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# Bibliometric Analysis of Studies on "Machine Learning in Geothermal Energy"

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**Abstract:** This study examines the scientific literature developing at the intersection of geothermal energy and machine learning from a bibliometric perspective. 300 academic publications published between 2010 and 2025, obtained from the Web of Science database, were analyzed using the R-based Biblioshiny tool. The study revealed the distribution of publications by year, citation performance, author, institution and country collaborations, the most cited studies and keyword co-occurrence networks. The findings show that there has been a significant acceleration in the field after 2019 and especially from 2022, with production reaching a high level in 2024–2025. While Geothermics was the journal with the most publications, multidisciplinary journals such as Renewable Energy, Energies, and Applied Energy also attracted attention. In the keyword analysis, technical themes such as Organic Rankin Cycle, Enhanced Geothermal System, reservoir, and temperature optimization were central; By 2024, new trends such as hydrogen and advanced geothermal systems have emerged. China leads by far in the number of publications and citations and maintains strong collaborations with the United States and Germany. The study comprehensively summarizes the status of the geothermal energy-machine learning field and provides a guiding framework for future research trends and areas of collaboration.

**Keywords:** Machine Learning, Geothermal Energy, Bibliometric Analysis, Biblioshiny, Web of Science

# "Jeotermal Enerjide Makine Öğrenmesi" Konulu Çalışmaların Bibliyometrik Analizi

**Öz:** Bu çalışma, jeotermal enerji ve makine öğrenmesi kesişiminde gelişen bilimsel literatürü bibliyometrik bir bakış açısıyla incelemektedir. Web of Science veri tabanından elde edilen 2010-2025 yılları arasında yayınlanmış 300 akademik yayın, R tabanlı Biblioshiny aracı kullanılarak analiz edilmiştir. Çalışmada yayınların yıllara göre dağılımı, atıf performansı, yazar, kurum ve ülke iş birlikleri, en çok atıf alan çalışmalar ve anahtar kelime eş-geçiş ağları ortaya konulmuştur. Bulgular, 2019'dan sonra ve özellikle 2022'den itibaren alanda önemli bir ivmelenme olduğunu, üretimin 2024-2025'te yüksek bir seviyeye ulaştığını göstermektedir. En çok yayını olan dergi Geothermics olmakla birlikte, Renewable Energy, Energies ve Applied Energy gibi multidisipliner dergiler de dikkat çekmiştir. Anahtar kelime analizinde Organik Rankin Döngüsü, Geliştirilmiş Jeotermal Sistem, rezervuar ve sıcaklık optimizasyonu gibi teknik temalar merkezi konumdadır; 2024 yılına gelindiğinde, hidrojen ve gelişmiş jeotermal sistemler gibi yeni trendler ortaya çıkmıştır. Çin, yayın ve atıf sayısında açık ara lider konumda olup, Amerika Birleşik Devletleri ve Almanya ile güçlü iş birliklerini sürdürmektedir. Çalışma, jeotermal enerji-makine öğrenmesi alanının durumunu kapsamlı bir şekilde özetlemekte ve gelecekteki araştırma trendleri ve iş birliği alanları için yol gösterici bir çerçeve sunmaktadır.

**Anahtar Kelimeler:** Makine Öğrenmesi, Jeotermal Enerji, Bibliyometrik Analiz, Biblioshiny, Web of Science

## 1. Introduction

As fossil fuels, a limited and exhaustible resource, are projected to be depleted soon, researching and implementing alternative energy sources to secure energy supplies and achieve sustainable development is increasingly urgent [1]. Furthermore, increasing global energy demand and intensifying efforts to combat climate change have made the shift towards sustainable and clean energy sources more crucial than ever. In this context, geothermal energy, which stands out among renewable energy sources with its potential to provide baseload power, is attracting attention as a stable and reliable alternative [2]. The exploration, development, and management of geothermal resources involve challenging processes requiring the understanding of complex geological structures and the analysis of large data sets. Traditional methods can be time-consuming and costly in these processes [3].

In recent years, as a reflection of the "Fourth Industrial Revolution," technologies such as artificial intelligence (AI), machine learning, and deep learning have led to a paradigm shift in the energy sector, as in many other areas of scientific research. Artificial intelligence applications, particularly in geothermal energy, have led to: It opens new horizons in critical areas such as reservoir modeling, identifying potential fields, optimizing drilling operations, and increasing production efficiency. The intersection of these two dynamic and innovative fields is attracting increasing interest in both academia and industry [4].

The aim of this study is to reveal the intellectual structure and research trends of scientific literature emerging at the intersection of geothermal energy and artificial intelligence using a bibliometric analysis method. For this purpose, 300 scientific documents published between 2010 and 2025 were examined using the Web of Science (WoS) database [5]. R-based Biblioshiny library is used for data analysis and visualization.

This analysis seeks to answer the following fundamental research questions:

- What is the distribution of publications on geothermal energy and artificial intelligence over the years, and how has scientific interest in this field evolved?
- Which authors, institutions, and countries have published the most and are the most influential in this field?
- What is the map of the main themes, key concepts, and intellectual accumulation of research?
- What are the potential future research trends and potential areas for collaboration?

This bibliometric analysis hopes to provide a comprehensive snapshot of the current state of knowledge in the field of geothermal energy and artificial intelligence, providing researchers, policy makers, and industry professionals with a roadmap for future work.

## 2. Material and Method

Bibliometrics [6], a widely used subdiscipline of science measurement, encompasses the study and measurement of scholarly communication. This field uses quantitative methods to analyze and evaluate scholarly literature, including journals, articles, and authors, allowing researchers to gain insight into the direction of the field [7]. Thus, it can provide valuable information about the productivity, impact, and growth of a particular research field. Bibliometric analysis can also reveal collaboration patterns, identify leading researchers, and track the evolution of research frontiers.

This study used scholarly mapping analysis to gain a comprehensive understanding of the evolving architecture of a particular field of study [8].

WoS database used in this study is an internationally recognized, comprehensive, and reliable information source. Owned by Thomson Reuters Corporation, the platform is considered the most comprehensive search resource of its kind, featuring journals from high-quality publishers and high-impact studies. Therefore, it has become the standard data source for bibliometric analysis [5].

Data collection was conducted in a general manner, and all articles resulting from the "Topic Sentences (TS)" search were included in the dataset. Therefore, a dataset consisting of 300 "Articles" was created, covering publications between 2010 and 2025. All bibliographic information (authors, institutions, countries, keywords, abstracts, citations, etc.) of relevant publications were exported in "Plain Text" format and prepared for analysis. The study methodology is presented in Figure 1, and TS was chosen as *"("geothermal energy" OR "geothermal power" OR "geothermal reservoir") AND ("artificial intelligence" OR "AI" OR "machine learning" OR "deep learning")".*

Biblioshiny, an interactive web interface supported by the R programming language-based Bibliometrix [9] package, was used for data analysis and visualization. The analysis process was conducted under two main headings, Performance Analysis and Scientific Mapping Analysis, as indicated in Figure 1. Performance analysis aims to measure the overall productivity and impact of the research field. The following metrics were examined in this context:

- *Publication and Citation Counts:* Annual publication counts and the total number of citations to these publications were analyzed to examine the temporal evolution of the field and the growth in scientific interest.

- *Publication Types and Research Areas:* Analyses were conducted to determine the publication types (articles, reviews, proceedings, etc.) the literature comprises and the research areas it focuses on according to WoS categories.
- *Highly Cited Publications:* The most cited articles were listed to identify the key publications that form the intellectual foundation of the field and have the greatest impact.

Scientific mapping is used to visualize the conceptual structure and social networks of a research field. These analyses reveal the intellectual dynamics of the field and the relationships between actors:

- *Burst Detection:* Kleinberg's burst detection algorithm was used to identify emerging and "hot" research topics by identifying sudden increases in the popularity of specific keywords.
- *Most Frequent Words:* Author keywords were analyzed to identify the key themes and concepts on which the research focused.
- *Author and Institution Co-authorship Analysis:* Co-authorship analyses were conducted to reveal collaboration networks between researchers and institutions. This analysis helps identify key research groups and centers in the field.
- *Collaboration Mapping*: A world collaboration map was created to visualize the level of scientific collaboration between countries.

This methodological framework provides a solid foundation for comprehensively assessing the current status of geothermal energy and artificial intelligence research and discussing future trends.

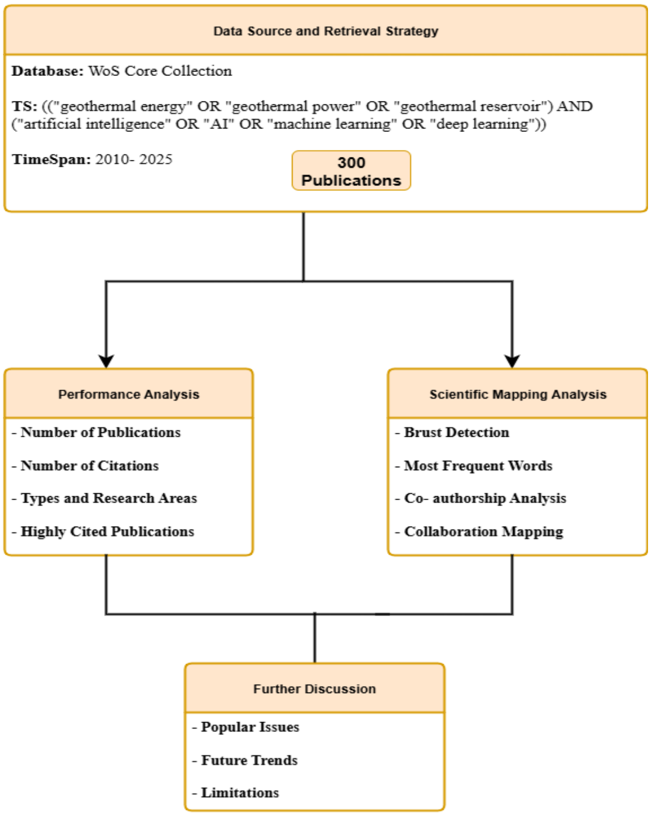


**Figure 1.** Framework of methodology

## 3. Result

### 3.1. Performance Analysis

Performance analysis in the examined period includes indicators such as the number of publications varying by year, the number of citations, the prevalence of the study and its role as a basis for different studies, research areas and the journals in which publications are concentrated, and the most highly cited studies.

The sixteen-year period examined in the study demonstrates two main phases in scientific production (Figure 2). The results, which appear as a stagnant initial period and a rapid acceleration period, indicate that the growth coefficient increased, particularly starting in 2022. A similar number of studies were published in 2024 and 2025. The process, which began with three publications in 2010, was interrupted by zero publications in 2011, 2014, and 2016. This suggests that the relevant research topic was either not yet discovered or had not attracted sufficient attention from the academic community during these years. The four publications recorded in 2019 can be considered the first harbinger of an increasing trend in the following years.

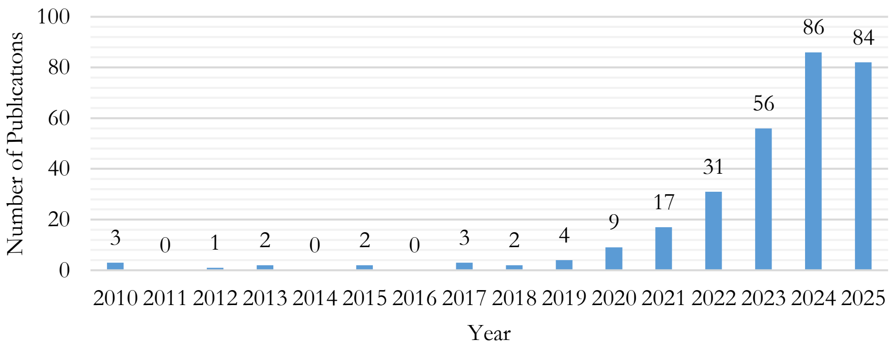


**Figure 2.** Annual scientific production

Examination of the dataset inferred (Table 1) "4" publications is single-authored. The collaboration index is a metric that measures the degree of collaboration among authors in a particular field or on a specific topic. It is calculated by dividing the number of co-authored publications by the total number of publications expressed as a percentage. A higher collaboration index indicates a higher degree of collaboration among authors in the field, while a lower collaboration index suggests that most of the publications are single-authored or have a small number of authors. The collaboration index is often used to study the collaboration patterns and trends within a field of research and to identify the most productive institutions and researchers. The collaboration index is calculated to be "3.17". This shows that collaboration is common in research in the field and that studies are generally conducted by multiple authors. Additionally, the average citations per document were computed to be "15.36".

**Table 1.** Spatial accessibility status of health service centers

| **Average citations per document** | **15.36** |
|---|---|
| Authors | 1350 |
| Multi-authored documents | 1346 |
| Single-authored documents | 4 |
| Co-Authors per Documents | 5.18 |
| Collaboration Index | 4.49 |

Table 2 shows that classification of publications in different categories. While the dataset contains mostly articles (265), it appears that there are very few scientific products in this field, such as papers and book chapters, scanned within WoS. This is a significant shortcoming.

**Table 2.** Document types

| **Document Type** | **Numbers** |
|---|---|
| Article | 265 |
| Book Chapter | 1 |
| Proceeding Paper | 7 |
| Review | 25 |
| Early Access | 2 |

Figure 3 indicated that the top 10 scientific sources where the publications were published most frequently and the number of publications in these sources. It is important for revealing which journals concentrate academic knowledge in the field and the interdisciplinary nature of the topic. The most striking finding is that the journal "Geothermics" is the clear leader, with 40 publications, compared to other sources. This clearly demonstrates that "Geothermics" is the primary, most fundamental, and specialized (core) publication outlet for this research topic. It appears that researchers in the field primarily choose this journal to publish their work. Journals such as "Renewable Energy" (21 publications), "Energies" (18 publications), and "Energy" (12 publications), which are at the top of the list, confirm that the topic is not limited to a specific niche area but also attracts broad and current interest within the renewable and general energy disciplines. This demonstrates that the research appeals to a broad academic audience and is relevant to general energy policy and studies. The presence of journals focused on applied science and engineering, such as "Applied Thermal Engineering" (9 publications), "Applied Energy" (7 publications), "Geoenergy Science and Engineering" (7 publications), "Energy Conversion and Management" (6 publications), and "Case Studies in Thermal Engineering" (5 publications), is noteworthy. This highlights that, in addition to the theoretical basis of the research, it has a strong engineering, application, and thermal sciences dimension. The field has a clear central and specialized focus, centered around the journal "Geothermics". The subject is strongly related to broader fields such as general energy and renewable energy. A significant portion of the research focuses on practical engineering solutions and thermal applications.

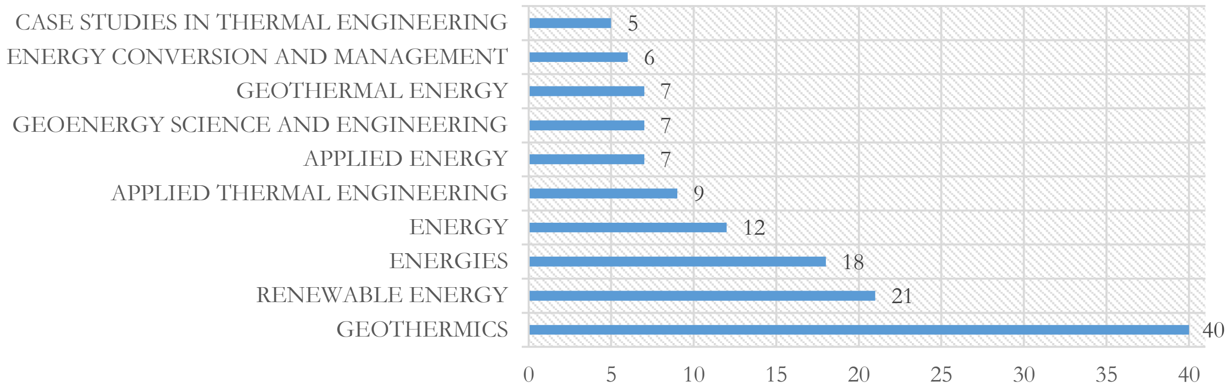


**Figure 3.** Top 10 most relevant sources

When examining the most cited journals (Figure 4), Geothermics reinforces its position as the leading field in the most cited fields. Despite its large number of publications, Energies appears to have received relatively few citations. In general, with the exception of Energies, the number of citations is high relative to the number of publications.

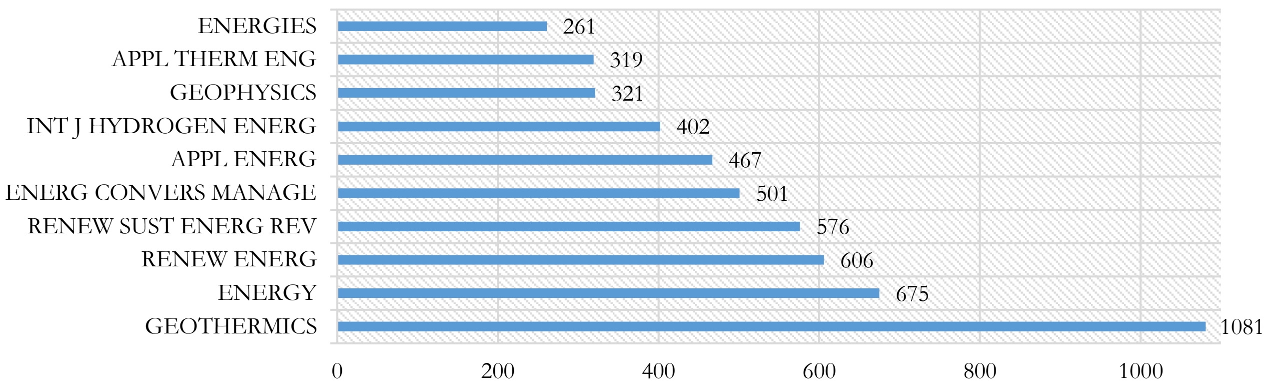


**Figure 4.** Top 10 most cited journals

Table 3 presents a comprehensive breakdown of information about the source, type, year of publication, citation count (NoC), average citations (ACit), number of authors (NoA), number of institutions (NoI), and number of countries/regions (NCount) for the publications under consideration. As expected, during the rising popularity of the concept, the oldest publications on this concept appear to be among the most cited. Furthermore, an examination of research types reveals that eight of the most cited publications are articles, while only two are reviews. It has been shown that method-based studies tend to receive more citations and attention than reviews. All studies have at least two authors, while some have more than five. Generally, there is not much institutional diversity. Studies have been conducted by a combination of at most three institutions.

**Table 3.** Highly cited publications

| Paper | Sources | Type | Year | NoC | ACit | NoA | NoI | NCount |
|---|---|---|---|---|---|---|---|---|
| A review on renewable energy and electricity requirement forecasting models for smart grid and buildings [10] | Renewable Sustainable Energy Review | Review | 2020 | 310 | 51.66 | 3 | 3 | 2 |
| Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of Enhanced Geothermal Systems (EGS) [11] | Comptes Rendus Geoscience | Article | 2010 | 224 | 14 | 5 | 4 | 2 |
| Renewable energy: Present research and future scope of Artificial Intelligence [12] | Renewable Sustainable Energy Review | Article | 2017 | 216 | 24 | 5 | 5 | 3 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| From Fluid Flow to Coupled Processes in Fractured Rock: Recent Advances and New Frontiers [13] | Geophysics | Article | 2021 | 148 | 37 | 11 | 10 | 1 |
| A review on machine learning forecasting growth trends and their real-time applications in different energy systems [14] | Renewable and Sustainable Energy Reviews | Review | 2020 | 114 | 19 | 2 | 2 | 2 |
| Machine learning optimization of a novel geothermal driven system with LNG heat sink for hydrogen production and liquefaction [15] | Energy Conversion and Management | Article | 2022 | 105 | 26.25 | 4 | 1 | 1 |
| Prediction of two-phase flow patterns in upward inclined pipes via deep learning [16] | Energy | Article | 2020 | 98 | 16.33 | 4 | 3 | 3 |
| Productivity prediction of a multilateral-well geothermal system based on a long short-term memory and multi-layer perceptron combinational neural network [17] | Applied Energy | Article | 2021 | 87 | 17.40 | 2 | 2 | 1 |
| A comparative performance analysis, working fluid selection, and machine learning optimization of ORC systems driven by geothermal energy [18] | Energy Conversion and Management | Article | 2023 | 83 | 27.66 | 3 | 2 | 1 |
| Machine learning in subsurface geothermal energy: Two decades in review [19] | Geothermics | Article | 2022 | 75 | 18.75 | 7 | 3 | 1 |

### 3.2. Performance Analysis

Scientific mapping analysis is used to identify patterns, trends, and connections within a field of study. This technique involves visualizing data and information using various types of maps, diagrams, and graphs. The goal of scientific mapping analysis is to provide a comprehensive overview of the state of research in each field and identify areas that may be open to further research. In bibliometric analysis, "burst detection analysis" is a technique used to detect sudden and significant increases in the number of publications on a given topic, also known as "bursts" in literature. This method helps identify research focuses and emerging trends in a field by detecting sudden increases in the number of publications that cannot be explained by normal growth or background noise. The analysis is typically conducted by comparing the number of publications in a given period with the number of publications in previous periods and identifying significant increases in the data. It can help researchers understand new and growing research directions.

Keyword analysis can be seen as a critical component in identifying topics within a given field. A minimum occurrence threshold of 2 was set, and 128 keywords meeting this criterion were found. The resulting concurrency network, shown in Figure 5, shows the connections between keywords appearing in the same publication which calld as “Co-Occurrence Analysis of Keywords”. Node size indicates keyword frequency, while link width corresponds to the number of concurrences. The main cluster related to the organic ranking cycle which is one most important process in geothermal power plants, enhanced geothermal system for efficiency, reservoir and reservoir temperature. These words are critical for geothermal systems in underground and surface applications. It can be said that researchers are focusing on these issues and are turning to production efficiency by improving geothermal systems or controlling their temperatures. It is understood that concepts related to plant efficiency increase and reservoir improvement studies have intensified after 2020.

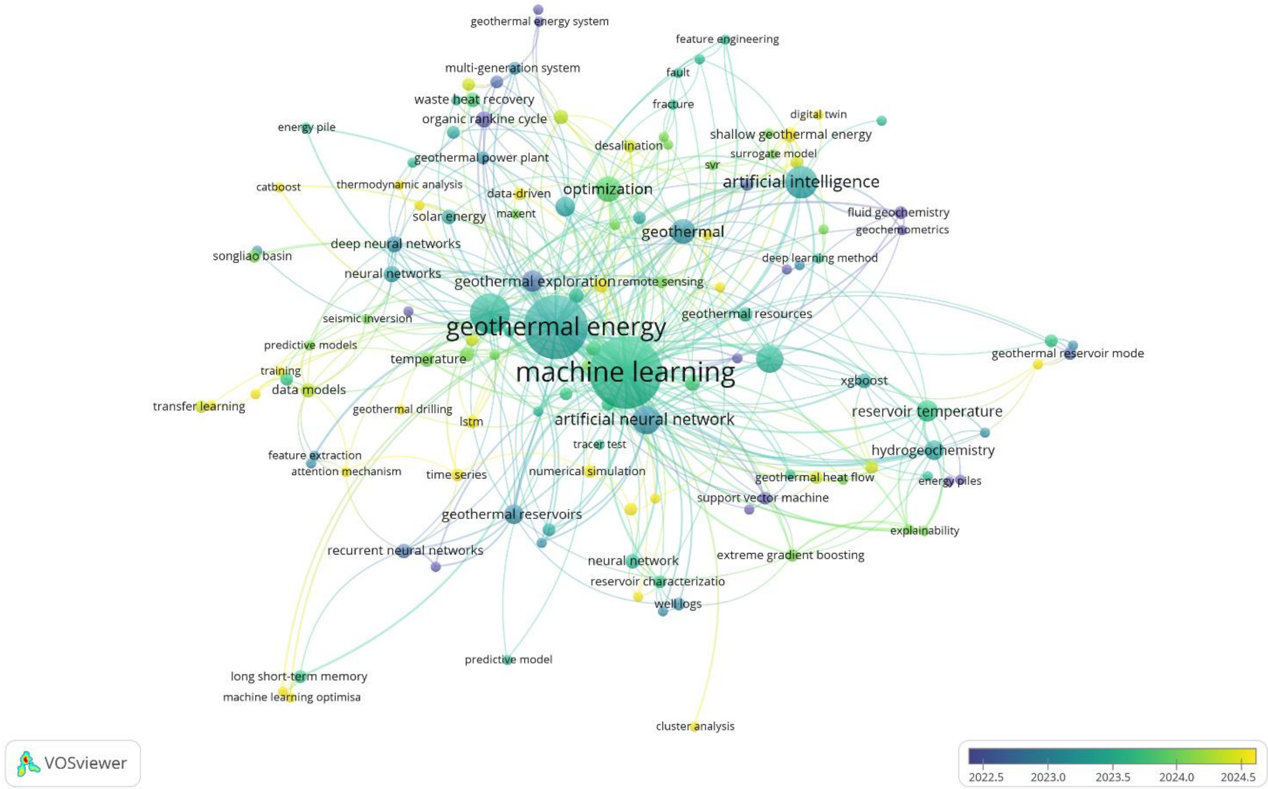


**Figure 5.** Network and time distribution visualization of keywords

Burst detection is a method utilized to identify sudden increases in the frequency of a specific keyword within a given period. This technique is employed to discern the emergence of new research trends or the sudden popularity of a particular topic. The burst score, which serves as a metric to measure the degree of burstiness, is calculated based on the relative increase in the frequency of the keyword in comparison to its historical trend. By visualizing burst scores over time, researchers can identify patterns in the emergence of new research topics and track the evolution of a field. Furthermore, burst analysis can also aid in identifying sudden changes in the discourse surrounding a particular keyword, providing valuable insights for researchers and practitioners.

According to Burst Analysis, research in geothermal energy and machine learning has been revealed to focus primarily on topics such as "performance" and "optimization" (Table 4). Also, word cloud is presented in Figure 6. This emphasis on predicting and identifying improvements for sustainable power plant operations, as well as predicting financial gains, aims to achieve greater competitiveness in the market. Furthermore, studies conducted after 2024, particularly in terms of "hydrogen" and "enhanced geothermal system," focus on both direct geothermal byproducts and holistic system improvement (Figure 7).

**Table 4.** Occurrences

| Words | Occurrences |
|---|---|
| Machine Learning | 94 |
| Geothermal Energy | 87 |
| Performance | 48 |
| Optimization | 42 |
| Energy | 38 |
| System | 36 |
| Deep Learning | 30 |
| Prediction | 28 |
| Artificial Intelligence | 27 |
| Model | 24 |

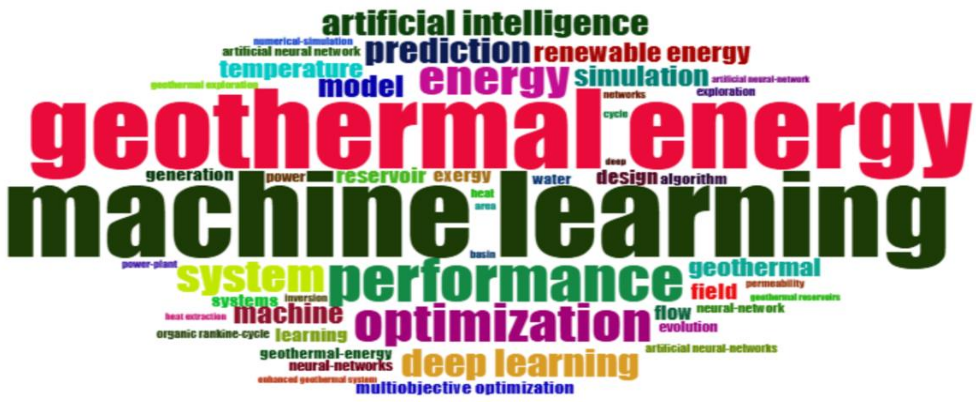


**Figure 6.** Word cloud

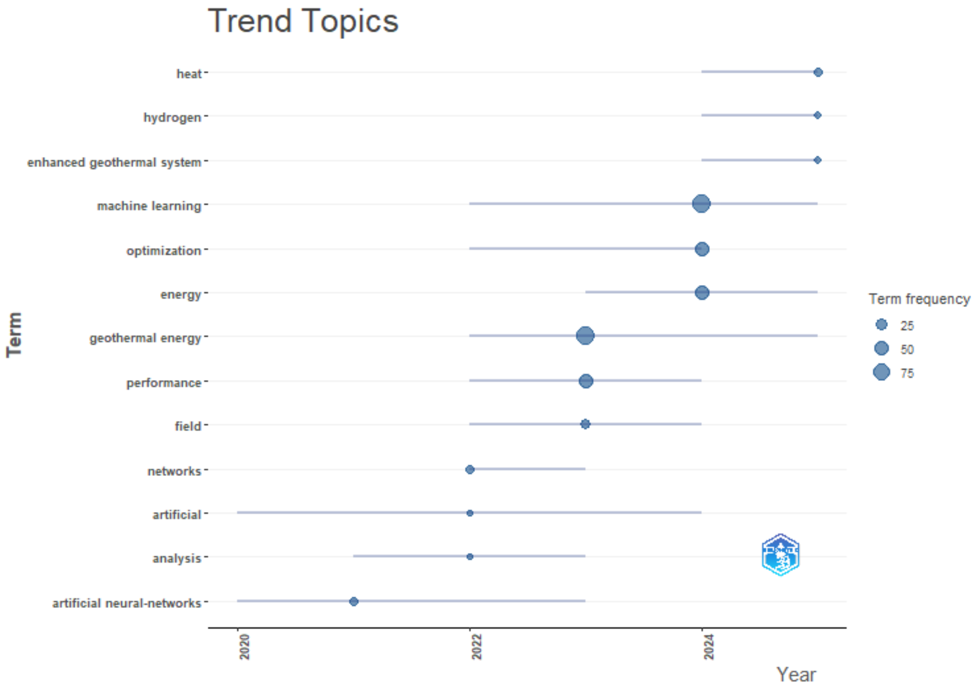


**Figure 7.** Trend topics

Co-authorship analysis is crucial for examining collaborations between researchers in a given field. The goal of this analysis is to understand the network of relationships between researchers and identify key players in the field. Country co-authorship analysis can be explained as a method for identifying collaboration patterns between researchers from different countries. This technique can provide valuable information about the global distribution of research activities and the nature of international collaborations. The goal of country co-authorship analysis is to identify the most active countries in each research field and the country's most likely to collaborate with each other.

According to the dataset, China has the highest number of documents with 95, significantly outpacing the United States, which has 40 documents, by approximately 2.5 times. Germany comes in third with 15 documents (Figure 8). In terms of citations, Chinese publications also have the highest number of publications with 1,319. This comparison reveals an approximately three-fold difference between the United States, which has 549 citations, and China (Table 5). The competition between the United States and China, the dominant powers in science, is also prominent here, with China leading the race. It produces twice as much scientific material as its closest rival and receives citations for these publications. This gives a positive impression of the quality of the published work. China is particularly active in joint projects with the United States and Germany, and countries such as Turkey and Saudi Arabia are also working to develop partnerships. Collaborations are also developing with countries such as Iran, India, South Korea, the United Kingdom, and Poland in a wide range of areas.

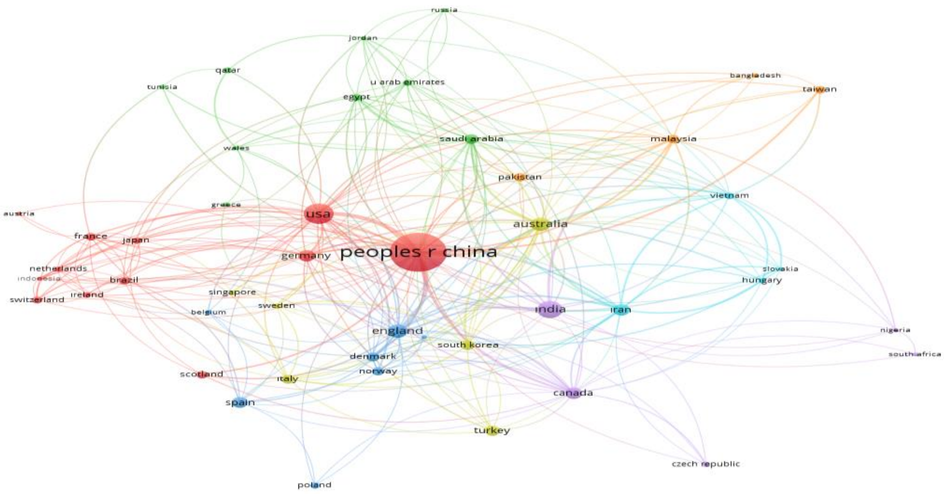


**Figure 8.** Network visualization of countries

**Table 5.** Most cited countries

| Country | Total Cite |
|---|---|
| China | 1319 |
| United States | 549 |
| Iran | 300 |
| Canada | 276 |
| France | 231 |
| Germany | 229 |
| Poland | 226 |
| Mexico | 193 |
| Saudi Arabia | 182 |
| Italy | 171 |

Collaboration network analysis uses bibliometric data such as co-authorship and citation networks to create a visual representation of collaboration patterns, enabling the identification of key actors and institutions, as well as potential areas for future collaboration.

The application of collaboration network analysis in the bibliometric field can provide a comprehensive understanding of the research landscape in a field. By identifying collaboration patterns, leading institutions and researchers in the field, as well as potential collaboration opportunities, can be identified. Furthermore, this approach can be used to evaluate the effectiveness of existing collaborations and identify potential new collaborations between researchers and institutions. By examining this map, a researcher can update the map of project and collaboration partnerships, identifying countries where they should focus their efforts.

The country collaboration map shown in Figure 9 provides a visual representation of collaborations between countries in each field of study. Examining the map reveals a significant number of collaborations established between countries. China and the United States appear to have a high level of collaboration with other countries. Additionally, partnerships with Canada, Middle Eastern countries, and, to a lesser extent, European countries demonstrate the potential for rich collaboration in this field. Despite significant geothermal resources in Africa (Kenya-Olkaria, etc.), the fact that research there is primarily conducted by East African researchers or researchers from other countries may be attributable to the region's socioeconomic underdevelopment.

This scientific alliance, which connects all continents, opens a window to more comprehensive and high-quality research that transcends national borders in the future. It can be concluded that this trend in international collaboration will foster innovation and lead to the production of value-added knowledge that can benefit society.

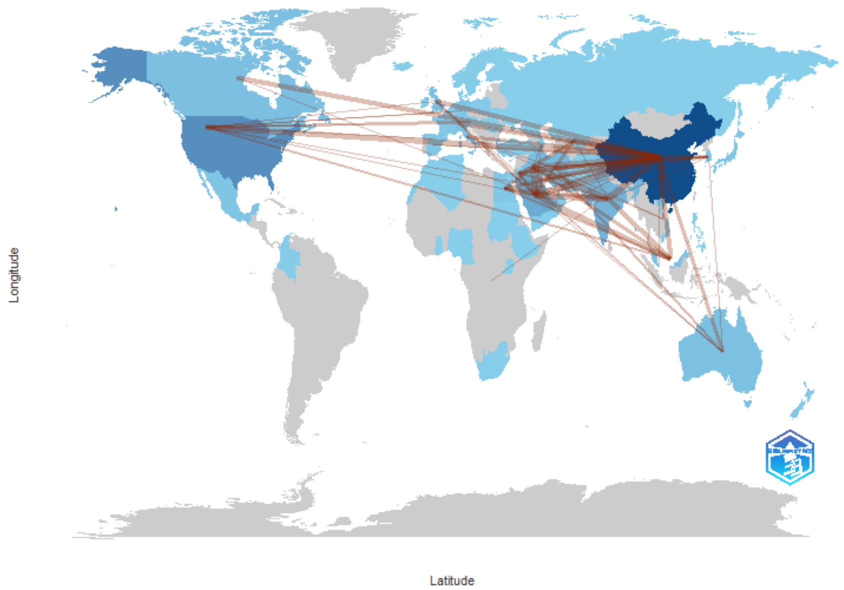


**Figure 9.** Collaboration map

**4. Discussion**

This bibliometric review reveals both the quantitative growth and intellectual structure of the literature accumulated at the intersection of geothermal energy and artificial intelligence/machine learning between 2010 and 2025. The findings indicate that the field has accelerated since 2019, with a particularly significant acceleration after 2022, and that production has plateaued in the 2024–2025 period. This pattern points to an application-oriented paradigm shift from exploration to optimization and operational efficiency, driven by both the global shift in renewable energy policies and the maturation of data-driven methods.

The predominance of articles (n=265) in the distribution of publication types confirms the experimental/applied nature of the field, while the relatively small number of reviews and presentations suggests that "status assessment" studies still offer opportunities in this rapidly developing field. The clear leadership of "Geothermics" in the source journals indicates the formation of a core subject-specific publication ecosystem. The concentration in journals such as "Renewable Energy," "Energies," "Energy," and "Applied Energy" demonstrates that this intersection is not merely a niche but is also being pursued by the general energy science and policy communities. The fact that a significant portion of the most cited studies are method/application-based articles suggests that innovative modeling contributions in this intersection resonate more quickly than in review articles. Author collaboration indicators (average co-authors per document ≈5.18; collaboration index ≈4.49; very low number of single-author publications) suggest that the network-oriented production model dominates and interdisciplinary clusters operate efficiently. The centrality of nodes such as ORC (Organic Rankine Cycle), EGS (Enhanced Geothermal Systems), reservoir, and temperature control in the keyword co-occurrence network suggests a strengthening of efficiency/optimization focuses after 2020, and the rise of holistic energy transformation themes such as "hydrogen" and advanced geothermal systems by 2024.

China's distinct superiority in document and citation production, coupled with its extensive partnerships with the US and Germany, highlight the importance of scale and R&D investments in data-intensive engineering problems. The growing multi-center networks between North America, the Middle East, and Europe provide a fertile ground for data sharing, comparable experimental setups, and the development of common software/benchmarking platforms. Conversely, despite Africa's rich geothermal potential, its relative limited representation in scientific production fuels calls for capacity building and equitable collaboration.

Trend-oriented topics center around "performance," "optimization," "prediction," and "deep learning." This aligns with the goal of generating real-time or near-real-time decision support using heterogeneous field data (drilling/circulation, two-phase flow, reservoir behavior). The following technical directions appear critical for the upcoming phase: (i) data-efficient learning with physics-informed models, (ii) uncertainty quantization and reliability (UQ) layers, (iii) multi-objective optimization (LCOE–emission–thermal depletion trade-off), (iv) portable/edge inference and autonomous control loops, and (v) online calibration of digital twins (especially drilling and surface facility) throughout their lifecycle.

From the perspective of implications for practitioners and policymakers, ML/AI integration across the geothermal value chain (exploration–drilling–reservoir management–surface facility–interconnection) has the potential to reduce investment risk and operating costs. This requires (a) open/anonymized data repositories and transparent benchmark sets at the institutional and international levels, (b) multi-scale performance metrics and reporting standards, (c) a reproducible software ecosystem (code/shared notebooks), and (d) model traceability within the security/ethics/occupational health context.

**5. Conclusion**

This study was based on a sample limited to WoS based and specific subject heading queries. Indexing policies, language/access biases, and differences in "early access" timestamps may affect the absolute magnitude of trends. Furthermore, stylistic inconsistencies in some table titles and in-text numerical indicators (e.g., title tags) highlight the need for standardized literature reporting. Therefore, the findings are indicative but open to validation with other databases and broader queries.

Open benchmarks: Common data/code packages for organic rankine cycle configurations, enhanced geothermal system scenarios, and two-phase flow prediction.

- *Physically informed and hybrid models:* Increasing generalizability in data scarcity, adapting to the field with transfer learning.
- *Uncertainty and explainability:* Decision transparency with methods like SHAP (Shapley Additive Explanations); risk-based maintenance and operations planning.
- *Real-time integration:* Low-latency inference in edge devices; closed-loop control with SCADA (Supervisory control and data acquisition).
- *Equitable and inclusive collaborations:* Capacity building in Africa and Latin America; data sovereignty and fair-sharing principles.

The geothermal-AI intersection is entering a mature phase, evolving from exploration and modeling to holistic system optimization. While geothermal-specific journals are at the core of the field, interdisciplinary expansion is strong, and collaboration networks are increasingly dense. The next leap forward will be made possible by physics-informed methods, standardized benchmarking environments, and transparent data/sharing protocols. Such a foundation will increase both scientific productivity and the speed and quality of energy transformation in the field, broadening the path to sustainable, reliable, and competitive geothermal systems.

**Competing Interest / Conflict of Interest**

The authors declare that they have no competing interests.

**Author Contribution**

This manuscript is written by single author.

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Not applicable.

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