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Research Article

Towards a Geobotanical Insight into Vegetation Adaptation in Quaternary Mud Volcanoes: Java Island, Indonesia

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Abstract
Since the Lusi eruption in 2006, interest in studying mud volcanoes in Indonesia has significantly increased, with most research focusing on the onshore Northeast Java Basin (Kendeng and Rembang Zone), yet comprehensive studies on the vegetation surrounding these mud volcanoes, particularly from a geobotanical perspective, are lacking. This study aims to document and analyze the vegetation around various 18 mud volcanoes in Java Island, Indonesia and explore its relationship with the geological characteristics of the volcanoes. Through field mapping and site visits to all identified 18 mud volcanoes on Java and Madura Island, samples of mud and vegetation were collected for detailed laboratory analysis. By examining the vegetation that grows at the center and the periphery of the mud volcanoes, a relationship between vegetation composition and the mud volcanoes in Java Island, Indonesia, can be identified. It becomes more interesting as saline substrates play a key role in their adaptation. The vegetation surrounding quaternary mud volcanoes in Java Island is significantly influenced by the characteristics of the erupted mud material. Plants from the families Poaceae, Fabaceae, Asteraceae, Cyperaceae, and Euphorbiaceae are well-adapted to the vicinity of mud volcanoes in both the Kendeng zone, rich in marl from the Kalibeng formation, and the Rembang zone, rich in clay. These plants can thrive and adapt to substrates with distinctive chemical characteristics, such as high salinity levels (>10%) and dominant calcium and magnesium content (30–60%). This research indicates a complex interplay between geological factors and plant species distribution in the unique environment of mud volcanoes. This research is expected to inspire further studies on this unique geological feature and advance the field of geobotanical study.

Keywords: geology, mud volcano, salse, geobotany

1. INTRODUCTION

This paper focuses on 18 mud volcano locations in East Java, visited during geological field mapping. The study of vegetation in Indonesian mud volcanoes is currently rare, with the only significant analysis being the impact of the Sidoarjo mud eruption (Lusi) on local vegetation [1]. That study found that at least 11 species of vegetation grow around the mud-affected areas. Research on vegetation in mud volcanoes dates back to at least 1962 when a study examined the vegetation in the Andaman mud volcanoes [2]-[4]. Other researchers have since studied vegetation and soil formation during mud volcano eruptions in Russia [5]-[7], North-East Borneo [8][9], and Azerbaijan [10][11]. Earlier studies integrated the chemical composition of the mud into the analysis of nearby vegetation [9]. The field of study, known as geobotany, focuses on the relationship between plants and their geological environment. Geobotany examines how different types of soils, rocks, and other geological factors influence plant distribution, growth, and adaptation [12][13]. It combines elements of geology and botany to understand how vegetation is affected by the earth's surface and subsurface conditions. In this study, we study this analysis to the surface of mud volcanoes in the Java Island region.

In addition to the mud volcanoes studied, other similarity occurrences have been identified in regions such as Nusa Tenggara Timur (including Sabu Island, Semau Island, Pariti, Napan, and Masin Lulik), East Kalimantan (Batu Putih - Samarinda), Maluku (Babar Island), and potentially unexplored areas in Papua. Despite the widespread distribution of mud volcanoes across Indonesia, the majority of documented cases are concentrated on Java and Madura Islands. Understanding the vegetation in Java and Madura mud volcanoes is essential to interpreting their activities. This research is an exploratory study of the vegetation composition associated with characteristics of Indonesian mud volcanoes, focusing on the onshore areas of the North East Java Basin and the Kendeng Basin [14]-[16]. These regions have been of particular interest since the Lusi eruption in 2006.

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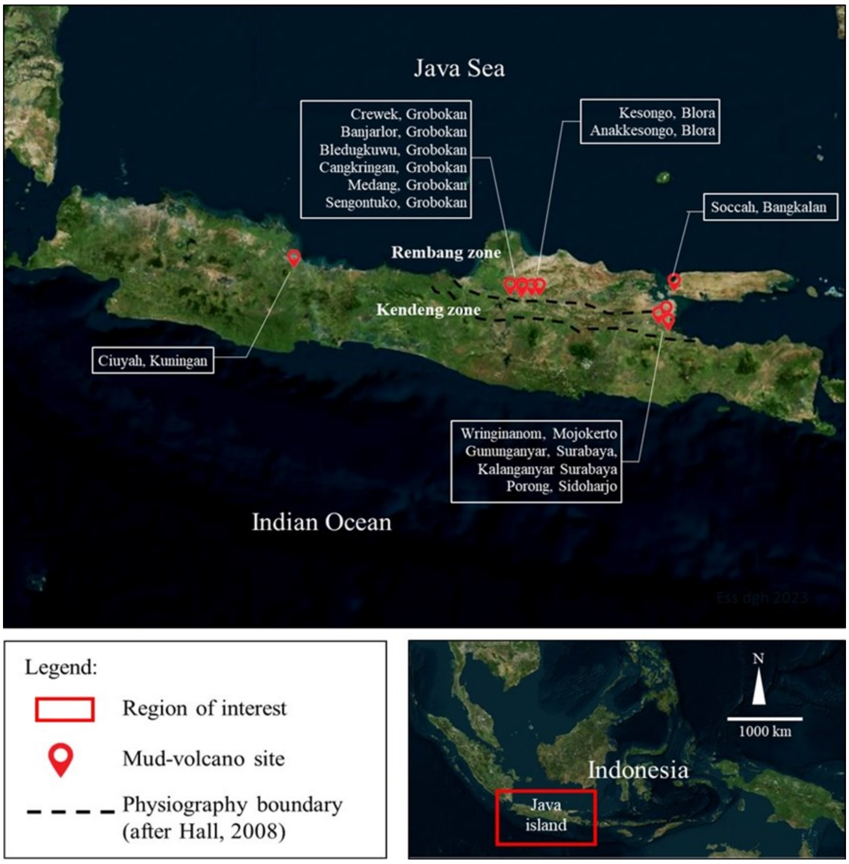

Figure 1. Distribution of identified active Quaternary mud volcanoes in Java and their position relative to physiographic zones in which study areas are located in the red box.

The geological observation and field visit study were conducted from April to June 2022. The prevalence of mud volcanoes in these areas makes the investigation of their associated vegetation and eruptive activity particularly important (Figure 1).

Research on the vegetation diversity of Indonesian mud volcanoes has been limited [17]. This study aims to document and analyze the vegetation around various mud volcanoes in Indonesia and explore its relationship with the geological characteristics of the volcanoes, offering a novel perspective that can serve as a reference for future research. All identified mud volcano sites in this study were known active during the Quaternary period. The mud material produced from these sites exhibits similar characteristics, reflecting their occurrence in Java Island. The study of 18 mud volcanoes hopefully can identify trends of similar geobotanical characteristics. The geobotanical study comprehensively examines the relationship between the distribution of vegetation and the properties of substrates formed by a series of geological processes, such as the mud material from each mud volcano site. Unfortunately, to date, there has been limited research conducted on this topic in Java Island.

2. MATERIALS AND METHODS

2.1. Geological Setting

The mud volcanoes in these regions are predominantly located within the Kendeng and Rembang zones, as indicated by the physiographic zone [15][18]. The active Kendeng Thrust Fault demarcates the boundary between these two zones. The Kendeng zone is characterized by claystone with volcanic material interference. It is situated near the Central Volcanic Zone, which was formed during subduction events between the Middle and Late Miocene (18 to 11 million years ago) [19][20]. In contrast, the Rembang Zone is characterized by sandstone [17][19][21][22]. The presence of mud volcanoes in these regions is influenced by volcanic activity on the southern side of study area, suggesting that the lithologies are subjected to over-pressured conditions [20][23].

The Kendeng Thrust Fault is connected to the Rembang-Madura-Kangean-Sakala (RMKS) fault, which trends in the east-west direction [24][25]. The northern segment of this fault is predominantly composed of Paternosfer-Kangean basement rock [15][20][26] while the southern segment is characterized by metamorphic basement rock (phyllite, schist, and intercalations of marble and quartzite) [20]. Based on the field observations, the mud volcanoes have been classified into three groups. The first group consists of the most active mud volcanoes, which continuously emit gas, mud, and fluid. This group includes Lusi, Socah/Bujel Tasek, Gununganyar, Bledug Kuwu, Kesongo, Anak Kesongo, Cakringan, Medang, Detil, Sengon Tuko, Crewek, Banjarlor, Wringinanom, Karangayar, and Ciuyah. Lusi, the youngest and largest mud volcano eruption in Indonesia, has undergone vegetation studies to identify and map the mud-affected areas [1].

The second group comprises less active mud volcanoes, which produce significantly lower amounts of fluid or gas and have reduced their eruptive activity. This group includes Makam Sengon and Pablengan. Makam Sengon is located near the Grobogan area, which also contains the mud volcano complex of Bledug Kuwu, Banjar Lor, Crewek, Detil, and Cakringan. In this area, remnants of old eruptions are still visible, although current activity is minimal. Pablengan, situated near the inactive Sangiran mud volcano, continues to emit small amounts of gas and fluid, reflecting its diminished activity. The third group includes inactive mud volcanoes, which no longer produce fluid, gas, or mud, and show no signs of volcanic activities. This group includes Sangiran and Bekucuk. Sangiran, an ancient mud volcano, features a collapsed synclinal depression associated with faulting. Although there are no ongoing eruptive activities, fragments of metamorphic rock that were previously expelled to the surface remain visible. Woody plants were found in the area surrounding this ancient volcano. Bekucuk mud volcano, is characterized by old gryphons or salses that are now covered with vegetation. It also supports a mixture of woody plants, which dominate the area alongside with grasses [27]. This type of vegetation is uncommon in other mud volcanoes.

The mud volcanoes in Java were categorized based on their surface lithology, as depicted on the regional geological map of Java. The first group is predominantly composed of alluvium, encompassing Crewek, Medang, Bledug Kuwu, Banjar Lor, Cangkringan, Bekucuk, Gunung Anyar, Lusi, and Detil areas. The second group is characterized by limestone of the Ledok formation, which includes Kesongo and Anak Kesongo areas. The Ledok formation is distinguished by alternating layers of hard and soft limestone at the lower levels and glauconitic limestone at the upper levels [20][28]. The lower part of Ledok formation consists of brownish-white limestone, varying from hard to moderately soft, with bedding that thickens upwards (3–25 cm). The glauconitic limestone in the upper part of Ledok formation is greenish-white, sandy, and clayey, with cross-lamination and bed thicknesses of 5–25 cm. This unit dates to the Late Miocene and has approximately 100–525 m thick , which was deposited in an inner neritic environment [20][28].

The third group is dominated by the claystone of the Lidah formation, which covers Wringinanom, Pulungan, and Kalanganyar areas. The Lidah formation is composed of blue claystone, which is locally blackish, massive, and complex. It is poorly fossiliferous and contains thin lenses of sandy claystone. This formation, with a thickness of approximately 300–550 m, was deposited in a middle to outer sublittoral environment during the Pleistocene [21][28]. The fourth group is predominantly composed of marl, covering the older mud volcanoes of Sangiran and Pablengan, as well as the Soccah/Buhjel Tase and Ciuyah mud volcanoes. Sangiran and Pablengan mud volcanoes are covered by marl from the Kalibeng formation, with the upper layer of Kalibeng formation consisting of massive marl and the lower layers contains intercalated marl with tuffaceous sandstone with limestone nodules [29]. This formation was deposited in marine environments ranging from neritic to bathyal during the Late Miocene to Pliocene. The Soccah/Buhjel Tase mud volcano is covered by marl from the Tawun formation, characterized by sandy marl interbedded with limestone and calcareous sandstone in the upper part, and calcareous claystone with calcareous nodules in the lower part [30]. This

Table 1. Locations of mud volcano sites and their surrounding vegetation in java.

Site	Coordinate	Family	Species
Kalanganyar	Surabaya, East Java N: -7.39993 E: 112.789275	Apocynaceae Asteraceae Burseraceae Cactaceae Cyperaceae Cyperaceae Cyperaceae Euphorbiaceae Fabaceae Gentianaceae Poaceae Poaceae Poaceae Typhaceae	*Calotropis gigantea* (L.) W.T.Aiton *Pluchea indica* (L.) Less. *Canarium littorale* f. littorale Blume *Opuntia ficus-indica* (L.) Mill. *Cyperus rotundus* L. *Eleocharis acicularis* (L.) Roem. & Schult. *Fimbristylis ferruginea* (L.) Vahl *Euphorbia thymifolia* L. *Indigofera tinctoria* L. *Enicostema axillare* (Poir. ex Lam.) A.Raynal *Brachypodium retusum* (Pers.) P.Beauv. *Cynodon dactylon* (L.) Pers. *Pogonatherum crinitum* (Thunb.) Kunth *Typha angustifolia* L.
Sidoharjo	Porong, Sidoharjo, East Java N: -7.52449 E: 112.707483	Cyperaceae Desmidiaceae Fabaceae Loganiaceae Poaceae Poaceae Poaceae Poaceae Poaceae Poaceae Primulaceae	*Cyperus rotundus* L. *Desmidium* sp. *Mimosa pudica* L. *Spigelia anthelmia* L. *Arthraxon* sp. *Dactyloctenium aegyptium* *Cynodon dactylon* L. *Imperata cylindrical* *Panicum* sp. *Panicum maximum* *Androsace villosa* Willd
Gununganyar	Surabaya, East Java N: -7337212 E: 112.782468	Asteraceae Cactaceae Cyperaceae Euphorbiaceae Fabaceae	*Pluchea indica* (L.) Less. *Opuntia ficus-indica* (L.) Mill. *Eleocharis acicularis* (L.) Roem. & Schult. *Euphorbia thymifolia* L. *Leucaena leucocephala* (Lam.) de Wit
Wringinanom	Surabaya, East Java N: -7381806 E: 112.512147	Asteraceae Asteraceae Cyperaceae Fabaceae Fabaceae Fabaceae Meliaceae Poaceae Sesbania Typhaceae	*Pluchea indica* (L.) Less. *Sonchus oleraceus* L. *Eleocharis acicularis* (L.) Roem. & Schult. *Acacia* sp. Mill. *Clitoria ternatea* L. *Tephrosia spinosa* (L.f.) Pers. *Melia azedarach* L. *Panicum repens* L. *Sesbania sesban* (L.) Merr. *Typha angustifolia* L.
Sengontuko	Grobokan, Central Java N: -7.133961 E: 111.117757	Cyperaceae Poaceae	*Fimbristylis polytrichoides* (Retz.) R.Br. *Paspalum vaginatum* Sw
Detil	Grobokan, Central Java N: -7.131142 E: 111.1188	Asteraceae Asteraceae Asteraceae Cyperaceae Cyperaceae Euphorbiaceae Malvaceae Poaceae Poaceae	*Galinsoga parviflora* Cav. *Pluchea indica* (L.) Less. *Sphaeranthus africanus* L. *Cyperus rotundus* L. *Fimbristylis polytrichoides* (Retz.) R.Br. *Euphorbia thymifolia* L. *Abutilon indicum* (L.) Sweet *Paspalum vaginatum* Sw *Pennisetum clandestinum* Hochst. ex Chiov.

Table 1. *Cont.*

Site	Coordinate	Family	Species
Cangkringan	Grobokan, Central Java N: -7.118583 E: 111.109361	Asteraceae	*Pluchea indica* (L.) Less.
		Cyperaceae	*Eleocharis geniculata* (L.) Roem. & Schult.
		Euphorbiaceae	*Euphorbia thymifolia* L.
		Fabaceae	*Indigofera tinctoria* L.
		Poaceae	*Cynodon dactylon* (L.) Pers.
Banjarlor	Grobokan, Central Java N: -7.132891 E: 111.119676	Euphorbiaceae	*Euphorbia thymifolia* L.
		Typhaceae	*Typha angustifolia* L.
Bledugkuwu	Grobokan, Central Java N: -7.118306 E: 111.121444	Asteraceae	*Pluchea indica* (L.) Less.
		Euphorbiaceae	*Euphorbia thymifolia* L.
		Fabaceae	*Pithecellobium dulce* (Roxb.) Benth.
		Fabaceae	*Pithecellobium* sp. (Roxb.) Benth.
		Poaceae	*Cynodon dactylon* (L.) Pers.
Medang	Grobokan, Central Java N: -7.098439 E: 111.147164	Convolvulaceae	*Ipomoea carnea subsp. fistulosa* D.F.Austin
		Cyperaceae	*Cyperus rotundus* L.
		Fabaceae	*Tephrosia cf. villosa* (L.) Pers.
		Poaceae	*Cynodon dactylon* (L.) Pers.
		Poaceae	*Puccinellia distans* (Jacq.) Parl.
Anakkesongo	Grobokan, Central Java N: -7.098439 E: 111.147164	Asteraceae	*Pluchea indica* (L.) Less.
		Cyperaceae	*Fimbristylis littoralis* Gaudich.
		Juncaceae	*Juncus inflexus* L.
		Poaceae	*Cynodon dactylon* (L.) Pers.
Crewek	Grobokan, Central Java N: -7.098439 E: 111.147164	Asteraceae	*Pluchea indica* (L.) Less.
		Asteraceae	*Porophyllum ruderale* (Jacq.) Cass.
		Cyperaceae	*Eleocharis geniculata* (L.) Roem. & Schult.
		Cyperaceae	*Fimbristylis quinquangularis* (Vahl) Kunth.
		Fabaceae	*Falcataria falcata* (L.) Greuter & R.Rankin.
		Fabaceae	*Mimosa invisa* Mart. ex Colla
		Gentianaceae	*Enicostema axillare* (Poir. ex Lam.) A.Raynal
		Lamiaceae	*Tectona grandis* L.f.
		Malvaceae	*Chorcorus aestuans* L
		Orobanchaceae	*Buchnera tomentosa* Blume
		Phyllanthaceae	*Phyllanthus tenellus* Roxb.
		Poaceae	*Dactyloctenium aegyptium* (L.) Willd.
		Verbenaceae	*Lantana camara* L.
Kesongo	Grobokan, Central Java N: -7.155385 E: 111.254899	Juncaceae	*Juncus inflexus* L.
		Typhaceae	*Typha angustifolia* L.
Socah/ Buhjel Tase	Bangkalan, Madura, East Java N: -7.0916245 E: 112.7074864	Asteraceae	*Pluchea indica* (L.) Less.
		Combretaceae	*Terminalia catappa* L.
		Cyperaceae	*Carex sylvatica* Huds.
		Fabaceae	*Acacia auriculiformis* A.Cunn. ex Benth.
		Fabaceae	*Gliricidia sepium* (Jacq.) Kunth
		Fabaceae	*Leucaena leucocephala* (Lam.) de Wit
		Malvaceae	*Hibiscus rosa-sinensis* L.

Table 1. *Cont.*

Site	Coordinate	Family	Species
Ciuyah	Kuningan, West Java N: -7.056652 E: 108.530201	Asteraceae	*Pluchea indica* (L.) Less.
		Combretaceae	*Terminalia mantaly* H.Perrier
		Cyperaceae	*Bulbostylis barbata* (Rottb.) C.B.Clarke
		Fabaceae	*Leucaena leucocephala* (Lam.) de Wit
		Poaceae	*Cynodon dactylon* (L.) Pers.
		Poaceae	*Sporobolus indicus* (L.) R.Br.
		Polygalaceae	*Polygala javana* DC.
		Pteridaceae	*Acrostichum aureum* L.

formation was deposited in a marine environment (outer neritic to upper bathyal) during the Early Miocene. The Ciuyah mud volcano is covered by marl from the Pemali formation, and consists of poorly to well-bedded greyish-blue Globigerina marl layers, with sparse intercalations of tuffaceous sandstone and greyish-blue sandy limestone. This formation was deposited in a marine environment during the Early Miocene and has a thickness of approximately 900 m [30][31].

2.2. Methods

The research methodology encompassed surface geological mapping and field observations conducted across all mud volcanoes from Sukabumi to Surabaya, and extended to Madura (Figure 1) from April to June 2022. The primary objectives of the surface mapping were to delineate the geometry of the mud volcanoes, evaluate their relative activity of erupted mud materials, and document the diversity of vegetation at each site. Primary mud samples were collected where the vegetation growth. Samples were meticulously collected and preserved before being sent to School of Life Sciences and Technology laboratory at the Institut Teknologi Bandung (ITB) and the Centre for Geological Survey in Bandung for analysis. Mud samples were collected for geochemical analysis for the concentration of sodium (Na), chloride (Cl), calcium (Ca), and magnesium (Mg). Mud samples were prepared for geochemical analysis at the Laboratory of Environmental Engineering at ITB using atomic absorption spectrometry (AAS). Vegetations were identified at the Laboratory of Identification and Determination within the School of Life Sciences and Technology at ITB. Some plant species were also identified using applications such as PlanNet, Google Lens, PictureThis, LeafSnap, Find Plant, NatureID, PlantSnap, and PlantDetect. The identification results were subsequently cross-referenced with the Global Biodiversity Information Facility (GBIF) database (www.gbif.org) to confirm the taxonomic classification of the plants.

3. RESULTS AND DISCUSSIONS

3.1. Results

Vegetation samples were collected from both the central and peripheral areas of the mud volcanoes. An investigation of at least 138 plant species around the mud volcanoes in Java and Madura led to the identification of dominant species in these areas (Table 1). No vegetation can grow at the center of the mud volcano; it only thrives in the peripheral areas surrounding it. The six species most commonly found in Indonesian mud volcanoes include *Pluchea indica* (L.) Less., *Cynodon dactylon* (L.) Pers., *Euphorbia thymifolia* L., *Typha angustifolia* L., *Cyperus rotundus* L., and *Leucaena leucocephala* (Lam.) de Wit. The dominant genera identified were *Pluchea* Cass., *Cynodon* Rich., *Euphorbia* L., *Leucaena* Benth., *Eleocharis* R. Br., *Fimbristylis* Vahl, *Cyperus* L., and *Typha* L. The dominant families included Poaceae, Fabaceae, Asteraceae, Cyperaceae, and Euphorbiaceae, with the order Poales being the most prevalent, followed by Fabales and Asterales. The area was primarily dominated by the classes Magnoliopsida and Liliopsida, with all identified plants belonging to the phylum Tracheophyta.

To illustrate the distribution of plant species relative to mud volcano activity, a Sankey diagram was created (Figure 2). This diagram reveals that the Poaceae and Fabaceae families dominate nearly all mud volcanoes, regardless of their activity level. The top five plant orders identified are Poales, Fabales, Asterales, Malpighiales, and Lamiales. Vegetation density increases with distance from the center of the mud volcanoes, suggesting that the toxic nature of the mud inhibits plant growth at the center. Older mud volcanoes, such as Sangiran and Bekucuk, host a more diverse range of vegetation, including large woody plants at their centers. Specifically, *Tectona grandis* L.f. and *Leucaena leucocephala* (Lam.) de Wit are present in Sangiran, while Bekucuk features *Crescentia cujete* L., *Leucaena leucocephala* (Lam.) de Wit (Lamtoro), *Ficus benjamina* L., and *Acacia auriculiformis* A. Cunn. ex Benth. Some woody plants are also found in more active mud volcanoes, such as Gununganyar, Kalanganyar, Wringinanom, Crewek, Soccah, and Ciuyah.

The growth of woody plants appears to be influenced by mud volcano activity and weather conditions, particularly the high precipitation rate in Indonesia, which averages 2,702 mm/year [17]. High precipitation may help wash away salts and other toxic elements from the mud, thereby facilitating plant growth. Mud volcanoes with lower fluid and mud production, such as Gununganyar and Kalanganyar, tend to support more vegetation. Some mud volcanoes, such as Crewek and

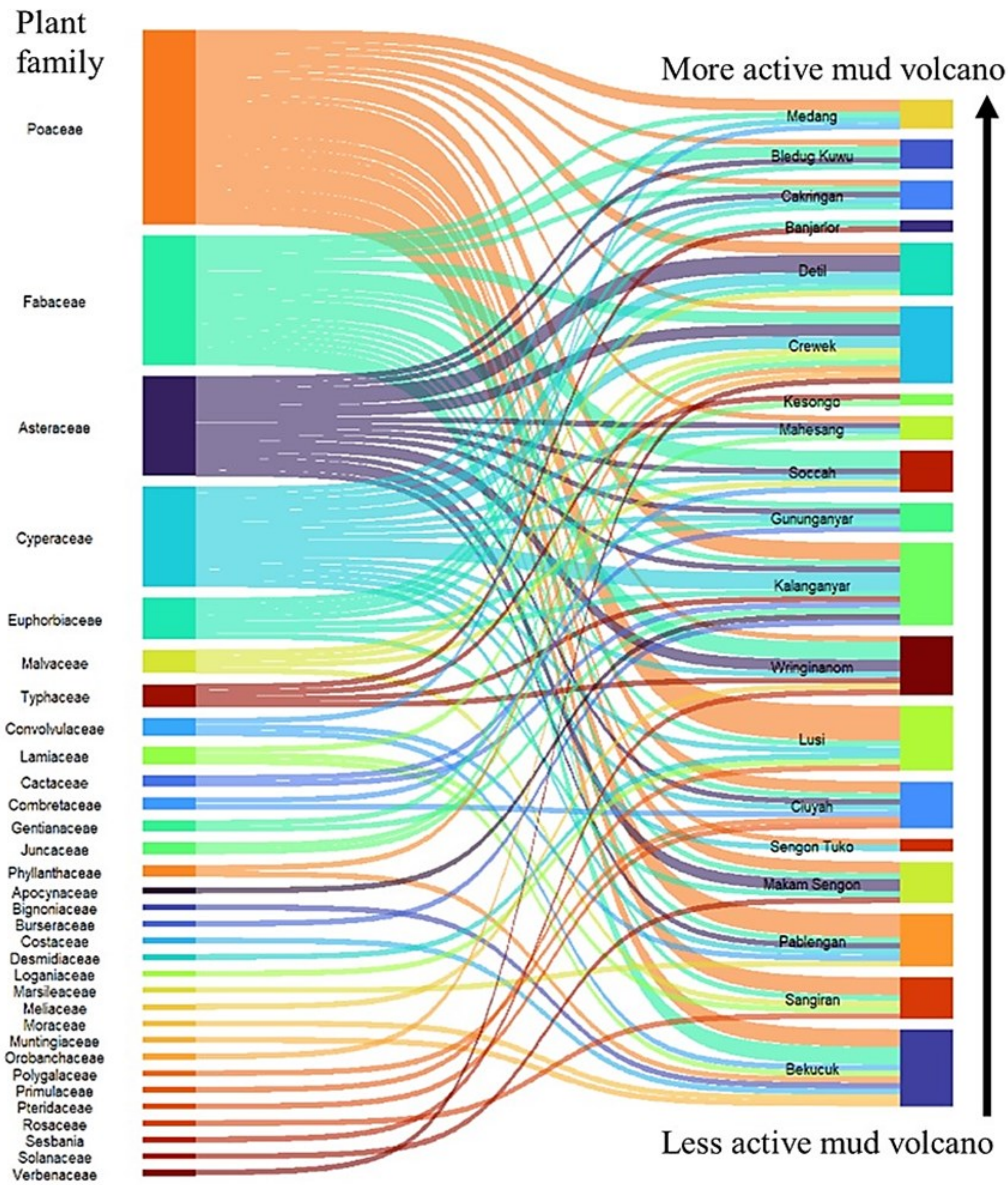

Figure 2. Sankey diagram of vegetation families in 18 Indonesian mud volcanoes.

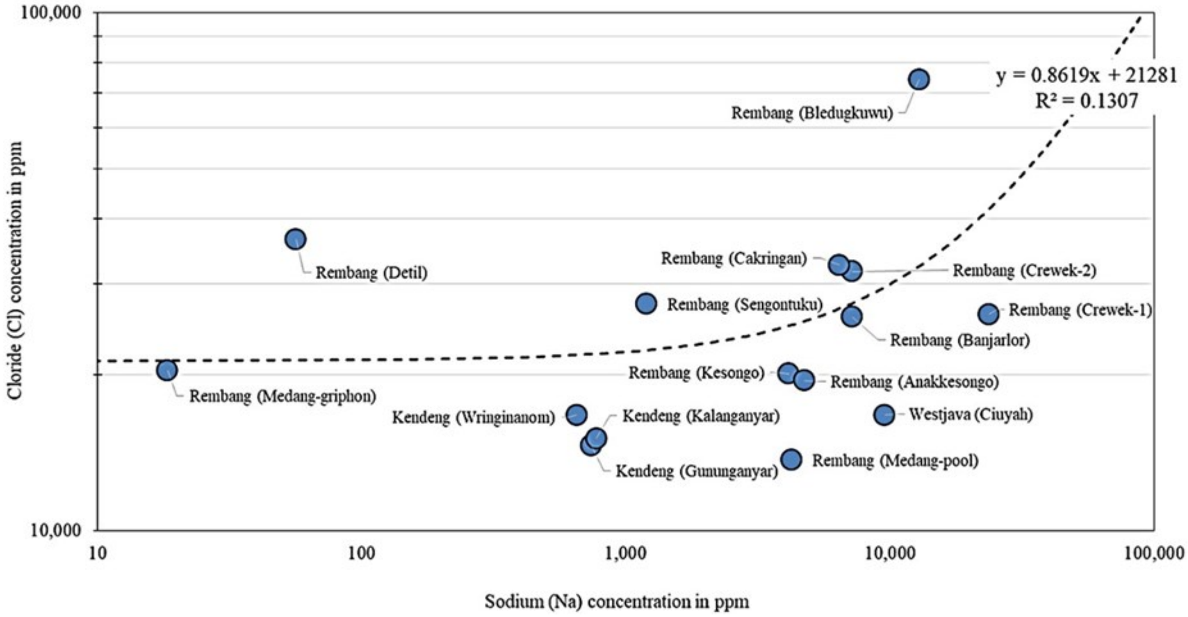

Figure 3. Sodium vs. chloride concentration of this study, representing the vegetation substrate salinity (Na/Cl ratio).

Wringinanom, have inactive salses that no longer produce fluids or gases. Notably, *Leucaena leucocephala* is present in almost all mud volcanoes.

Chemical analysis of the fluids from the mud volcanoes indicated that the mud material is characterized by high Cl content, followed by Na, Ca, and Mg. The elevated chloride content renders the water ejected from the mud volcanoes saline fluid (>10%) and unsuitable for consumption (Figures 3 and 4), which impacts plant growth. The pH of the fluid ranges from 6.48 to 8.17.

Mud samples of the Rembang zone mud volcanoes, including Bledug Kuwu, Cakringan, Banjarlor, Crewek, Kesongo, Anak Kesongo, Medang, Sengon Tuko, and Detil, are derived from sediments in the Tawun formation, which dates back to the Early Miocene to Mio-Pliocene. In contrast, mud volcanoes of Kendeng zone, including Lusi, Kalanganyar, Gununganyar, Pablengan, Sangiran, and Wringinanom, originated from sediments in the Upper Kalibeng and Kerek formations, dated to Middle Miocene to the Pliocene. Mud samples from Anak Kesongo and Gununganyar were found to contain a predominance of foraminifera fossils and smectite clay minerals.

Opuntia ficus-indica (L.) Mill., a species commonly found in arid environments, is present only in the Gununganyar and Kalanganyar mud volcanoes. This plant is not salt-tolerant, and its growth may be prevented by high salt concentrations. The lower salt concentrations in areas where prickly pears are found suggest that high rainfall may leach away the salt, facilitating the plant's growth. Gununganyar and Kalanganyar produce less gas, fluid, and mud compared to Bledug Kuwu or Lusi mud volcanoes. Carbon dioxide (CO_2), which supports root and biomass growth of *Opuntia ficus-indica*, is lower in these two mud volcanoes compared to others like Bledug Kuwu, Detil, Cakringan, and Crewek, potentially restricting the plant's spread. *Acrostichum aureum* L., which can tolerate salinity, is found in the Ciuyah mud volcano, located 33 km from the coast and 253 m above sea level. This plant grows near the eruption center, where salinity levels are high, alongside *Leucaena leucocephala*.

The Sankey diagram illustrates minor differences in the dominant plant families across these volcanic mud complexes, especially in active mud volcanoes. In the Kendeng mud volcanoes, the Fabaceae family is more prevalent, whereas the Poaceae family is more dominant in the Rembang mud volcanoes. The Fabaceae family, known for its large and agriculturally significant dicotyledonous plants, contrasts with the generally smaller monocotyledonous grasses of the Poaceae family.

This distinction is also represented in the pie chart, which summarizes the findings of this study (Figure 5).

3.2. Discussions

From the eighteen mud volcano sites we observed, they can be classified based on their position relative to Java's physiographic zones: the Kendeng Zone and the Rembang Zone, as previously illustrated in Figure 1. These physiographic zones appear to influence the geochemical characteristics of the mud volcanoes, specifically in the proportions of Na vs. Cl and Mg vs. Ca. This pattern of geochemical similarity also impacts the types of vegetation that can thrive in the peripheral areas surrounding the mud volcanoes. The mud in the Kendeng mud volcanoes is likely derived from the Kalibeng formation, which is rich in marl containing 30–60% calcium carbonate ($CaCO_3$) [15][20]. Calcium carbonate is a crucial element for plant growth, commonly used to neutralize soil acidity and provide Ca for plant nutrition [32][33]. Conversely, the mud from the Rembang mud volcanoes is believed to originate from the Tawun formation, characterized by claystone with little or no calcium carbonate [17][34]. The Fabaceae family hosts rhizobial bacteria in its root nodules [17][35][36], which convert atmospheric nitrogen into usable form through nitrogen fixation, enhancing soil fertility and promoting plant growth. This may account for the prevalence of larger plants in the Kendeng mud volcanoes compared to those in the Rembang zone.

Salinity is another significant factor influencing vegetation growth [37][38]. The Kendeng mud volcanoes exhibit lower salinity levels in their fluids compared to the Rembang mud volcanoes, where high salinity levels can hinder the growth of most plant species (Figure 6). High salinity can inhibit the growth of most plant species [17], with only certain species able to survive under such conditions. However, in older mud volcanoes such as Bekucuk and Sangiran, located in the Kendeng Zone, large plants are dominating and providing more shade and potentially limiting the presence of certain species such as herbaceous plants due to sunlight limitation for photosynthesis [39].

The vegetation of less active and inactive mud volcanoes (Sangiran, Pablengan, Bekucuk, and Makam Sengon) was compared to that of active mud volcanoes. Several plant families, including Solanaceae, Marsileaceae, Rosaceae, Moraceae, Muntingiaceae, and Bignoniaceae, are found exclusively in less active and inactive mud volcanoes. In contrast, families such as Typhaceae, Cactaceae, Combretaceae, Gentianaceae,

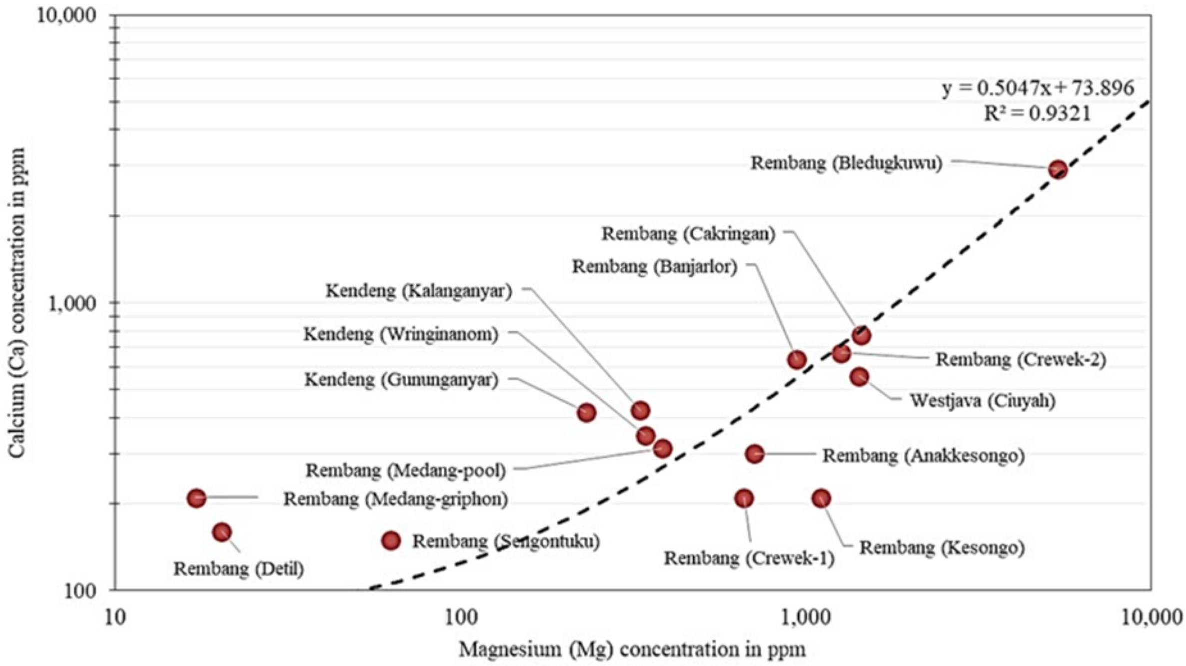

Figure 4. Magnesium vs calcium concentration of this study, representing the vegetation substrate Ca/Mg ratio.

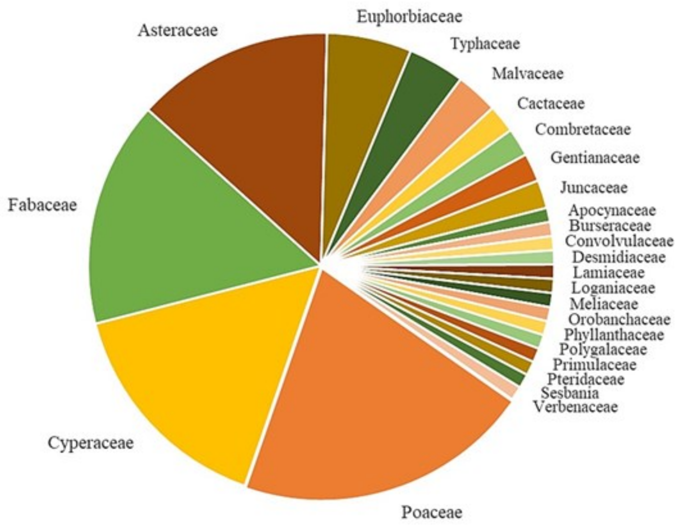

Figure 5. Distribution and proportion of plant families known to grow in this study.

Juncaceae, Apocynaceae, Burseraceae, Desmidiaceae, Loganiaceae, Meliaceae, Orobanchaceae, Polygalaceae, Primulaceae, Pteridaceae, Sesbania, and Verbenaceae are unique to active mud volcanoes. Typha angustifolia L. from the Typhaceae family is the most frequently observed plant in active mud volcanoes, serving as a potential indicator of volcanic activity. Other families found in several active mud volcanoes but not in less active and inactive ones include Gentianaceae, Cactaceae, Juncaceae, and Combretaceae. These families can also serve as indicators of active mud volcanoes [39].

The remaining species and families are present across all types of mud volcanoes, regardless of their activity levels, including Poaceae, Fabaceae, Asteraceae, Cyperaceae, Euphorbiaceae, Malvaceae, Convolvulaceae, Lamiaceae, and Phyllanthaceae. In addition to nutritional contributions, chemical elements, and climate, shading from large trees can also suppress the growth of certain species. This classification of vegetation can aid in determining the activity levels of mud volcanoes in Indonesia.

Weather plays a crucial role in plant growth. For example, vegetation in the Azerbaijan mud volcanoes, where giant plants are rarely found [10][40] as it is dominated by plants adapted to dry environments due to lower precipitation like grass. In contrast, The high precipitation in Indonesia helps wash away the salinity in the soil around mud volcanoes, allowing the soil to support woody vegetation [39]. Additionally, rain provides essential nutrients for vegetation. For example, the Fabaceae family is uniquely present in Indonesian mud volcanoes but not in Azerbaijan or Sakhalin (Russia), though it is found in Trinidad [27].

Mud volcano activity can disrupt natural ecosystems by significantly altering abiotic conditions such as high temperatures, salinity, and toxic mud content [41][42]. These changes can directly impact the biotic components of the ecosystem. Despite these harsh conditions, some vegetation is capable of growing and developing around mud volcanoes. Although research on the vegetation of mud volcanoes in Indonesia is limited, plants have been able to adapt to extreme conditions by exhibiting specific growth patterns and morphological traits, such as leaf succulence, stunted growth, and the production of unique metabolites [8][43]. Therefore, the presence of plants near mud volcanoes is significant, as they can serve as bioindicators of mud volcano activity and environmental changes in the surrounding area.

This study demonstrates that certain vegetation such as Typhaceae families (in Banjarlor mud volcano) can thrive around mud volcanoes despite the harsh environment. While trees and larger plants are scarce, the majority of the vegetation comprises herbaceous species, such as grasses with fibrous roots and rhizomes. These plants can grow and reproduce vegetatively without relying on pollinators, which is crucial for survival in disturbed environments. The ability of these plants to adapt and undergo natural recovery and succession is essential for their survival in such challenging conditions [8][27][44].

Toxic materials released by mud volcanoes such as salinity can deter pollinating insects and soil decomposers like worms and ants. These animals typically form symbiotic relationships with Poaceae families. This symbiotic relationship is beneficial to plants, aiding in reproduction, pollination, nutrient intake, and matter cycling. Despite the toxic conditions, several plant species, such as Typhaceae families (in Banjarlor mud volcano) have been observed growing around mud volcanoes, suggesting that they have developed unique adaptations, particularly in their root systems. Notably, nodules have been found on the roots of these plants, indicating microbial symbiosis in the root zone [1][45][46]. These nodules play a critical role in converting insoluble soil components into nutrients vital for both plants and soil microorganisms. Research has shown that symbiotic microorganisms in plant roots can

Figure 6. Represented field documentation of mud volcano morphologies of this study, that was covered by adapted vegetation.

significantly enhance plant survival, even in soils that are contaminated with high levels of hydrocarbons and heavy metals [1][17][47]. Some microorganisms can degrade long-chain and aromatic hydrocarbons into shorter, non-toxic compounds [48], while others can neutralize heavy metals through oxidative enzymatic processes and cellular accumulation. Our findings highlight the potential for further research into bioremediation and ecosystem recovery in areas impacted by mud volcano disturbances, utilizing the unique adaptations and symbiotic relationships of these resilient plant species such as Typhaceae families (in Banjarlor mud volcano).

Geobotany in mud volcano environments is important as it reveals how unique geochemical conditions influence local vegetation patterns. Plants around mud volcanoes often adapt to high mineral levels, serving as natural indicators of the soil's chemical composition and reflecting environmental changes. This research also has practical implications, as it aids in ecological restoration, environmental monitoring, and even mineral exploration by identifying plant species that thrive in challenging soil conditions.

4. CONCLUSIONS

The dominant vegetation families in Indonesian mud volcanoes include Poaceae, Fabaceae, Asteraceae, Cyperaceae, and Euphorbiaceae. The distribution of these families in the Rembang and Kendeng mud volcanoes is strongly influenced by the geological composition of the mud source in each complex. In the Kendeng mud volcanoes, where the source of mud is derived from the marl-rich Kalibeng formation, the Fabaceae family is more prevalent because of the lithology support from the Kalibeng formation and also the ability of its root to host rhizobial bacteria which convert atmospheric nitrogen into an usable form through nitrogen fixation, enhancing soil fertility and promoting plant growth. Conversely, the Poaceae family predominates in the Rembang mud volcanoes, which are formed by the claystone-rich Tawun formation showing that more active mud volcanoes will host more grass plants. The growth of these plant families is influenced by various factors, including weather conditions, chemical elements such as sodium, chloride, calcium, and magnesium, salinity levels, and the availability of calcium carbonate. These findings underscore the complex interplay between geological factors and vegetation distribution in the unique environments of Indonesian mud volcanoes.

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Conflicts of Interest

The authors declare no conflict of interest.

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