for being one of the most active and relatively young volcanoes. Its primary hazard is pyroclastic flows, and it is located administratively within Central Java Province and the Yogyakarta Special Region. Mount Merapi, a strato-volcano, contains andesitic-basaltic magma and stands at an elevation of 2978 meters, with a diameter of 28

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km, covering an area of 300-400 km^2, and a volume of 150 km^3. It exhibits a regular eruption pattern, with an average frequency of every 2-5 years, as documented by [1].

Mount Merapi's eruption history reveals two primary patterns [2-3]. The first is the effusive eruption, characterized by the formation of a lava dome and occurring approximately every 4-6 years, leading to pyroclastic flows known as "Merapi-type nuees ardentes". The second pattern involves explosive eruptions that cause material collapses and pyroclastic flows extending up to 10-15 km from the summit.

The role of pyroclastics in soil formation and weathering processes is well-recognized. Post-eruption, the deposition of pyroclastic material marks the inception of soil genesis, altering the elemental composition and mineralogy of both the volcanic material and the underlying soil [4-5]. The addition of fresh pyroclastics not only rejuvenates the soil and sustains productivity but also mitigates soil erosion or degradation [6]. These deposits provide an ideal medium for plant growth, offering physical support, essential nutrients, and available water [7]. Additionally, in arid regions, pyroclastics can act as mulch to conserve water [8].

The eruption of Mount Merapi, while having adverse effects on the community, also offers significant benefits, such as enhancing soil quality. During an eruption, the soil undergoes a rejuvenation process, enriched with nutrient-rich materials, leading to re-fertilization. Following the passage of pyroclastic flows, the soil begins initial reforming through the decomposition of elements and minerals present within. Pyroclastic materials create an environment conducive to plant growth by providing essential nutrients through their mineral content [3]. Volcanic materials from eruptions typically contain numerous primary minerals that can act as nutrient sources for plants. The decomposition rate of these primary minerals into plant-usable forms is largely determined by their constituent cations and anions. Weatherable primary minerals are often identified by their high content of alkali and alkaline earth metals, such as sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg) [9].

Plants generally require at least 17 nutrient types throughout their life cycle. Of these, nine are macro-nutrients found in plant tissues, each constituting more than 0.1% of the dry weight. These include carbon (C), hydrogen (H), oxygen (O), nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), and sulfur (S). Additionally, there are eight micronutrients, each present in levels below 100 micrograms per gram of dry weight, namely boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn) [10]. Beyond macro and micronutrients, certain elements are categorized as 'beneficial,' including cobalt (Co), sodium (Na), and silicon (Si). Plants obtain essential nutrients like carbon (C), hydrogen (H), and oxygen (O) through photosynthesis, utilizing carbon dioxide (CO_2), water (H_2O), and organic matter.

Ferromagnesian silicate aluminosilicate minerals, along with other minerals found in rocks, are key sources of essential nutrients [11]. Macronutrients, such as potassium, predominantly derive from mineral or rock sources. Notably, potassium is sourced from minerals like feldspar, lava, granite, diorite, diabase, basalt, and volcanic ash, among other rock-based minerals [12-16]. Moreover, minerals such as basalt, diabase, phonolite, and lava are identified as sources of Ca, Mg, and Fe [13]. Granite, diabase, basalt, and volcanic ash also serve as sources of Ca, Mg, and P [14]. Furthermore, minerals like gneiss, syenite, and amphibole are recognized for their Mg content. Research has shown that these rock minerals are vital sources of micronutrients essential for plant growth [13-14]. The group of primary weatherable minerals, characterized by a dominant presence of alkali and alkaline earth metals such as Na, K, Ca, and Mg, contributes significantly to nutrient enrichment in soils. These minerals are often found in material from volcanic eruptions. Analyzing the mineral content of pyroclastic material is essential to determine the composition of primary minerals from Mount Merapi's 2010 eruption. This study aims to analyze the mineralogical properties of pyroclastic materials from Mount Merapi, providing an overview of the potential nutrients available to plants.

2 Methods

2.1 Study area

The study focused on collecting pyroclastic material, specifically sand-like deposits found from the surface to a depth of 5 cm, at Mount Merapi in Yogyakarta. The sampling site was geographically located at coordinates 7°32.5' N and 110°26.5' E. This area was significantly impacted by the substantial eruption of Mount Merapi in 2010, which resulted in the expulsion of voluminous pyroclastic materials. The 2010 eruption was a pivotal event, profoundly influencing soil development and landscape alteration in the region. The emitted pyroclastic deposits played a critical role in the geomorphological and pedological changes, making it a key area of interest for understanding the effects of volcanic activity on soil characteristics and mineral composition.

2.2 Data and analysis

The methodology for mineral analysis in this study involves three distinct techniques: polarization microscopy, X-Ray Diffraction (XRD), and petrographic analysis.

2.2.1 Polarization Microscopy Analysis

The objective of the mineral type analysis in the sand fraction is to quantify the weatherable mineral content in pyroclastic materials, pivotal for acting as a reservoir of plant nutrient reserves. Employing a polarizing microscope, this analysis involves two primary stages: the separation of the sand fraction and the identification of various mineral types.

In the sand fraction analysis, the core principle is the removal of cementing substances that surround or adhere to the sand grains, facilitating the segregation of sand, silt, and clay-sized mineral grains. Once the mineral grains are isolated, the sand fraction undergoes separation using a sieve with mesh sizes ranging from 1 to 0.05 mm. The analysis is generally categorized into two types: heavy fraction and total fraction. The heavy fraction sand mineral analysis necessitates the initial separation of the denser sand fraction from the lighter one. This heavier fraction includes minerals that sink in a bromoform solution with a specific gravity of 2.87. Conversely, the total fraction sand mineral analysis involves a direct examination of the sieved materials.

For the identification of sand minerals, essential tools include a glass plate measuring 2.5 cm x 5 cm, liquid nitro benzene, and a polarizing microscope. The process begins with evenly distributing sand grains on the glass plate, followed by the addition and mixing of nitro benzene to ensure no sand remains afloat. The prepared slide is then placed under the microscope for detailed observation. The "line counting" method is applied, focusing on counting only those sand minerals situated along a horizontal line within the microscope's field of view. In standard analysis practices, the count is conducted up to 100 grains, providing a comprehensive understanding of the mineral composition within the sand fraction of pyroclastic materials.

2.2.2 X-Ray diffraction analysis

The objective of clay mineral analysis using X-Ray Diffraction (XRD) is to discern the various types of clay minerals present in pyroclastic materials. This information is vital for assessing the ease of tillage and the efficacy of fertilizers. The analysis process encompasses two key steps: the separation of the clay fraction and the identification of clay minerals.

The separation of the clay fraction involves removing larger particles and cementitious materials, thus isolating the clay from the dust and sand fractions. This process can utilize the same sample as the one used for the sand fraction analysis, facilitating simultaneous iron and carbonate elimination. The separation technique mirrors that of texture fractionation, primarily based on sedimentation principles.

For the identification phase, an X-ray diffractometer (XRD) is employed. Preparation begins with the sedimentation of the clay fraction onto a ceramic plate. Subsequently, the sample undergoes saturation with various agents like Mg^{2+}, Mg^{2+} with glycerol, K^{+}, and K^{+}, followed by heating at 550°C for an hour. This saturation is important for determining the mineral type present in the pyroclastic material, specifically distinguishing between 1:1 and 2:1 mineral types. The principle of XRD analysis lies in capturing and displaying the reflection patterns of X-rays off the crystal lattice, typically visualized as a graph. This graph is then analyzed to ascertain the presence and proportionate composition of clay minerals.

2.2.3 Petrographic analysis

Petrographic analysis is a specialized petrological technique that involves the microscopic examination of thin rock sections using a polarizing microscope. The primary goals of this observation are to determine the mineral composition, assess rock texture, investigate the optical properties of minerals, and gather other microscopic data, all of which contribute to enhanced accuracy in rock identification. This analysis aims to identify the mineral composition of rocks, classify rock types, and assign appropriate rock names, thereby providing a comprehensive understanding of the geological and mineralogical characteristics of the studied samples.

3 Results and discussions

3.1 Polarization microscopy

Based on observations using a polarizing microscope, the mineral composition within the sand fraction is detailed in Table 1. The predominant mineral identified is Augite, constituting 50% of the sample, followed by Amphibole/hornblende and Hypersthene.

Table 1. Mineral observation results of sand fraction.

No.	Name of Mineral	Opportunity Found	
		Times	Percentages
1	Augite	51	51%
2	Amphibole/Hornblende	27	27%
3	Hypersthene	19	19%
5	Lava encased mass	3	3%
Total minerals		100	100%

Source: Observations using a polarizing microscope 2023

Augite, a member of the pyroxene mineral group, is chemically represented as (Ca, Na)(Mg, Fe, Al, Ti)(Si, Al)$2O_6$. This mineral exhibits distinct optical properties, appearing translucent in various colors like brown, green, or black when exposed to light. Augite is typically found in mafic and intermediate igneous rocks such as andesite, basalt, diorite, and gabbro. On the other hand, Amphibole minerals belong to a group of silicate minerals forming prismatic or needle-like crystals, predominantly dark green to black in color. The chemical formula for Amphibole minerals is $(Ca,Na,K)_{2,3}(Mg,Fe,Al)_5(OH)_2[(Si,Al)_4O_{11}]_2$, indicating their presence in a variety of igneous and metamorphic rocks. Hypersthene, composed of $(Mg, Fe)SiO_3$, adds to the mineral diversity. The chemical compositions of these minerals highlight their potential to contribute essential macro-nutrients such as Ca, Mg, and K, as well as micro-nutrients including Na, Al, Fe, and Si, thereby underscoring their significance in geological and agronomic contexts.

3.2 X-Ray diffraction

The results from the X-Ray Diffraction analysis, as shown in Table 2 and Figure 1, offer an in-depth view, along with the chemical formulas of the minerals present in the pyroclastic materials from Mount Merapi, Yogyakarta. The data reveals the presence of primary, easily weathered minerals, notably Albite (81.3%), Augite (15.5%), and Magnetite (3.2%). The composition of these primary minerals is important for soil management strategies.

The composition and interplay of various primary minerals serve as indicators of potential nutrient reserves in the soil. Soils enriched with easily weatherable minerals typically have higher nutrient reserves. In contrast, soils dominated by resistant minerals often indicate lower nutrient reserves. According to the mineral percentage data, the majority, at 96.8%, consists of primary weatherable minerals, predominantly Albite and Magnetite, while the resistant minerals, mainly Magnetite, account for approximately 3.2%. This distribution highlights the potential for nutrient availability in the soil and informs the management and sustainability of the land.

3.3 Petrographic

The petrographic analysis results reveal that the rock type present in the pyroclastic material from Mount Merapi's 2010 eruption is andesite. Andesite rock typically contains SiO2 ranging from 52% to 63%. The SiO2 content is indicative of the rock's susceptibility to weathering; higher SiO_2 levels correlate with increased resistance to weathering, while lower SiO_2 content implies greater ease of weathering. According to its SiO_2 percentage, andesite is classified as having an intermediate level of weatherability.

Table 2. Results of XRD analysis.

Sample ID	Mineral Phase identification	Mineral Chemical Formula	Quantitative analysis (%)	Error of fit (%)
Pyroclastic sands	Albite	$NaAlSiO_8$	81.3	1.14
	Augite	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$	15.5	1.14
	Magnetite	Fe_3O_4	3.2	0.35

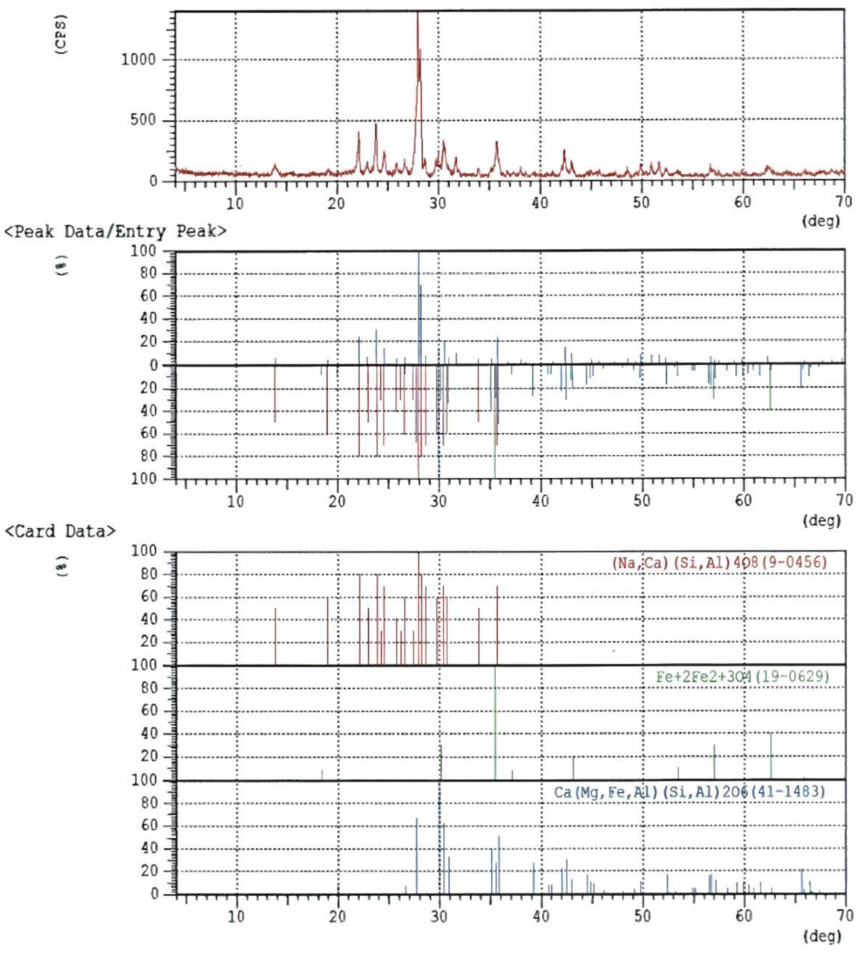

Fig. 1. Peak graph of X-Ray diffraction analysis.

Soils derived from andesitic-basaltic materials predominantly feature mineral associations that include hypersthene, augite, amphibole, intermediate plagioclase, volcanic glass, andesine, and labradorite. Unlike soils originating from purely andesitic parent material, those from andesitic-basaltic sources have a higher concentration of augite minerals (from the pyroxene group) compared to amphibole minerals. This primary mineral composition suggests two key aspects: (1) the mineral association points to an intermediate nature of the parent material, and (2) the prevalence of pyroxene (hypersthene and augite) and amphibole mineral groups indicates the presence of ferromagnesian minerals. These minerals, being easily weathered, contain iron (Fe), calcium (Ca), and magnesium (Mg). In this context, the andesitic-basaltic parent material has a higher Ca content compared to purely andesitic parent material, as noted in [17]. This composition has implications for the nutrient availability and soil management practices in areas impacted by volcanic activity.

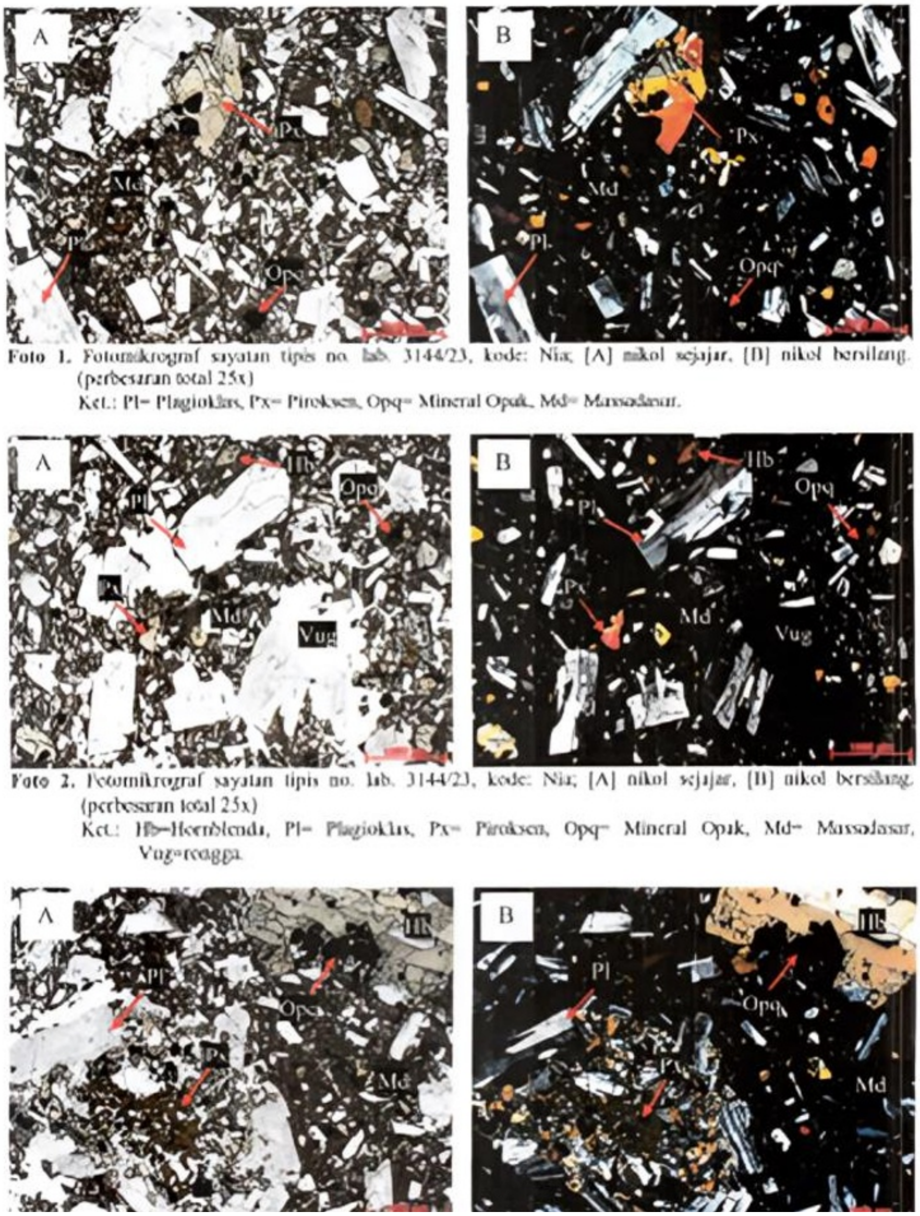

Fig. 2. Lab. number thin section photomicrograph, 3144/23. [A] aligned niches, [B] crossed niches (total magnification 25x). Caption: Hb=Hornblende, Pl=Plagioclase, Px=Piroxene, Opq=Opaque mineral, Md=Massadar. Name of Rock: Andesite.

4 Conclusion

The findings from this research clearly demonstrate that the pyroclastic material from Mount Merapi predominantly consists of easily weathered minerals, particularly albite and augite. Given the chemical composition of these minerals, they are likely to contribute essential macro elements such as Ca, Mg, and K to the soil, thereby enhancing its fertility. The presence of these minerals in the pyroclastic material can be a key indicator of the availability of abundant nutrients. Consequently, when undertaking agricultural activities in the vicinity of Mount Merapi, there may be a reduced need for extensive fertilization. Instead, introducing elements that promote the weathering of these existing minerals could be an effective strategy to release their nutrient content for plant growth.

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References

1. Pusat Vulkanologi dan Mitigasi Bencana Geologi, *Balai Penyelidikan dan Pengembangan Teknologi Kegunungapian* (2006)
2. B. Santoso, A., Philippe L., Sapari, D., Sri S.,Phillippe J., Jean- Philippe, M. J. jvolgores. **261**, 153-170 (2013)
3. D. Fiantis, M. Nelson, V. Ranst, E., J. Shamshuddin, N.P. Qafoku, M. Sci. **6**, 240-254 (2009)
4. S. Shoji, M. Nanzyo, R. A. Dahlgren. (Elsevier, Amsterdam, the Netherlands 1993)
5. R. Dahlgren, M. Saigusa, F. C. Ugolini. J. Advan. in Agronomy, Academic Press. **82**, 113-182 (2004)
6. F. Ugolini, A. Dahlgren. J. Glob. Environ. Resea. **6**, 69-81 (2003)
7. S. Shoji, T. Takahashi. J. G. Environ. Resour. **6**, 113-135 (2003)
8. M. Tejedor, C. J. F. Díaz. Geoderma. **117**, 283-295 (2003)
9. L. R. Aini, M. Mulyono, E. Hasanuddin. J. Agro Sci. **4**, 84-94 (2016)
10. Welch, R. M. Crit Rev Plant Sci. **49**, 82 (1995)
11. A. Harley, R. Gilkes. Nut. Cyc. Agr. **56**, 11 – 36 (2000)
12. S. Scovino, J., I., D. Rowell. Fert. Res. 1**7**, 71 – 83 (1988)
13. V. Fragstein, P. W. Perlt, H. Vogtmann. J. Pflanzenernaehr Bodenk **151**, 141 – 146 (1988)
14. W.E.H. Blum, B. Herbinger, A. Mentler, F. Ottner, M. Pollack, E. Unger, W.W. Wenzel. Z Pflanzenernaehr Bodenk. **152**, 421 – 425 (1989)
15. C. Coroneos, P. Hinsinger and R.J. Gilkes. Fertilizer Res. **45**, 143 – 152 (1996)
16. P. Hinsinger, M.D.A. Bolland, R.J. Gilkes. Fertilizer Res. **45**, 69 – 79 (1996)
17. S. Purwanto, A. G. Rachmat, J. Sukarman. J. SDL. **12**, 83-98 (2019)