



Geophysics Quantitative Research Mapping of Geomagnetic Method Implementation for Geothermal Exploration: A Bibliometric Analysis

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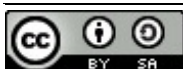
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Abstract: Indonesia holds the world's second-largest geothermal potential, driven by its numerous volcanoes and active tectonic activity. However, the nation's soaring population growth rate starkly contrasts with the declining availability of non-renewable energy. Consequently, developing renewable energy, such as geothermal, is crucial. Nonetheless, geothermal exploration in Indonesia faces challenges related to high costs and complex terrain. The geomagnetic method, known for its efficiency and effectiveness in mapping geothermal systems, remains underutilized in the Indonesian context. This study employs a bibliometric analysis to map the global research landscape and identify trends in the application of the geomagnetic method for geothermal exploration, specifically examining the research gap in Indonesia. Data from 200 indexed articles (2015-2025) were extracted from Google Scholar using Publish or Perish and analyzed quantitatively. The data were then visualized using VOSviewer to map keyword co-occurrence networks and the geographical distribution of research output. The results show a significant annual increase in global publications on this topic. VOSviewer network visualization identified key research clusters, focusing on themes like "magnetics", "curie depth", "anomaly", and "renewable energy". Density visualization confirmed the method's widespread application internationally. However, overlay visualization of publication timelines revealed that contributions from Indonesian-affiliated research remain sparse and lag behind global trends, highlighting a distinct research-implementation gap. These findings underscore the critical need for increased research focus and adoption of this cost-effective geomagnetic method to accelerate the exploration and harnessing of Indonesia's vast geothermal potential.

Keywords: Geophysics, Magnetic method, Geothermal Exploration, Alternative energy, Bibliometric analysis



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1. Introduction

Energy is important in life as a driver of something to work more for human life or objects. Human body activities require energy to move, breathe, think, without energy humans will die. In general, energy is divided into 2, namely renewable energy and non-renewable energy, for example non-renewable energy (non-renewable) comes from fossils which will run out if used continuously and energy comes from nature, for example biomass energy, solar energy, wind energy, geothermal energy, ethanol energy and wave energy [1].

The importance of renewable energy is that it can replace non-renewable energy, because renewable energy is widely available on earth and will not run out. At this time humans utilize a lot of non-renewable energy (non-renewable), if this habit continues then gradually energy will run out and human life will experience a crisis. High energy demand makes non-renewable energy reserves shrink. Humans are increasingly researching about energy sourced from natural materials that are renewable, sustainable, and will never run out if used sustainably [1].

One of the renewable energy sources is geothermal energy, which comes from the heat found in the earth's core and is naturally occurring. Other types of energy, such as electricity and non-fossil fuels, are produced from geothermal energy. Electricity can be generated using geothermal energy. The heat energy contained in hot water, water vapor, rocks, minerals, and other gases that are genetically inseparable from the geothermal system is known as geothermal energy. Its direct applications, such as power generation. Geothermal energy generally comes from the earth's core, specifically from hot water vapor, volcanic eruptions, and heat energy from the earth's crust [2]. The natural energy that comes from within the earth due to the interaction between the heat of the rock and the surrounding air is known as geothermal. Geothermal energy has a low level of carbon emissions, making it an environmentally friendly renewable energy source. As long as the environment is maintained, geothermal resources always be formed and regenerated [1].

Indonesia faces major challenges in meeting its energy needs in the future. High dependence on fossil energy sources, such as petroleum and coal, is increasingly non-renewable as available reserves are depleted. On the other hand, Indonesia's population continues to grow, which automatically increases the demand for energy for various purposes, ranging from households to industries. This situation is exacerbated by the inevitable rise in fuel oil prices, burdening the public and other economic sectors. Therefore, the development and implementation of renewable energy solutions is an urgent need to ensure national energy security, reduce environmental impacts, and improve people's welfare [3,4].

The solution to renewable energy is to utilize renewable energy because Indonesia's natural resources are very broad, the development of solar energy, for example, is the maximum utilization of solar panels in helping to optimize the receipt of solar energy [5,6]. Wind energy also offers significant opportunities, as evidenced by studies showing the potential for wind farms that could make a major contribution to the national electricity supply [7,8].

The origin of geothermal energy is from magma that comes from the earth's crust, this energy will never run out (renewable). Geothermal energy can be converted into other forms; one example is geothermal energy can be utilized for electricity supply and can be converted into a power plant. Geothermal energy when utilized as fuel will produce little greenhouse gas discharge. So, you could say that geothermal renewable energy is more environmentally friendly [1].

Geomagnetic method is one of the geophysical exploration techniques that utilizes variations in the earth's magnetic field to identify subsurface structures as sources of geothermal energy and

describe low anomalous areas associated with geothermal manifestations. Geomagnetic method is one of the geophysical methods used to investigate the condition of the earth's surface by utilizing the magnetic properties of materials identified by the magnetic susceptibility of rocks [9].

Basically, the geomagnetic method uses the physical ideas of the potential method, which takes into account variations in the direction and magnitude of the magnetization vector during measurement. There is a direct correlation between rock composition and total magnetic anomaly, which indicates subsurface characteristics. The magnetic anomaly of the magnetic field affects the magnetic field properties of the rock, which requires data reduction to explain the anomaly. Magnetic anomalies are changes in the magnetic field caused by differences in rock type, composition and size. Less obvious structures due to various minerals above the surface can be detected by mapping variations in the magnetic field [10].

Geomagnetic field data tends to be more complex due to the residual nature it exhibits, causing significant variations over time. Magnetic anomaly maps show a large number of these residual anomalies, which are indicative of large variations in the magnetic mineral content of near-surface rocks. These variations arise from the magnetic reduction processes experienced by the rocks. This complexity of data and anomalies needs to be considered in interpretation to understand the subsurface geology more accurately. Therefore, careful analysis is required to separate relevant signals from noise in geomagnetic data [10].

Previous geomagnetic research in the search for geothermal energy identified three types of significant magnetic anomalies. First, very low anomalies (600-200nT) indicate the presence of strongly weathered and altered rocks. Second, low anomalies (more than 200 to 300nT) point to shallow alluvial rocks. Finally, high anomalies (200-300nT) are also associated with shallow alluvial rocks. The presence of hot water and geological control by faults further strengthens the indication of geothermal potential in an area [11].

Literature Review Study: Identification of Geothermal Distribution in Indonesia by Magnetic Method. The results showed that the subsurface of each research area has a geothermal system characterized by the presence of reservoir rocks which are rock formations in the subsurface that are able to store and flow thermal fluids (steam and or hot water). Based on the study, it can be concluded that the magnetic method is a fairly accurate method in identifying geothermal distribution in Indonesia [12].

The identification of geothermal potential in Krakal using geomagnetic methods shows the presence of moderate magnetic anomalies that indicate geothermal prospects based on high temperature characteristics and the effect of rock demineralization. The identification of geothermal in Krakal by utilizing geomagnetic methods as information for the development and construction of potential areas. Data processing and interpretation revealed that the study area falls into the category of moderate magnetic anomalies, with a range between -120 nT to 80 nT. The location is said to be a geothermal prospect if an area has a high temperature which results in a magnetic anomaly having a negative value and causes the emergence of a rock mineralization effect [13].

Based on the statement of previous studies regarding geothermal exploration using geomagnetic methods using literature review studies that have weaknesses, namely limited access to literature, researchers have freedom in choosing and interpreting literature, which can be influenced by personal opinions or theoretical views. Studies using different methodologies and

outcome measures are difficult to synthesize. Literature reviews can become outdated quickly due to the rapid development of knowledge.

Because of its vital role in communication, information exchange, and the advancement of science, the bibliometric method, with a focus on scholarly articles on Google Scholar, was chosen as the solution. This mapping focuses on scholarly articles available on Google Scholar, one of the largest and most comprehensive research portals. [14]. scientific articles are an important tool for communicating and sharing information, essential for the advancement of science [15]. The purpose of the study is to determine the current trend in research on the topic of utilization of geomagnetic methods for geothermal exploration in 2015-2025 and to know the visualization of network mapping, data overlay and data density visualization in research on the topic of utilization of geomagnetic methods for geothermal exploration in 2015-2025.

2. Materials and Method

The research method used is descriptive quantitative method, where bibliometrics search for data by typing keywords. Data analysis uses trends, patterns and relationships, and data visualization uses graphs, and network maps. Bibliometric analysis is a popular and rigorous method for searching and filtering data from large amounts of scientific work. Bibliometric approaches are used to search for domain-specific evolutionary relevance and to focus on specific research areas [16]. Data source criteria include articles that explicitly discuss geothermal exploration using one of the geophysical methods, namely magnetic methods with the keywords “geomagnetic method AND geothermal exploration” applied to identify articles related to geothermal exploration, in journals published in the period 2015-2025. The database of this journal uses Google Scholar integrated publish or perish. The steps of our research can be seen in Fig. 1.

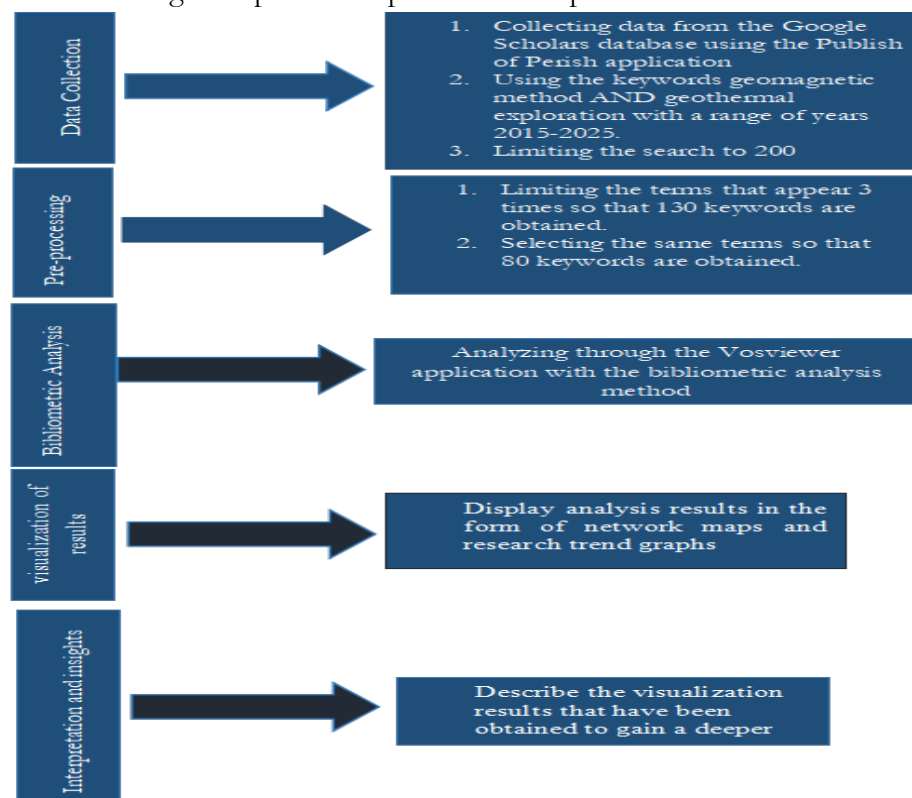


Figure 1. Research Steps for Bibliometric Analysis

The first research step is data collection activities, namely collecting data from the Google Scholars database using the Publish or Perish version 8 (PoP) application. The search was conducted by selecting the Google Scholar database and entering keywords that match the research topic: “geomagnetic method AND geothermal exploration.” The publication year was limited to the period 2015–2025, in order to focus on more recent research developments while still including relevant past studies within the timeframe.

Inclusion criteria for the dataset were: (1) articles published between 2015–2025, (2) research articles (journal articles) only, as they are considered to provide new knowledge contributions, and (3) relevance to the topic of geomagnetic methods in geothermal exploration. Exclusion criteria were: (1) conference papers, book chapters, theses, reports, and reviews, (2) duplicate entries, and (3) articles not directly related to geothermal exploration despite mentioning geomagnetic terms. After applying these criteria, the total number of articles was limited to 200. The PoP review results were then exported in both CSV and RIS/Ref Manager formats for further processing.

The second step is pre-data processing. At this stage, keyword frequency analysis was carried out. Keywords that appeared fewer than three times were excluded, leaving 130 candidate keywords. The keyword table generated from the dataset was then refined through a combination of automated filtering and manual validation. Specifically, VOSviewer’s thesaurus function was used to automatically merge synonymous terms, while irrelevant terms were manually excluded by the researchers to ensure contextual accuracy. As a result, a final set of 80 relevant keywords was obtained for analysis.

The third step is bibliometric analysis, conducted using VOSviewer version 1.6.20 software, a widely used tool for constructing and visualizing bibliometric networks. The analysis focused on co-occurrence networks of keywords, where VOSviewer identified and mapped key terms that frequently appeared together in the literature. This process provided a structured visualization of research themes and trends in the application of geomagnetic methods to geothermal exploration [17].

The fourth step is visualization of results. Data on the number of articles and publication years obtained from Publish or Perish were visualized using Microsoft Excel to identify research trends over time. Meanwhile, data processed in VOSviewer produced three types of bibliometric maps: (1) network visualization, (2) overlay visualization, and (3) density visualization. These maps provide a comprehensive overview of relationships between terms and their evolution across the studied period. The fifth research step is Interpretation and insight, 3 maps that have been obtained on VOSviewer are then described, first this network visualization helps identify groups of closely related terms, which indicate the main research focus and gaps in the existing literature, thus providing a basis for further research. Secondly the data overlay visualization helped identify which years the articles were searched for. Thirdly the density of the data helped identify the most, and least found keywords.

VOSviewer is a commonly used application for knowledge visualization. VOSviewer can also be defined as software that builds and visualizes networks. VOSviewer identifies and maps key terms that often appear together in the literature. The VOSviewer biometric application can be uploaded on the official website www.vosviewer.com. the application of VOSviewer can create a network of scientific publications, scientific journals, researchers, research organizations, countries, keywords, or terms [7].

3. Results and Discussion

2.1. Results

Based on Bibliometric Analysis and the research that has been done, it produces a trend in the utilization of geomagnetic methods for geothermal exploration. The results of this study are not too far from the objectives that the author conveyed. Through data processing, the relationship between the measured variables can be seen. The presentation of the data obtained will be visualized in the form of graphs, data net images, data overlay images, and data density images.

2.1.1. Research trends

Figure 2 presents a graph of data on article publishing activities each year, data collection taken using publish or perish and then will be analyzed using excel. The purpose of presenting this graph is to provide an overview of the distribution pattern, article publishing activities with the title utilization of geomagnetic methods for geothermal exploration every year and identify which years the publication of articles has increased and which years the publication of articles has decreased.

Based on Figure 2, it can be explained that the annual publishing activities of geothermal exploration using geomagnetic methods are very low, although there is an increase each year. In 2015-2016 there was an increase, but in 2016-2017 there was a decrease to 6 articles due to the low submission of articles in 2017, 2018-2021 experienced a stable situation of 20 articles 2020-2021 increased to 21 articles, 2021-2022 became 18 articles, 2022 experienced an increase to 22 articles, 2023-2024 experienced a significant increase to 26 articles, and in 2024-2025 experienced a significant decrease to 6 articles, this decrease was due to the year of making this article 2025 in May and still the beginning of the year.

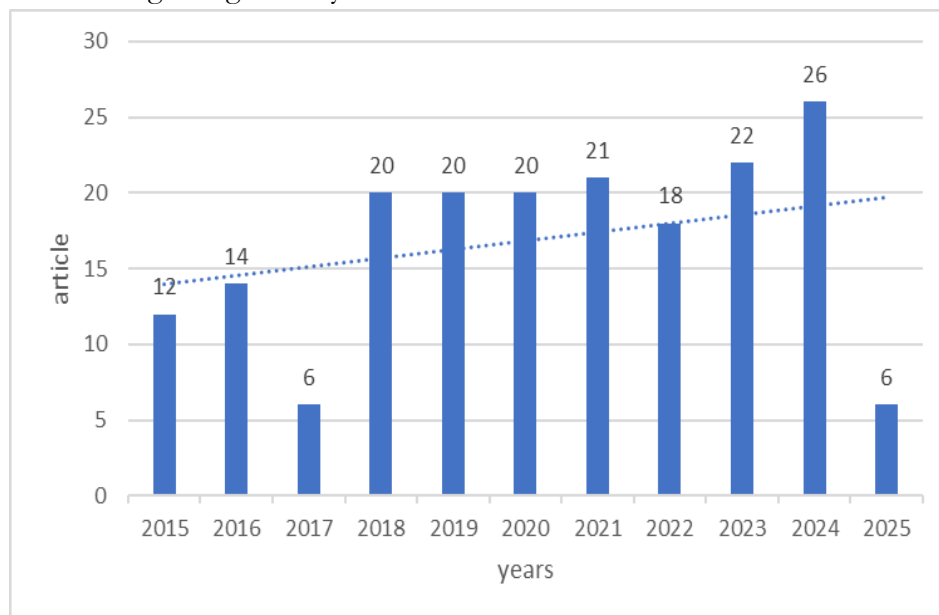


Figure 2. Sketch of Article Publication

2.1.2. Data Network Visualization

Network visualization is a visualization that considers each item represented as a node, generally in the form of a circle. The size of the node or circle reflects the weight of the item; the greater the weight of the item, the larger the node or circle that represents it. To prevent overlaps that interfere with visualization, some nodes may not be displayed. Meanwhile, the color of the

item is used to indicate the cluster or group that the item belongs to. Figure 3 presents the data network visualization of the scatter mapping results using Vosviewer. The purpose of presenting this figure is to provide an overview of identifying patterns, patterns that may be interconnected by looking at clusters based on color, the same color indicates the keywords of one cluster.

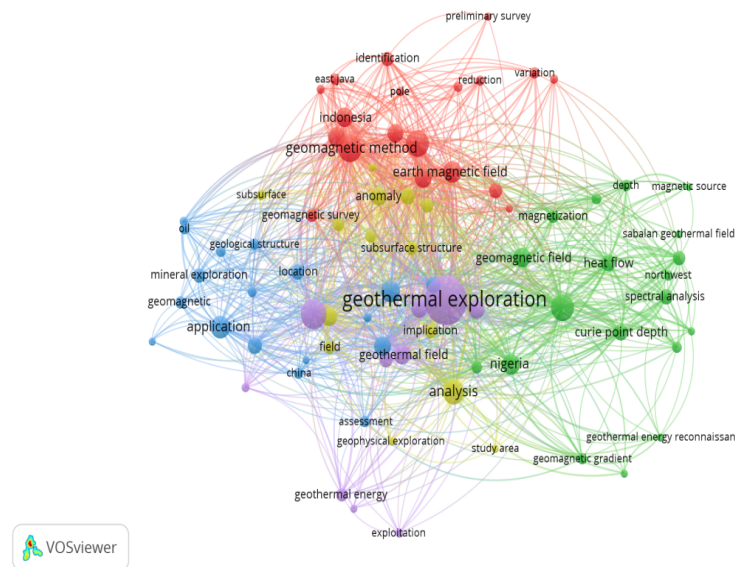


Figure 3. Results of Data Netting with Vosviewer

Mapping results in Figure 3 show the relationship between geothermal exploration (central node) with various countries with geothermal potential and other terms. In cluster 1 red keywords available there are 19 namely characterization, earth magnetic field, east java, focus, geomagnetic method, geomagnetic survey, geothermal area, geothermal reservoir, geothermal system, identification, Indonesia, integration, magnetic, method, modeling, pole, preliminary survey, reduction, rock, variation. In cluster 2 in green color, there are 19 keywords available, namely, curie point depth, depth, geomagnetic data, geomagnetic field, geomagnetic, gradient, geothermal energy reconnaissance, geothermal gradient, heat flow, high resolution aeromagnetic data, international geomagnetic, Iran, magnetic source, magnetization, Nigeria, northwest, Nigeria, potential, Sabalan geothermal field, southeast Nigeria, spectral analysis. The 3 blue clusters contained 18 keywords, namely, application, assessment, case study, China, fault, gas exploration, geological structure, geomagnetic, geothermal manifestation, geothermal potential, geothermal, geothermal exploration, gis, location, mapping, measurement, mineral exploration, oil. In cluster 4 in yellow there are 14 keywords, namely, analysis, anomaly, field, geophysical exploration, geophysical methods, geothermal, geothermal, geothermal energy exploration, geothermal investigation, image, implication, magnetic data, research area, subsurface, subsurface structure. In purple-colored cluster 5 there are 10 keywords, namely, exploitation, exploration methods, geothermal energy, geothermal energy potential, geothermal exploration, geothermal field, geothermal prospects, interpretation, region, structure.

2.1.3. Data Overlay Visualization

Data visualization is the final type of visualization provided by VOSviewer, in which brighter colors indicate higher values for a given variable. By default, the color scale ranges from blue to green to yellow. The color of each item depends on its density (which is determined by its cluster). Yellow indicates keywords that are frequently used, while the closer the color is blue, the less frequently the keyword appears. Figure 5 presents a data density visualization resulting from a distribution mapping using VOSviewer. The purpose of this figure is to provide an overview of keyword patterns based on color, and to identify how frequently keywords are used, as indicated by the color scale.

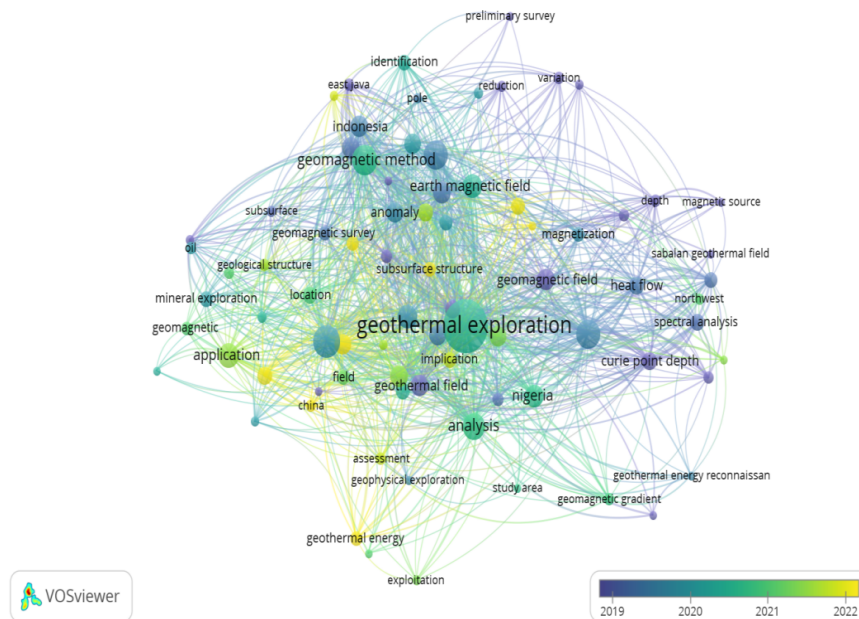


Figure 4. Data Overlay Visualization

The mapping results shown in Figure 4 indicate that research related to geothermal exploration appeared frequently in 2020, geothermal potential studies were prominent in 2020, and research on geothermal in Indonesia was most common in 2019, particularly in the East Java region. Meanwhile, international geothermal research in Nigeria appeared mostly in mid-2020, research in China peaked in 2022, geothermal in the Northwest appeared frequently in 2021, and studies in Iran were most prominent in mid-2018. This can be observed from the color representation, ranging from blue for the lowest scores to yellow for the highest. The above studies provide insight into how geothermal exploration contributes to the development of geothermal energy in each respective country.

2.1.4. Data Density Visualization

Data visualization is the final type of visualization provided by VOSviewer, in which brighter colors indicate higher values for a given variable. By default, the color scale ranges from blue to green to yellow. The color of each item depends on its density (which is determined by its cluster). Yellow indicates keywords that are frequently used, while the closer the color is blue, the less

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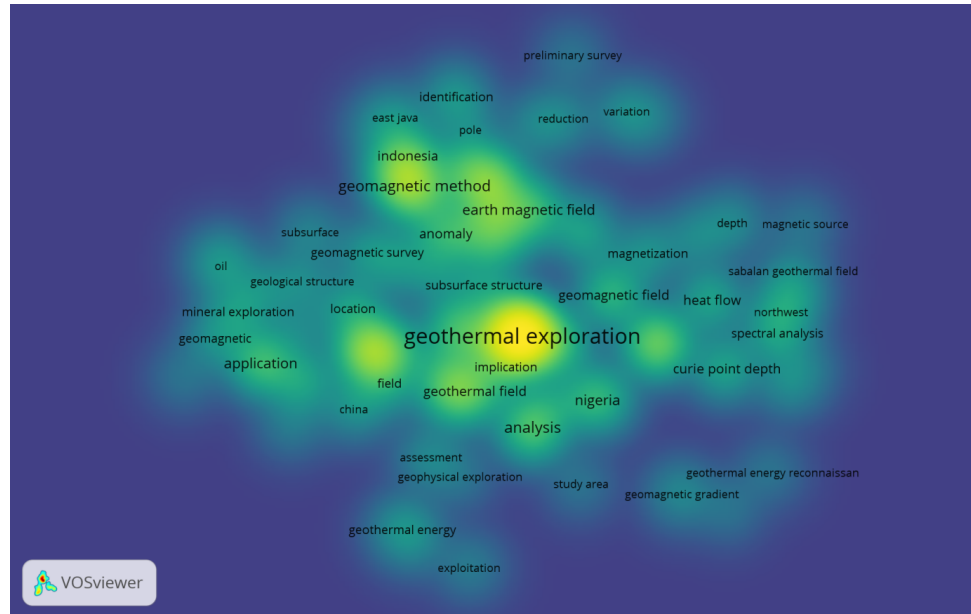


Figure 5. Density visualization results

The data visualization results indicate that the brighter the color, the more frequently the keyword appears. The bright keywords in this case are shown in yellow, including: “geothermal exploration, Indonesia, East Java, geomagnetic method, Earth's magnetic field, implications, geothermal field system, geomagnetic method, geothermal area, geothermal potential, geomagnetic measurement data, exploration method, and application.” Meanwhile, the darker keywords-represented by green and blue-appear less frequently. These keywords include: geothermal prospects, geothermal energy, Iran, northwest, geothermal gradient, mineral exploration, geomagnetic structure, and international geology.

2.2. Discussion

The results of this study on the application of geomagnetic methods for geothermal exploration using VOSviewer provide a comprehensive overview of global research trends based on bibliometric analysis of 200 articles. The density visualization highlights frequently occurring keywords such as geothermal exploration, Indonesia, East Java, geomagnetic method, Earth's magnetic field, geothermal potential, and exploration methods. These findings emphasize the prominent role of geomagnetic techniques in geothermal energy exploration. However, the practical implications of these keyword patterns require deeper examination. For instance, geomagnetic methods enable the early identification of magnetic anomalies associated with geothermal systems in a relatively cost-effective, rapid, and non-invasive manner compared to seismic or gravity methods, which typically involve higher costs. Nevertheless, geomagnetic surveys are limited by their sensitivity to external magnetic disturbances and their inability to provide

detailed reservoir depth information. Therefore, integration with other geophysical methods is essential to improve exploration accuracy.

The overlay visualization further illustrates the temporal dynamics of geothermal research. In Indonesia, particularly East Java, geothermal exploration research peaked in 2019, while studies on geothermal potential reached their highest intensity in 2020. Internationally, research in China increased significantly in 2022, in line with the country's rapid progress in geothermal energy utilization, both for power generation and direct use. In contrast, geothermal research in Nigeria and the Northwest region remains in its early stages, focusing mainly on identifying potential areas without substantial implementation. Iran recorded the most active geothermal research in 2018, coinciding with the construction of the first geothermal power plant in Western Asia. These temporal variations reflect that each country faces distinct technical, social, and policy contexts in adopting geothermal technologies.

In the case of Indonesia, despite its vast geothermal potential, utilization remains limited to only three operating geothermal power plants [18,19] and indirect applications such as hot springs [20], agricultural product drying, industrial processes, aquaculture, and agriculture [21]. These limitations suggest that barriers are not only technical but also rooted in social, cultural, and regulatory factors. Hence, successful geothermal development requires strategies that ensure local community participation, clear energy policies, and stronger support for innovation.

From a methodological perspective, relying solely on Google Scholar as the database provides a broad yet limited foundation for bibliometric analysis. The exclusion of established databases such as Scopus and Web of Science may result in the omission of highly indexed and peer-reviewed literature, thereby creating a potential bias in representation. This limitation is crucial to acknowledge, as integrating multiple databases in future studies will yield a more robust and accurate mapping of geothermal research trends.

Accordingly, this study contributes to three key areas. First, in terms of energy policy, it highlights the importance of incorporating geomagnetic methods into exploration strategies as part of renewable energy diversification. Second, from a technological perspective, the findings demonstrate that geomagnetics can serve as an efficient preliminary exploration tool before employing more expensive techniques. Third, in terms of research directions, this study opens opportunities for interdisciplinary approaches that integrate technical, social, and policy dimensions in the sustainable management of geothermal resources.

4. Conclusion

This study provides a comprehensive bibliometric analysis of 200 research articles, mapping the global trends in the application of geomagnetic methods for geothermal exploration. The findings reveal that while research output on this topic has gradually increased over time, the implementation of geomagnetic techniques remains uneven across countries. Indonesia, with its abundant geothermal potential, still exhibits limited utilization, whereas countries such as China and Iran have shown more significant progress in both research activity and practical application. These variations underscore the importance of aligning exploration technologies with socio-political contexts and energy policies.

The use of geomagnetic methods emerges as both a strength and a challenge. On the one hand, geomagnetic surveys are cost-effective, rapid, and non-invasive, making them a valuable

preliminary tool for identifying geothermal anomalies. On the other hand, their limited resolution and sensitivity to external disturbances highlight the need for integration with complementary geophysical methods. This analysis contributes to academic knowledge by demonstrating how bibliometric approaches can uncover global research dynamics, identify methodological gaps, and connect keyword trends to practical implications in geothermal exploration.

Beyond academic contributions, the results carry important implications for policy and industry stakeholders. By highlighting the role of geomagnetic methods in exploration, this study underscores their potential contribution to renewable energy strategies and the broader energy transition. Policymakers can draw on these insights to design clearer regulations, encourage innovation, and promote community engagement in geothermal projects. Investors and industry actors can use the findings to identify research hotspots and emerging opportunities for geothermal development.

Looking ahead, future research should expand the bibliometric scope by integrating multiple databases such as Scopus and Web of Science to provide a more comprehensive and unbiased picture. Moreover, interdisciplinary studies that bridge technical, social, and policy dimensions are essential for advancing sustainable geothermal energy utilization. Ultimately, this study demonstrates that geomagnetic-based bibliometric mapping is not only valuable for understanding research trends but also for guiding strategic decision-making in the global transition toward renewable energy.

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