

PROGRESS OF RESEARCH ON VOLCANIC-GEOMORPHOLOGY IN SOUTHEAST ASIA: A SYSTEMATIC LITERATURE REVIEW

Perkembangan Penyelidikan Geomorfologi-Gunung Berapi di Asia Tenggara: Kajian Literatur Sistematis

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ABSTRACT Southeast Asia, with its large number of volcanoes, wide distribution, and high occupancy and population growth in volcanic environments, has a high potential to emerge as one of the world's centres for volcanic geomorphology studies. In this article, we present information on the progress and trends of volcanic-geomorphology research topics in Southeast Asia. This article is a systematic literature review organized by the PRISMA approach. Search keywords were determined using the PICO method. The documents reviewed were obtained from the Scopus database, with the criteria of research articles published in journals or conference proceedings, English language, and territory/area limited to Southeast Asia. A total of 214 documents were collected with these keywords and criteria. Of these, 53 articles were selected through the extraction process and continued with the review. The findings of this study show that studies on volcanic geomorphology in Southeast Asia are relatively few, even though studies on volcanoes themselves have been conducted from various perspectives. Volcanic geomorphology studies indexed in the Scopus database were conducted from 1963 to 2024. The two most discussed topics are genesis/landform and geomorphological processes that occur in landforms, while the other topics that are relatively little discussed are materials and the environment. Implementing other methods like remote sensing, geophysics, and environment often supports geomorphological survey and analysis methods.

Keywords: geomorphology, volcano, volcanic landform, Southeast Asia

ABSTRAK Asia Tenggara, dengan bilangan gunung berapi yang banyak, taburan yang luas, dan penghunian yang tinggi serta pertumbuhan penduduk dalam persekitaran gunung berapi, mempunyai potensi yang tinggi untuk muncul sebagai salah satu pusat kajian geomorfologi gunung berapi di dunia. Dalam artikel ini, kami membentangkan maklumat tentang kemajuan dan trend topik penyelidikan geomorfologi-gunung berapi di Asia Tenggara. Artikel ini merupakan kajian literatur sistematik yang menggunakan pendekatan PRISMA. Kata kunci carian ditentukan menggunakan kaedah PICO. Dokumen yang disemak diperolehi daripada pangkalan data Scopus, dengan kriteria artikel penyelidikan yang diterbitkan dalam jurnal atau prosiding persidangan, bahasa Inggeris, dan

wilayah/kawasan terhadap kepada Asia Tenggara. Sebanyak 214 dokumen telah dikumpul dengan kata kunci dan kriteria ini. Daripada jumlah ini, 53 artikel telah dipilih melalui proses pengekstrakan dan diteruskan dengan ulasan. Penemuan kajian ini menunjukkan bahawa kajian berkaitan geomorfologi gunung berapi di Asia Tenggara agak sedikit, walaupun kajian gunung berapi itu sendiri telah dijalankan daripada pelbagai perspektif. Kajian geomorfologi gunung berapi yang diindeks dalam pangkalan data Scopus telah dijalankan dari 1963 hingga 2024. Dua topik yang paling banyak dibincangkan ialah genesis/bentuk muka bumi dan proses geomorfologi yang berlaku dalam bentuk muka bumi, manakala topik lain yang agak sedikit dibincangkan ialah bahan dan alam sekitar. Pelaksanaan kaedah lain seperti penderiaan jauh, geofizik dan persekitaran menyokong kaedah penyelidikan dan analisis geomorfologi.

Kata kunci: geomorfologi, gunung berapi, bentuk muka bumi gunung berapi, Asia Tenggara

1. Introduction

Over thousands of years, geomorphology has developed into an established modern science. This is inseparable from the role of geomorphology experts, scholars, and authors who contributed through various studies conducted over time. The achievements and updates from these studies have led geomorphology through five phases of development, namely before the 17th century, the 17th and 18th centuries, the early 19th century, the 19th century, and the early 20th century (Huggett, 2017; Oldroyd, 2013; Pramono & Ashari, 2014; Sack & Orme, 2013). Geomorphological studies are conducted on various landforms. One of the most discussed is volcanic landforms. In the Scopus database, for example, there are more than 3,000 publications with the search keywords "volcanic" and "landform".

In the study of geomorphology in volcanic landforms, Southeast Asia has the potential to play an important role, whether as a study location or contributor. This is due to the large number of volcanoes in the region. As part of the Pacific Ring of Fire with a tectonic configuration with a lot of subduction between plates, it allows many volcanoes to form in Southeast Asia. Indonesia, one of the countries in this region, is even one of the countries in the world with the largest number of volcanoes, including Holocene volcanoes that have been active in the last 10,000 years. Other countries, such as the Philippines, have many volcanoes and are included in the top ten countries with the largest number of Holocene volcanoes (Pramono & Ashari, 2014; SIEBERT et al., 2010). Moreover, other facts show that the highest population density of volcanic areas in the world is in Southeast Asia. Over the past 40 years, the region's highest population growth has occurred at distances of less than 10 km near volcanoes (Freire et al., 2019; Small & Naumann, 2001).

Studies on the geomorphology of volcanic landforms conducted in Southeast Asia have also been widely published. However, to reinforce the region's central role as one of the leading centres for the study of volcanic landforms, comprehensive

information is needed that summarizes the study's progress in this area over time. This information is relatively scarce in the literature, suggesting a gap that needs to be filled by further study. This study is required to describe the achievements as a reflection of future development. Also, the findings from Southeast Asia can be compared with those of other regions as a parameter in evaluating the study's progress.

In this article, we present the results of a literature review of previous studies on volcanic geomorphology in Southeast Asia. This article has three more specific objectives. First, we present a description of the research profile of volcanic geomorphology in Southeast Asia indexed in the Scopus database. Second, we analyze the trend of research topics over time. Last, we analyze the methodological variations used in these studies. This article provides alternative information regarding volcanic geomorphology in Southeast Asia. In summary, this article offers new insights into the progress of geomorphological studies in tropical Southeast Asia, especially on volcanic landforms, which are the most populated locations in this area.

2. Method

This study employs the systematic literature review (SLR) method. This SLR method begins by creating a research question using the PICO framework: "In Southeast Asia, what are the achievements of volcanic geomorphology studies, both topics and methods used, on various aspects of geomorphological studies?". Referring to the PICO framework, the research question includes population, intervention, comparison, and outcome (Table 1).

The next step is to determine the electronic search step in the database. This step is determined based on the keywords identified from the formulation of the research problem and the PICO framework developed previously. The keywords used in this study are (1) geomorphology, (2) landscape, (3) landform, (4) geomorphic process, (5) volcano, (6) volcanic, (7) Southeast Asia, (8) Indonesia, (9) Philippines, (10) Malaysia, (11) Singapore, (12) Thailand, (13) Vietnam. From these keywords, boolean operators were determined for searching in the database, namely: "geomorphology" OR "landscape" OR "landform" OR "geomorphic process" AND "volcano" OR "volcanic" AND "Southeast Asia" OR "Indonesia" OR "Philippines" OR "Malaysia" OR "Singapore" OR "Thailand" OR "Vietnam".

Table 1.*Framework PICO for formulating study problems*

P	I	C	O
Population	Intervention	Comparison	Outcome
Research on volcanic geomorphology in Southeast Asia	Outcomes of volcanic geomorphology research over time	Various aspects of geomorphology that are the focus of the study of volcanic geomorphology	Summary of research progress on volcanic geomorphology in Southeast Asia
How is volcanic geomorphology studied in Southeast Asia? Which countries were chosen as study sites?	How has the study of volcanic geomorphology in Southeast Asia progressed over time?	How studies in various aspects of geomorphology have been conducted over time?	What are the achievements of volcanic geomorphology studies in Southeast Asia over time?

Source: Modified from Mathley et al., (2014).

Furthermore, the criteria for inclusion and exclusion were determined. Articles included in the requirements are (1) research articles, (2) published in Journal or Conference Proceedings, (3) English language, and (4) country/territory limited to Southeast Asia. Subject areas are limited to earth and planetary sciences, environmental science, and social science. Articles must ensure that they address topics relevant to the keywords used. The articles are categorized as irrelevant reports if they do not meet these criteria. The screening process to determine exclusion consists of two stages. In the first stage, articles that were completely irrelevant because they were off-topic or the study area was not in Southeast Asia were not used in the study. In the second stage, articles whose discussion does not match the expected criteria will be categorized as excluded with reasons. The data source for obtaining articles in this study was Scopus. The review procedure was conducted using the PRISMA method, as shown in Figure 1.

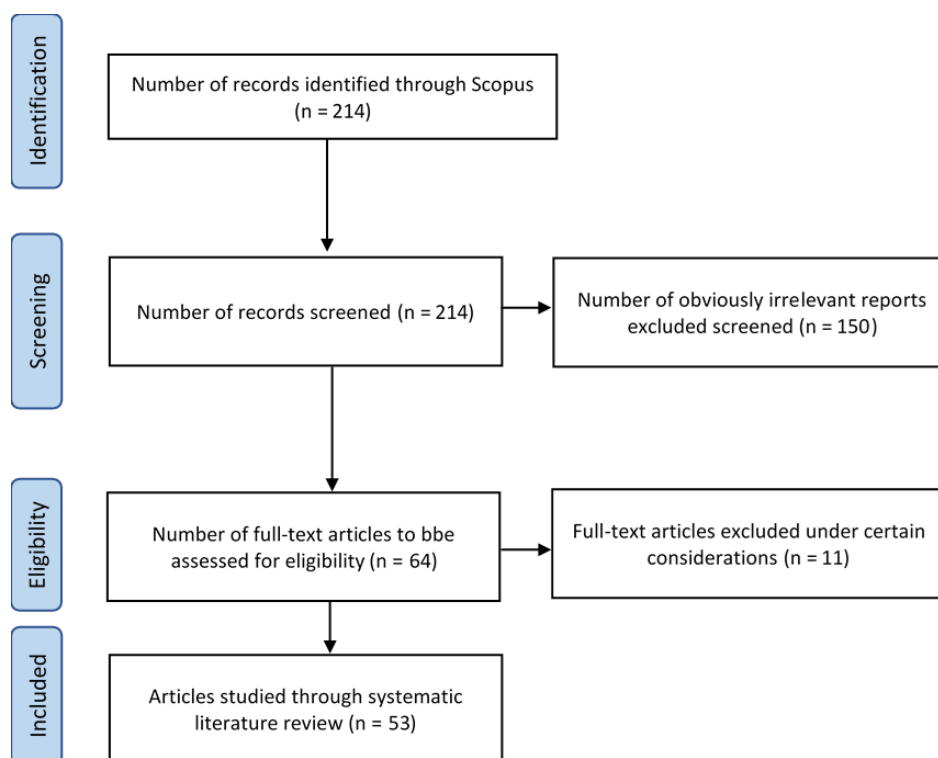


Figure 1. PRISMA flow diagram of the systematic literature review in this study
Source: Pollock and Berge (2018).

3. Findings and Discussion

3.1. Profile of volcanic geomorphology studies in Southeast Asia on Scopus database

In this section, we present a profile description of studies on volcanic geomorphology in Southeast Asia on the Scopus database. The profile description includes the number of documents per year, the contributing authors, the country of the first author, the institution of the first author, the country location where the study was conducted, as well as the journals that published articles resulting from studies on volcanic geomorphology in Southeast Asia. Publications in this field started in 1963 with one article. In the following years, published articles were still very few and not always available yearly. Only one article was published in 1982, 1994, 1996, and 1997. Starting in 2000, there was a slight increase with two articles published, although the number dropped back to just one article in 2004 and 2005. In 2008, there was a significant increase, with six articles published. During the period 2011-2016, the graph of the number of publications shows an up-and-down condition, with one article in 2011, two articles in 2012, three articles in 2013, and two articles each in 2015 and 2016. In 2017-2024, the number of publications was more stable, ranging from one to six articles per year. 2020 and 2021 saw a significant spike, with six articles published each. 2024, by mid-year, five articles had been published, indicating a further increase (see Figure 2).

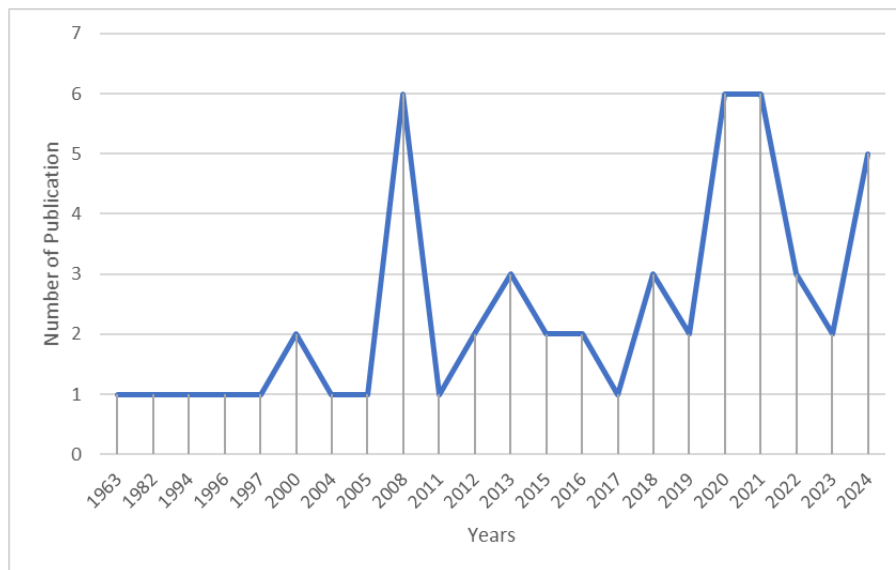


Figure 2. The number of published articles (1963-2024)

Source: Scopus Database (2024)

Overall, this trend indicates a growing interest and research activity in volcanology-geomorphology in Southeast Asia. In the early period (1963-1997), publications were rare and not regularly produced yearly. However, in the last two decades (2000-2024), the number of studies has increased consistently. This is due to the support of more advanced technology, more international cooperation, and higher awareness of the importance of volcanological-geomorphological research for disaster mitigation and regional development. The spike in 2020 and 2021 is likely related to the increasing need for natural disaster research and volcanic risk mitigation, especially in vulnerable regions such as Southeast Asia.

The number of authors contributing to studying volcanic geomorphology in Southeast Asia is vast. Of all the documents used in this study, 151 authors contributed, either as main author, corresponding author, or regular author. There are five top authors with the most contributions. Franck Lavigne made the most contributions from Universite Paris 1, France, which produced 20 publications. Next is Danang Sri Hadmoko, with 16 publications; Junun Sartohadi and Muhammad Ngainul Malawani, each with ten publications; and Bachtiar Wahyu Mutaqin, with eight publications. The four authors are all from Universitas Gadjah Mada, Indonesia (see Figure 3).

Eleven countries of origin of the first authors contributed to this study, namely Indonesia, France, the United Kingdom, the Netherlands, Japan, the United States, Germany, Singapore, New Zealand, Belgium, and Russia. Indonesia contributed the most with 22 articles, followed by France with five articles, and Russia and Japan with four. Furthermore, the UK, Germany, New Zealand, and Belgium produced three articles, and the Netherlands, Singapore, and the United States made two (see Figure 4).

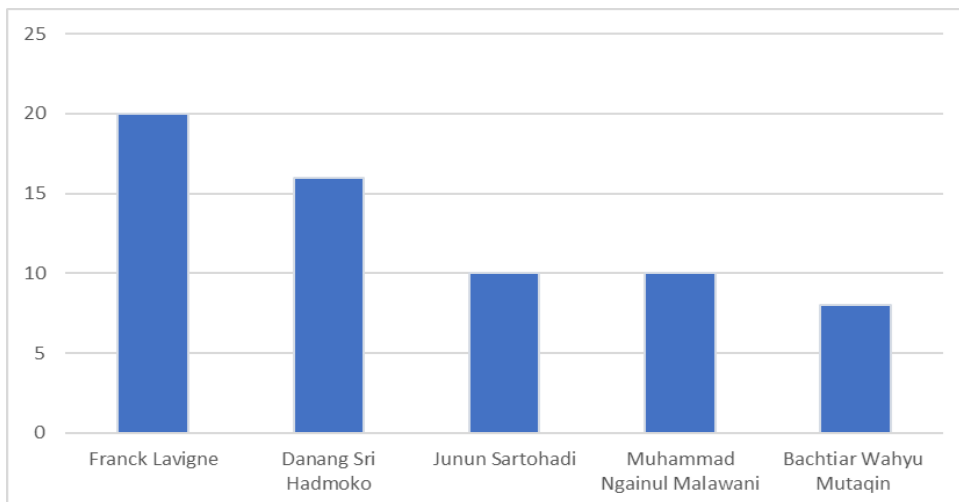


Figure 3. Top five authors contributing to volcanic geomorphology publications in Southeast Asia

Source: Scopus Database (2024)

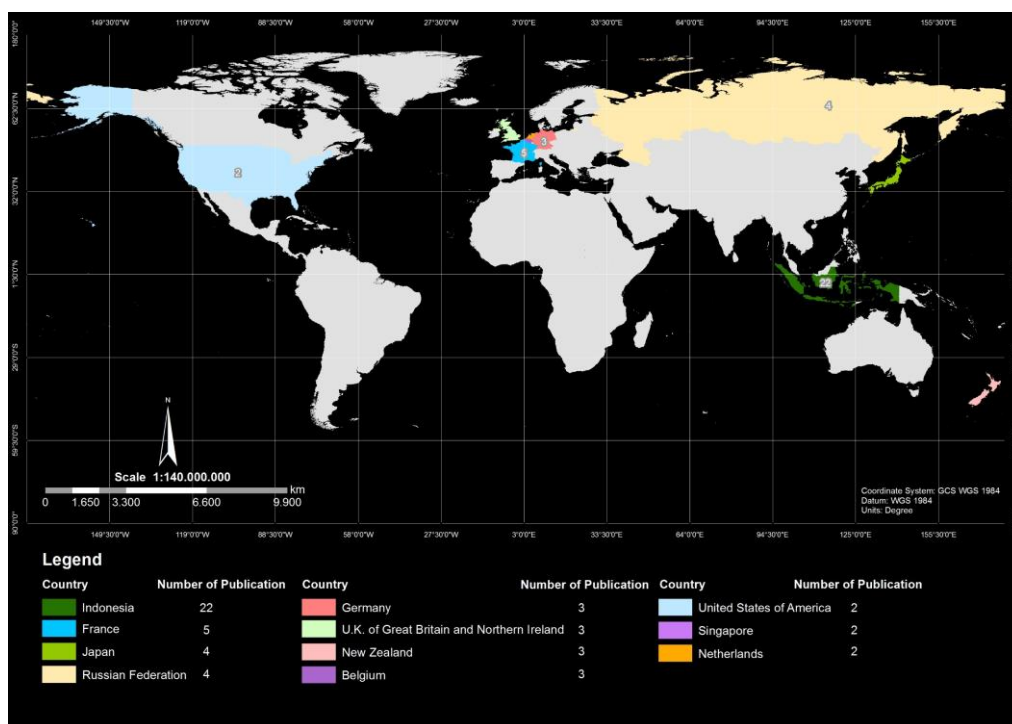


Figure 4. Distribution of countries of origin of first authors in volcanic geomorphology studies in Southeast Asia

Source: Scopus Database (2024)

Following the distribution of first-author countries described above, first-author affiliations are also dominated by the top five first-author countries. The institutions that contribute the most as first author affiliations are Universitas Gadjah Mada with 18 articles, Universite Paris 1 Pantheon Sorbonne with 15 articles, and the Russian Academy of Science with four articles. Some institutions that produced two

articles include Utrecht University, Keele University, Kyoto University, Nanyang Technology University, Universite Paris Nanterre, and Indonesian National Institute of Aeronautics and Space. Other organizations that produced one article include Universitas Negeri Yogyakarta, Universitas Negeri Malang, University of D'Orleans, University of Hawaii, University of Canterbury, Cambridge University, Universitas Jambi, Federal Institute for Geoscience and Natural Resources, University Paris, University Brussel, Akita University, and Massey University.

In contrast to the diverse countries of origin of the authors, the countries where the study was conducted were minimal, namely only Indonesia and the Philippines. In addition, several countries outside Southeast Asia are used as a comparison or multi-country, including Italy and the United States. The results of this study were published in journals and conference proceedings. The top three journals and conference proceedings are (1) *Journal of Volcanology and Geothermal Research* with 15 articles, *IOP Conference Series: Earth and Environmental Science* with six articles, and *Geomorphology* with three. Studies on volcanoes in Southeast Asia are generally only conducted at certain periods. Even on the Merapi volcano, where a lot of research has been done, the research is not sustainable. Continuous research was conducted on Samalas volcano by Malawani, Lavigne, Mutaqin, Hadmoko, Syamsuddin, from 2019-2024.

Publications on volcanic geomorphology in Southeast Asia indexed in the Scopus database are relatively limited. The search needs to be extended to other databases to get more results. For example, suppose the search is conducted in the Google Scholar database. In that case, articles on spatial and temporal patterns in fluvial recovery following volcanic eruptions in the Philippines (Gran & Montgomery, 2005), volcanic geomorphology such as in Merapi (Ashari, 2017; Setyawati & Ashari, 2017) and geomorphological hazards in the Dieng Volcanic Complex (Wardoyo et al., 2021).

3.2 Progress study of volcanic geomorphology in Southeast Asia

In this section, we analyze the study's progress on volcanic geomorphology in Southeast Asia. Studies on volcanic geomorphology conducted over six decades have produced many achievements. Analyses of the 53 articles used in this study show that various topics have been discussed over time. Also, these topics show trends and developments characterized by the novelty of the study results at each stage of development.

Keyword analysis using the VOS Viewer tool shows that the keywords used in the volcanic geomorphology study documents form three clusters. The first cluster seems to emphasize the discussion of volcanic morphology. This is evident from the keywords used in this cluster, including geomorphology, volcano, volcanic eruptions, volcanic landform, volcanology, topography, surveying, remote sensing, and digital elevation model. In addition, the first cluster also has a specific

geographical area, namely in Indonesia, specifically in Lesser Sunda Island, Western Nusa Tenggara, and Lombok.

The second cluster seems to discuss volcanism in a specific area, which does receive a lot of attention due to the high intensity of volcanic activity. This is indicated by the keywords that refer to specific geographical areas, including Greater Sunda Island, Sunda Isles, Java, East Java, Merapi, Merapi Volcano, hazards, and hazards assessment. The volcanic events of concern in this second cluster appear to be in the context of natural disasters that have harmed many residents in the region. The emphasis of volcanism is on Merapi Volcano, one of the world's most active volcanoes and the most active during the Holocene (Ashari, 2017; Ashari & Purwantara, 2022).

The third cluster discusses geomorphic processes in volcanoes, especially the eruption process. This cluster also accommodates specific geographical areas outside Indonesia. The keywords used in the third cluster include lahar, pyroclastic flow, Asia, Southeast Asia, and the Philippines. These three clusters are relatively close together, indicating a strong linkage in citations between the various clusters. Even the keyword volcanoes used in the third cluster is close to the first and second clusters (see Figure 5).

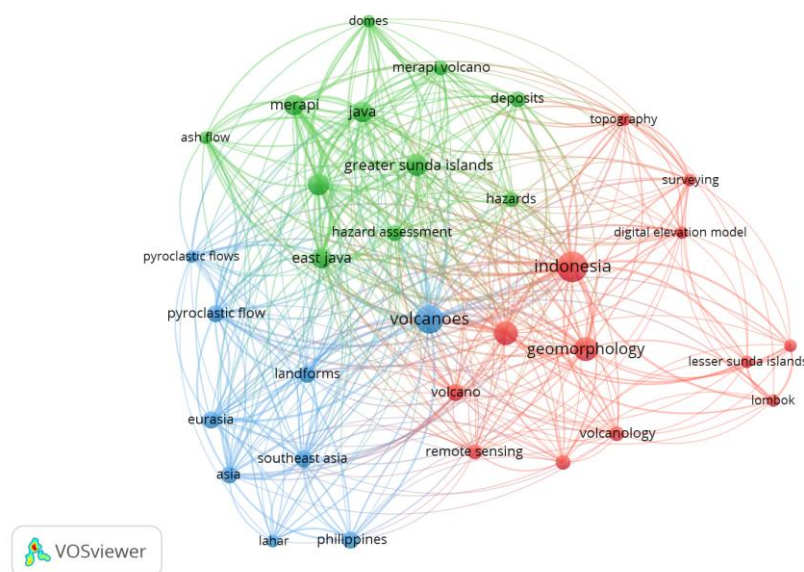


Figure 5. Clusters of keywords in publications on volcanic geomorphology in Southeast Asia

Source: VOS Viewer Analysis.

Various keywords were used in the last decade (2010-2020). At the beginning of the decade, around 2010, the keywords widely used were ashflow, pyroclastic flow, lahar, Eurasia, Asia, Southeast Asia, Philippines, and volcanic landform. This shows that the discussion of geomorphic processes in the form of eruptive activity over a wider geographical area was common a decade ago. In the middle of the decade, around 2013-2016, there were many discussions on Indonesia, Sunda Isles,

Table 2.*The volcanoes studied in Southeast Asia and the number of publications*

No	Name Volcano	Country	Number of publications
1	Merapi	Indonesia	14
2	Krakatau	Indonesia	4
3	Pinatubo	Philippines	4
4	Samalas	Indonesia	4
5	Kerinci	Indonesia	2
6	Rinjani	Indonesia	2
7	Sumbing	Indonesia	2
8	Tidore	Indonesia	2
9	Welirang	Indonesia	2
10	Merbabu	Indonesia	1
11	Semeru	Indonesia	1
12	Sinabung	Indonesia	1
13	Buyan-Bratan	Indonesia	1
14	Raung	Indonesia	1
15	Hiri	Indonesia	1
16	Bicol	Philippines	1
17	Gede-Pangrango	Indonesia	1
18	Ungaran	Indonesia	1
19	Gamalama	Indonesia	1
	Total		46

Overall, keywords are widely used and indicate the most studied topics. The most used keywords are volcanoes, geomorphology, volcanic eruption, and Indonesia. This shows that the study of volcanic geomorphology in Southeast Asia mainly focuses on eruption as the primary geomorphic process, with Indonesia as the specific geographical area. In addition, other keywords that are relatively widely used are Greater Sunda Island, Sunda Isles, Java, East Java, and Merapi, which indicates that the specific geographical area in Indonesia for study is Java Island. Even Merapi Volcano receives special attention from the authors because it is widely studied in volcanic geomorphology in Southeast Asia (see Figure 7).

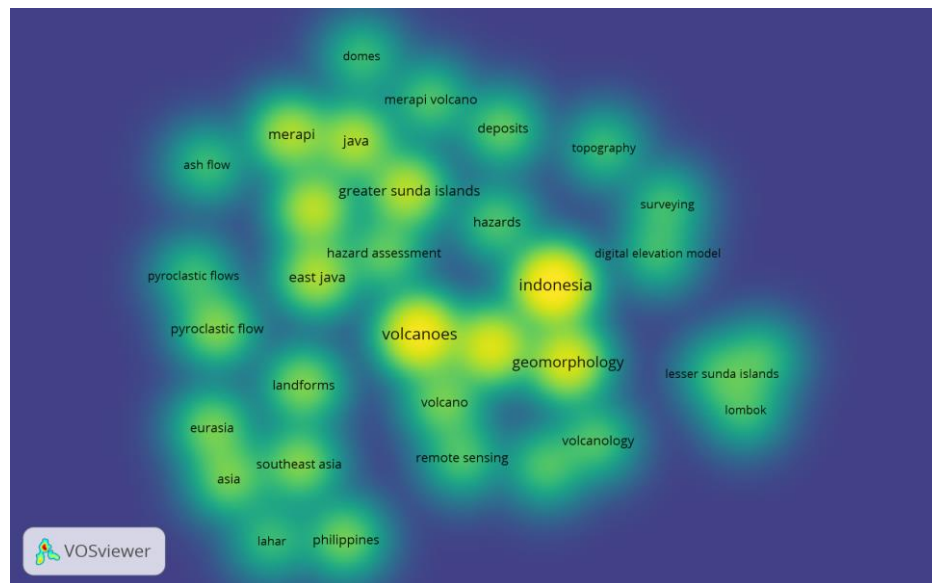


Figure 7. Keywords in the publication *Volcanic Geomorphology* based on the usage intensity

Source: VOS Viewer Analysis.

For more than six decades, studies on volcanic geomorphology in Southeast Asia have undergone various stages of development. The analysis shows that there are five stages of development. Meanwhile, there are three categories of volcanic landform studies: regional volcano-geomorphology, volcano-morphology, and geomorphological process (Figure 8). The first stage lasted from 1963-1994. In this period, the number of publications produced was still minimal. The first stage was the era of pioneers such as Van Bemmelen and Verstappen. In the first stage, the study of regional volcano-geomorphology was the most prominent, where volcanism was discussed on a general and broad scale concerning tectonism or regional geology (Bemmelen, 1949; Verstappen, 1994). Studies on volcano-geomorphology have also been conducted on the morphology of Krakatau volcanoes resulting from catastrophic eruptions (Richards, 1982). Obviously, in this era, the discussion is general on a regional scale. Specific discussions on certain volcanic units were only carried out on world-renowned volcanoes with a history of eruptions that had a broad impact.

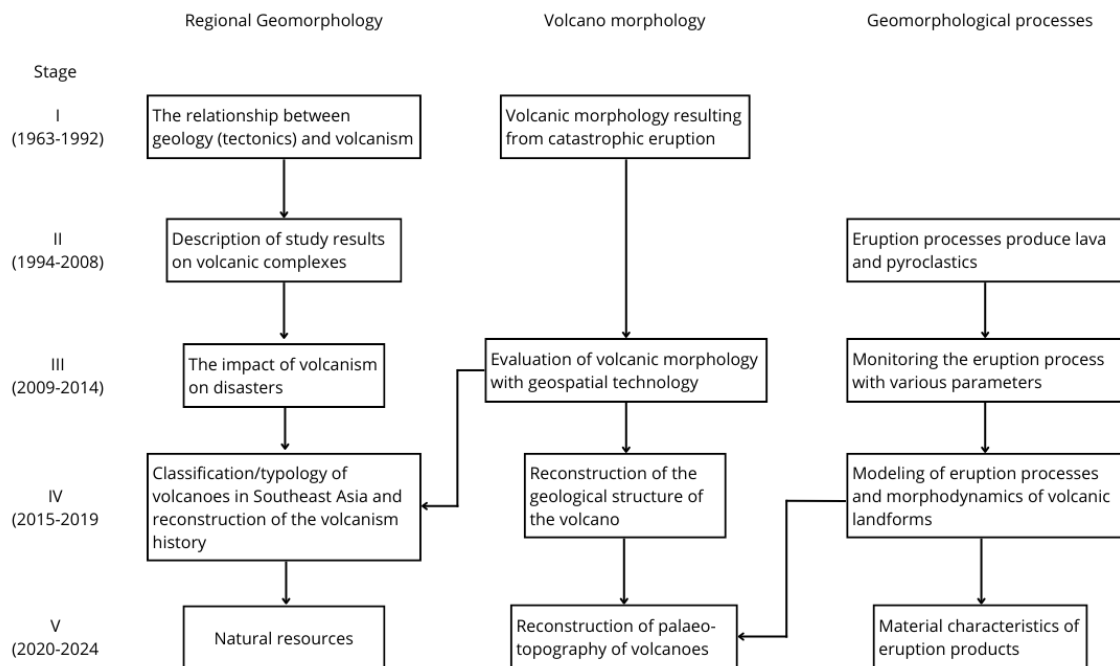


Figure 8. The development stage of the study of volcanic geomorphology in Southeast Asia

Source: Data Analysis.

The second stage took place in the period 1995-2008. During this period, regional geomorphology studies still dominated. However, in contrast to the previous stage, which saw volcanism on a regional scale as a consequence of the tectonic setting, during this period, many studies were conducted that described volcanic geomorphology in specific regions such as the Sunda Volcanic Complex in West Java (Nossin et al., 1996), the Lamongan Volcanic Complex in East Java (Carn, 2000), the Bicol Arc in the Philippine Mobile Belt (Andal et al., 2005). At this stage, for the first time, a study discusses geomorphic processes, namely lava flows and pyroclastics generated from stratovolcano eruptions. Two volcanoes are of interest at this stage, namely Pinatubo in the Philippines (Torres et al., 2004; Rodolfo and Umbal, 2008) and Merapi (Abdurachman et al., 2000; Charbonnier & Gertisser, 2008; Gomez et al., 2008). On the other hand, discussion on the topic of volcano morphology was absent during this second stage.

The third stage lasted briefly between 2009-2014. However, this stage saw study achievements in all themes of regional geomorphology, volcano morphology, and geomorphological processes. Regional geomorphology in this era discussed the disastrous impacts of eruptions on the surrounding environment, such as post-eruption sedimentation (Gran et al., 2011), rain lava flooding (De Bélizal et al., 2013) and losses due to eruptions (Cronin et al., 2013). On the topic of volcano morphology, this era is characterized by various studies conducted to understand the topography of volcanoes by utilizing geospatial technology, as performed by (Gertisser et al.,

2012). Meanwhile, on geomorphological processes, some studies monitor the eruption process at this stage with various parameters, as (Charbonnier et al., 2013).

The fourth stage took place in the 2015-2019 period. This era is characterized by progress in all three themes. In the regional geomorphology theme, there has been progress in studies that have classified or typified Southeast Asian volcanoes (Whelley et al., 2015). In addition, there is also a discussion about the reconstruction of volcanic history, as conducted by (Selles et al., 2015), who discussed the volcanic history of Mount Merapi as the most active andesite volcano in Indonesia. Discussions about the morphological structure of volcanoes, including their reconstruction, have been very much done, and volcano morphology has been characterized at this time. Some of the studies conducted include the landscape structure of Kerinci Volcano (Belyanin, 2017), the post-caldera volcanic landscape in Buyan-Bratan caldera, Bali (Okuno et al., 2018), and Samalas Volcano, which erupted in 1257 (Mutaqin et al., 2019). The topic of geomorphological processes during this period was marked by advances in modeling the eruption process using DEMs (Yulianto et al., 2016) and volcanic landscape morphodynamics in the form of fluvial readjustment of the Opak River in Java after the major eruption of Mount Merapi in October and November 2010 (Gob et al., 2016) .

The final or fifth stage is the period 2020-2024. This stage is still ongoing, so it is not yet known when the era will change, depending on the new achievements produced by the authors of volcanic geomorphology. The most recent achievement that occurred in this era is the thought of various potential natural resources in the volcanic environment, including groundwater (Setiawan et al., 2020), soil potential for agricultural land (Noviyanto et al., 2020), and mining minerals (Juhadi et al., 2022) These studies mark the topic of regional geomorphology in the fifth stage.

The topic of volcano morphology in the fifth stage is characterized by advances in the study of palaeo-geomorphology reconstruction of volcanoes as a follow-up to the reconstruction of volcanic structures in the previous era. Interestingly, the analyses used are inspired by models from the last era, such as those used by (Jhanesta et al., 2020) at Anak Krakatau Volcano. (Paguican et al., 2021) also examined volcanic morphology using SRTM data and the MORVOLC algorithm in the Philippines. Meanwhile, on the topic of geomorphological processes, there are many discussions on the characteristics of eruption products, especially debris deposits (Malawani et al., 2020; Moktikanana et al., 2021), morphological evolution of the volcanic environment (Ashari et al., 2021), and the impact of anthropogenic activities on the evolution of volcanic morphology such as in the Gede-Pangrango Volcano (Belyanin, 2021) and Welirang (Masruroh et al., 2024).

4. Conclusion

As part of the Ring of Fire, Southeast Asia has an essential place in the discussion of volcanism in the world. Here, we present a review of the results of volcanic geomorphology studies conducted in Southeast Asia. There are 53 studies that we reviewed. Various studies were conducted in Indonesia and the Philippines, two Southeast Asian countries with many volcanoes. The studies were conducted over six decades and divided into five stages of development, namely stage I (1963-1994), stage II (1995-2008), stage III (2009-2014), stage IV (2015-2019), and stage V (2020-2024). The studies were contributed by authors from 11 countries, with Indonesia and France being the two central contributing countries. The studies are diverse, ranging from descriptive-exploratory regional geomorphology discussions, reconstruction of volcanic morphology, and geomorphic processes dominated by eruptions.

This study still has limitations, namely that the source documents are limited to Scopus only. To obtain broader results, future studies are highly recommended to expand the search by using other databases, such as Web of Science, Google Scholar, and ProQuest, supported by databases of various credible publishers. Moreover, we also recommend exploring the study of environmental geomorphology related to potential resources and natural disasters, because this topic is widely discussed primarily in the last stage.

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Conflicts of Interest: The authors declare no conflict of interest.

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