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Application of machine learning and deep learning in geothermal resource development: Trends and perspectives

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Abstract

This study delves into the latest advancements in machine learning and deep learning applications in geothermal resource development, extending the analysis up to 2024. It focuses on artificial intelligence's transformative role in the geothermal industry, analyzing recent literature from Scopus and Google Scholar to identify emerging trends, challenges, and future opportunities. The results reveal a marked increase in artificial intelligence (AI) applications, particularly in reservoir engineering, with significant advancements observed post-2019. This study highlights AI's potential in enhancing drilling and exploration, emphasizing the integration of detailed case studies and practical applications. It also underscores the importance of ongoing research and tailored AI applications, in light of the rapid technological advancements and future trends in the field.

KEYWORDS

artificial intelligence, deep learning, geothermal energy development, machine learning

Highlights

- Recent machine learning/deep learning advancements in geothermal development up to 2024.
- Case studies are presented on AI's practical impact in seismic detection and reservoir engineering.
- AI application trends in geothermal energy from 2000 to 2024 are analyzed.
- Future AI integration into geothermal drilling and production is explored.

1 | INTRODUCTION

1.1 | Overview of geothermal energy

As global efforts intensify toward achieving net-zero carbon dioxide emissions, the shift from traditional energy sources to sustainable alternatives has become imperative. In this transition, geothermal energy stands out for its reliability and sustainability, leveraging the Earth's heat for power generation. Despite its growing demand and potential, the geothermal industry faces challenges in exploration, drilling, and resource management, where artificial intelligence (AI) could play a transformative role (Aljubran et al., 2022). However, there remains a gap in comprehensive reviews that analyze the extent and impact of AI applications in this field (Aljubran et al., 2022; Holditch, 2013; Pandey et al., 2017). While geothermal energy offers a sustainable energy solution, its development is fraught with challenges that can be effectively addressed through the integration of AI, particularly machine learning (ML) and deep learning (DL) (Franki et al., 2023)

1.2 | Principles of ML and DL in geothermal resource development

In recent years, ML and DL have emerged as transformative technologies in geothermal resource development (Aljubran et al., 2022; Benti et al., 2023). They are crucial in interpreting complex geological data (Azhari et al., 2023), optimizing drilling operations (Yang et al., 2023), and predicting reservoir behavior (Al-Fakih, Kaka, et al., 2023). ML, a subset of AI, utilizes statistical techniques to enable computers to learn from data (Ahmed et al., 2023). DL, a further subset of ML, uses layered neural networks for sophisticated pattern recognition (Taye, 2023). In the realm of geothermal development, these technologies are instrumental in seismic interpretation (Alqahtani, Aboud, et al., 2023), reservoir characterization (Patterson et al., 2017), and thermal energy prediction (Alqahtani, Ehsan, et al., 2023). Techniques such as artificial neural networks (ANNs) (Noor et al., 2024), convolutional neural networks (CNNs) (Qin et al., 2024), and support vector machines (SVMs) (Abrasaldo et al., 2024) are extensively used. A notable application is the use of DL models to accurately predict the thermal output of geothermal wells (Ma et al., 2024), enhancing energy extraction efficiency and reducing exploration risks (Mudunuru, Ahmmed, Frash, et al., 2023; Mudunuru, Ahmmed, Rau, et al., 2023).

1.3 | AI's integration and potential in geothermal energy development

In the rapidly evolving field of geothermal energy development, the integration of AI has opened new frontiers. Despite significant advancements, there remains a notable gap in comprehensive literature reviews that thoroughly analyze the extent and impact of AI applications in this domain (Danish & Senjyu, 2023; Ezhilarasan et al., 2023; Mira et al., 2023; Raihan, 2023). Existing studies have primarily focused on specific aspects or applications of AI, leaving a need for a holistic review that encapsulates the full spectrum of AI's role in this field (Zhou et al., 2024). Aiming to fill this gap by providing a comprehensive review of literature from 2000 to 2024, this study examines the integration and potential of AI in enhancing geothermal energy development. In particular, this study endeavors not only to understand the current role of AI but also to identify emerging trends and potential future applications that could revolutionize the sector. It contributes to a deeper understanding of AI's transformative potential in optimizing exploration, drilling, and resource management in geothermal energy.

2 | OPTIMIZING GEOTHERMAL RESOURCE MANAGEMENT: THE IMPACT OF ML/DL

2.1 | Introduction to geothermal resource challenges

Geothermal energy, a critical component of sustainable energy portfolios, confronts a principal challenge: the accurate identification and efficient exploitation of geothermal resources. Jolie et al. (2021) underscored the complex geological controls that make exploration challenging, while Rohit, Vipin Raj et al. (2023) highlighted the difficulties posed by diverse geological formations. Ratnasingam (2023) and Sardjono et al. (2023) further stressed the need for sustainable and efficient extraction methods. The previous studies introduce the key challenge: the difficulty in precisely locating viable geothermal sites and managing these resources sustainably and efficiently.

2.2 | Role of ML/DL in tackling the challenge

Addressing the identified challenges, ML/DL technologies emerge as transformative solutions. Reddy et al. (2024) illustrated how AI accelerates material and process design in renewable energy, directly benefiting geothermal site identification and resource management. Wang et al. (2023) reviewed the application of ML in enhancing geothermal systems, showing how these technologies can precisely predict geothermal hotspots and optimize operational efficiency, effectively addressing the primary challenges in exploration and sustainable management.

2.3 | Real-world impact: ML-driven improvements in geothermal energy

Practical applications of ML in geothermal energy further illustrate its role in resolving the key challenge. Li et al. (2023) showed how ML in geothermal energy mapping significantly improves exploration success, directly addressing the issue of site identification. Buster et al. (2021) and Xue et al. (2023) demonstrated the application of ML in operational optimization and thermo-economic modeling of geothermal systems, enhancing both efficiency and sustainability in resource management.

2.4 | Future directions and research

Future research in ML/DL holds great promise for further addressing the key challenge in geothermal extraction. Chen, Jiao et al. (2024) explored advanced algorithms for optimizing heat extraction, indicating pathways for more efficient resource utilization. Fasogbon and Igboabuchukwu (2024) pointed to the potential of ML in real-time environmental impact monitoring, suggesting ways to enhance sustainable practices in geothermal energy extraction.

3 | AI APPLICATION STATUS IN VARIOUS GEOTHERMAL ENERGY DOMAINS

3.1 | Current state and trends

The integration of AI in the geothermal energy sector has been transformative, closely mirroring its applications in the petroleum industry due to their shared exploration and production processes. AI and ML have become critical in enhancing the efficiency and management capabilities of geothermal operations. Advanced AI systems, such as those developed by Beyond Limits (Amariles & Baquero, 2023), are at the forefront of this integration, demonstrating significant strides of AI's role in the geothermal sector (Luis, 2020).

3.2 | Case studies: Pioneering AI solutions in geothermal development

A key example of an AI application is Beyond Limits' contribution to drilling position selection and subsurface model construction. Their integration of ML datasets with reservoir engineering data has enabled the identification of high-productivity wells in a fraction of the usual time, thus significantly enhancing development prospects. In well productivity management, Beyond Limits' cutting-edge ML methodologies for risk assessment have been proven effective in optimizing well operations and reducing operational expenses. Building upon these innovative applications by Beyond Limits, several other noteworthy implementations of AI in the geothermal industry further demonstrate the versatility and effectiveness of ML/DL technologies. Notably, the innovative design and implementation of a low-enthalpy geothermal probe by Merlos et al. (2023) mark significant strides in optimizing geothermal energy for air conditioning systems. Additionally, Michael J. Friedel's work on multimodal ML has advanced the 3D characterization of geothermal resources, offering new perspectives in resource exploration and assessment. These applications, along with others, are comprehensively detailed in Table 1, which delineates various AI-driven solutions, their targeted problems, and the resultant improvements in the geothermal industry.

3.3 | Challenges and opportunities

While the integration of AI in the geothermal industry marks a significant step forward, it still faces unique challenges. Adapting AI solutions to the specific needs of geothermal systems and fostering interdisciplinary collaboration remain key areas of focus. These challenges, however, open doors for opportunities in research and development, where AI can be tailored more precisely for the geothermal sector, leading to increased accuracy, efficiency, and productivity in various operations.

TABLE 1 Artificial intelligence (AI) applications in geothermal energy domains.

Case	Problem	Solution	Result	References
Drilling position selection and subsurface model construction	How to predict subsurface modeling and target drilling locations.	ML datasets are combined with reservoir engineering information sources in the cognitive reasoner.	Beyond limits identifies high-productivity wells in physically important reservoir sections in minutes to hours, significantly reducing the cycle time and expanding the number of viable development possibilities.	Moraga et al. (2022), Nyokabi et al. (2022)
Well productivity	Managing massive production rates and particle issues in wells.	Beyond limits uses cutting-edge ML and data science methodologies to evaluate risks and assess production hazards.	The beyond limits well health system accurately diagnoses severe particle production issues, reducing operational expenses and ensuring optimal well operations and production control.	Mercier-Laurent et al. (2021), Basosi et al. (2020)
Monitoring of refinery production	Dealing with operational deviations in refineries and making quick decisions to mitigate risks.	Beyond limits provides a cognitive decision-support system for refinery management, enhancing operations strategies, and standardizing industry practices.	The AI system detects off-plan activities, predicts behavior, and offers remedial suggestions based on optimal techniques outlined in the plan.	Duijn et al. (2013), Holmes (2021), Raos et al. (2022)
Low-enthalpy geothermal probe	Optimizing air conditioning systems using geothermal energy.	Design and implementation of a low-enthalpy geothermal probe.	The efficiency in air conditioning is enhanced, showcasing practical applications of AI in geothermal energy systems.	Merlos et al. (2023)
3D characterization of geothermal resources	Identifying and characterizing hidden groundwater and geothermal resources.	Multimodal ML workflow for 3D spatial analysis.	Effective detection and mapping of geothermal resources are achieved, exemplifying ML's capability in complex spatial data analysis.	Friedel et al. (2023)
Geothermal flow in Northern Morocco	Analyzing geothermal flow patterns in Northern Morocco.	Application of ML algorithms for data analysis and prediction.	Understanding and prediction of geothermal flows are enhanced, contributing to the efficient management of geothermal resources.	Ouzzaouit et al. (2023)

4 | THE WORKING PATH OF AI TO HELP GEOTHERMAL PRODUCERS

AI revolutionizes geothermal energy production by introducing advanced capabilities in resource identification, operational efficiency, and risk management. This section explores how AI technologies transform the geothermal industry, enhancing both exploration strategies and operational methodologies (Luis, 2020).

4.1 | Resource identification improvement

AI technologies, particularly ML algorithms, are revolutionizing geothermal energy production by enhancing resource identification. For instance, Luis (2020) emphasized how AI technologies transform the geothermal industry, enhancing exploration strategies and operational methodologies. Further, Perozzi et al. (2019) demonstrated ML's capability in seismic data analysis to locate geothermal hotspots accurately. Rohit, Kiplangat et al. (2023) and Gao et al. (2024) showcased the strides in AI-driven geothermal resource identification, specifically detailing the process of integrating geospatial data with ML models for improved prediction accuracy. These advancements are founded on AI's ability to process and interpret complex datasets, identifying patterns and anomalies indicative of geothermal resources.

4.2 | Optimal drilling and reservoir management

In optimizing drilling operations, AI algorithms have shown remarkable efficacy. A noteworthy example is a study by Inamat and Mansour (2023), where advanced ML algorithms were used to analyze real-time drilling data. These algorithms dynamically adjusted drilling parameters, such as drill speed and pressure, leading to improved production efficiency and reduced risk of equipment failure. Complementing this, Chen, Du et al. (2024) detailed an innovative method for real-time optimization of offshore drilling parameters using intelligent algorithms and ML. This method significantly enhanced operational efficiency in challenging drilling environments. Similarly, in reservoir management, AI's role is pivotal. Qin et al. (2024) and Cetin et al. (2024) presented the AI's application in predicting reservoir behavior and optimizing power generation in geothermal systems. These studies collectively highlight AI's transformative impact in both optimizing drilling operations and enhancing safety and efficiency in reservoir management.

4.3 | Enhanced efficiency and performance

AI-driven predictive models, as showcased in a recent study, are capable of forecasting energy demand, enabling strategic planning for power generation. This capability is highlighted in the previous studies. Just to name a few, Somu and Kowli (2024) evaluated building energy demand forecast models, and Wei et al. (2024), demonstrated the application of AI in hierarchical thermal management for PEM fuel cells. Additionally, AI's role in integrating geothermal energy with other renewable sources has been instrumental in improving the efficiency of the energy network, as reported in the paper by Zhang, Ling et al. (2022). These advancements indicate AI's crucial role in enhancing the efficiency and performance of the energy sector, particularly in the context of geothermal energy.

4.4 | Maintenance and asset management

The application of AI in geothermal plant maintenance involves predictive algorithms for equipment health monitoring and significantly reduced operational costs. Hai et al. (2024) discussed optimizing power plant operations through AI. Similarly, Ren et al. (2024) emphasized ML's role in renewable energy system health monitoring. Uchôa et al. (2023) specifically detailed how AI tools enable continuous equipment monitoring and anomaly detection, crucial for preemptive maintenance strategies. These processes leverage AI's pattern recognition capabilities to predict potential failures, allowing for timely interventions.

4.5 | Decision support and risk analysis

AI systems offer invaluable decision support in the geothermal sector, enabling comprehensive scenario evaluations and risk assessments. Mwaura and Kada (2017) highlighted AI's capability to analyze vast datasets for operational scenario simulation, aiding in data-driven decision-making. On this basis, Caldeira et al. (2024) applied advanced geographic information system (GIS) and multicriteria decision analysis (MDA) in assessing the geothermal potential of the Paraná Basin, demonstrating AI's role in maximizing prospects. Furthermore, Boretti (2024) evaluated the value of energy storage systems, showing AI's effectiveness in complex energy scenario analyses. The integration of AI in these facets underlines its crucial role in driving the geothermal energy sector toward more sustainable and cost-efficient practices, with its ongoing evolution promising further advancements and innovative applications.

4.6 | Considerations for effective ML/DL application in geothermal development

In implementing ML/DL algorithms for geothermal development, several critical considerations ensure their effective application. Foremost, data quality is paramount, as the accuracy of ML/DL models is directly influenced by the integrity and comprehensiveness of the input data (Budach et al., 2022). Additionally, the selection of algorithms must be aligned with specific geothermal challenges, necessitating a nuanced understanding of both ML/DL capabilities and geothermal operational needs (Abrasaldo et al., 2024). Computational resources also play a vital role, where the scalability and complexity of models must match available processing power (Gill et al., 2022). Integration of domain expertise is essential for interpreting ML/DL outcomes and integrating them into practical geothermal exploration and production strategies (Moraga et al., 2022).

5 | AI TRENDS IN GEOTHERMAL DEVELOPMENT

5.1 | Advancements in reservoir management and exploration

The integration of AI in reservoir management has witnessed notable advancements, particularly with the "Digital 4" model by Muther et al. (2022). This model marks a significant step in applying AI/ML technologies in geothermal operations, enhancing reservoir analysis, performance, and optimization. Equally important are the developments in geothermal exploration. The hybrid ML probabilistic ranking system, initially proposed by Wardoyo et al. (2021) and further developed by Ekeopara et al. (2022), merges pattern recognition algorithms with drilling and log data. This innovative approach has been proven effective in accurately predicting lithology within geothermal formations, showcasing the precision and efficiency of AI in geological analysis and exploration.

5.2 | Breakthrough in temperature forecasting

A significant breakthrough in AI application within the geothermal field is the ML/DL model developed by Al-Fakih and Li (2021), designed for forecasting bottom hole temperature (BHT) and static formation temperature (SFT). The effectiveness of this model in accurately estimating BHT and SFT demonstrates its potential as a cost-effective tool for critical temperature assessments, vital for the optimal operation of geothermal wells. These advancements in temperature forecasting underline AI's role in enhancing the accuracy and efficiency of critical operations in the geothermal industry.

5.3 | Conclusion and future outlook

The collective progress highlighted in these studies underscores the expanding role and importance of AI in the geothermal sector. From reservoir management and geological analysis to temperature forecasting, AI applications are significantly improving operational efficiencies, reducing costs, and enhancing resource utilization. Looking forward, the continuous evolution of AI technologies is expected to bring further innovation in geothermal exploration and development. Future research should aim to refine AI models, explore new AI applications, and integrate these technologies with emerging data analytics techniques. Such advancements will be crucial in realizing the full potential of AI in fostering the sustainable development of geothermal resources.

5.4 | Potential for further ML/DL applications in geothermal development

The potential applications of ML/DL in deep geothermal exploitation extend beyond current practices, with several emerging areas ripe for innovation. Predictive maintenance, powered by ML algorithms, can significantly reduce operational downtimes and costs, ensuring more efficient geothermal energy production (Soori et al., 2023). Environmental impact assessments using DL models offer a more detailed understanding of potential ecological effects, guiding more sustainable development practices (Joseph et al., 2019). Furthermore, the exploration of enhanced geothermal systems (EGS) presents a frontier where ML/DL can revolutionize the identification and utilization of deep geothermal resources, addressing existing challenges in exploration under complex geological conditions (Maury et al., 2022).

6 | ML/DL TECHNIQUES FREQUENTLY EMPLOYED IN THE GEOTHERMAL SECTOR

In the rapidly evolving field of geothermal energy development, various ML/DL techniques are being used to address complex challenges. Techniques such as ANN, CNN, deep neural networks (DNN), K-nearest neighbors (KNN), and recurrent neural networks (RNN) have been pivotal in advancing the sector. These techniques are chosen based on specific requirements like the nature of the data set, the complexity of the task, and the desired outcomes in geothermal applications. Table 2 provides a comprehensive overview of these algorithms, highlighting their applications, advantages, disadvantages, and key references that underscore their utility in the geothermal domain.

Each of these ML/DL techniques brings unique strengths to the field of geothermal energy. For example, ANNs are extremely versatile, making them suitable for a wide range of tasks including predictive modeling and data analysis. CNNs, with their prowess in image processing, are invaluable in seismic data interpretation. DNNs, with their DL capabilities, are effective in handling complex, large-scale geothermal datasets. KNN algorithms offer simplicity and effectiveness in classification tasks, making them useful in exploratory data analysis. RNNs are particularly useful in sequential data analysis, and relevant in time-series forecasting in geothermal reservoir management. The choice of algorithm depends on the specific problem being addressed, the nature of the data, and the desired outcome, underscoring the need for a nuanced understanding of each technique's applicability in geothermal energy development.

7 | SUCCESSFUL AI IN GEOTHERMAL—A CASE STUDY

7.1 | Overview of the case study

In the realm of geothermal energy, the application of AI in seismic facies detection represents a significant technological leap. This case study showcases how AI,

TABLE 2 Most widely used machine learning (ML)/deep learning (DL) algorithms.

ML/DL approach	Usage	Pros	Cons	References
ANN	Suitable for clustering, classification, and regression tasks.	Not dependent on the regularity of any function. Suitable for difficult or impractical formula acquisition.	Difficult to understand or analyze due to its “black box” nature. Not suitable for small data.	Jung and Choi (2021), Mohaghegh (2000), Wang et al. (2018)
		ANNs could be utilized to perform tasks that conventional algorithms cannot do. Several issues are accessible.	Training is required for use. The learning and analysis times for wired environments are extensive.	Sibai et al. (2011), Vialetto and Noro (2019)
		Capable of learning from practice and avoiding retraining.	Parallelization capabilities are required.	Raj (2019), Aniyom et al. (2022)
		Capable of handling complex datasets. Superb matching implications.	The performance of the model is a danger. Learning requires a lot of time.	Liu and Lang (2019), Nyokabi et al. (2022)
CNN	Primarily used in image processing, classifications, and regression tasks.	Can detect important attributes from the data set. Can be used for various issues with the same variables.	Challenging to fine-tune settings. Requires a significant amount of data.	Pandey and Janghel (2019), Zhang, Li et al. (2022)
		Fast learning	Low accuracy	Hu et al. (2019), Chen et al. (2021), Xiong et al. (2022), Suzuki et al. (2022), Liu and Misra (2022), Huang and Kuo (2019)
DNN	Effective for large-scale regression and classification tasks.	Recommended for large datasets. Can adjust to new datasets. Resistant to issues like vanishing/exploding gradients.	Requires excessive coding. Inverse approach. Time-consuming learning.	Belkin (2021), Park et al. (2020), Ibrahim et al. (2023), Haklidir and Haklidir (2019)
KNN	Applied in classification and clustering.	Simple to understand and apply. Fast learning. Stable in the presence of related noise. Useful for multifunctional categorization.	Requires regional awareness. Data architecture limitations. Training is supervised. Slow technique.	Devi et al. (2015), Shahdi (2021), Hall (2016), Santamaria-Bonfil et al. (2022), Ouzzaouit et al. (2023), Vivas and Salehi (2021)
		Excellent performance. An irregular measurement appears. Execution is fast. Fewer complicated.	Algorithmically costly. Overfitting concerns. It is not affected by factors. The initial structure of the data set is ignored.	Taunk et al. (2019), Scheidt et al. (2018), Ekeopara et al. (2023)
RNN	Suitable for regression and classification tasks.	Can save data as activation functions over time. Handles arbitrary lengths of sequence prediction.	Affected by vanishing/exploding gradients. Stacking is not possible in deep models.	Pandey and Janghel (2019), Jiang et al. (2022, 2023), Puppala et al. (2023)

specifically DNNs and the EarthAdaptNet architecture, was utilized to automate and enhance seismic data analysis at the Roosevelt Hot Springs Geothermal site in Utah. Advanced AI applications, studied by Mathur et al. (2024) and Eruteya et al. (2024), showcase the transformative role of AI in this field.

7.2 | Application of AI in seismic facies detection

The traditional process of seismic facies detection in geothermal exploration is often labor-intensive and time-consuming. In this case study, AI was used to automate this process, thereby increasing efficiency and accuracy. DNNs were used to analyze seismic data, with the EarthAdaptNet architecture providing a framework for processing and interpreting these data. The seismic images were meticulously labeled and trained to detect crucial seismic horizons, a vital step in identifying potential geothermal energy resources. This is supported by the findings from Lai et al. (2024) and Mousavi et al. (2024).

7.3 | Impact and results of the AI application

The application of AI in this context has brought about a significant improvement in seismic facies detection. The AI algorithms achieved a pixel accuracy of approximately 80% and a mean class accuracy of around 75%, as reported by Nasim et al. (2022) and supplemented by Das et al. (2024). These results not only demonstrate the technical prowess of AI over traditional methods but also highlight the potential for substantial gains in computational efficiency and cost-effectiveness. The use of AI in this manner can greatly reduce the time and resources needed for seismic data analysis, leading to more efficient and informed exploration decision-making processes in geothermal energy projects. These studies underline the technical superiority of AI over traditional methods.

7.4 | Visualization and interpretation

Figure 1 provides a visual representation of this case study, illustrating a seismic section alongside the interpreted and predicted seismic horizons, supported by Liu et al. (2024). This visualization effectively demonstrates the AI's capability to accurately predict seismic horizons, thereby validating the practical application and benefits of AI in geothermal exploration. The side-by-side comparison of the actual seismic section with the interpreted and AI-predicted horizons offers a clear insight into the precision and reliability of AI in this field.

7.5 | Further implications and future prospects

To conclude the section, the future of AI in geothermal energy is discussed. Axelsson (2024) and Abrasaldo et al. (2024) provided insights into the ongoing evolution and potential advancements of AI in this sector.

8 | METHODOLOGY FOR LITERATURE ANALYSIS IN GEOTHERMAL FIELDS

As for the methodology for literature analysis in geothermal fields, a systematic and comprehensive approach was undertaken, starting with the collection of 23 815 articles from Scopus and Google Scholar as of August 20, 2022. The articles were programmatically screened for AI-related terms, further refined by a panel of 215 practitioners for relevance, and expanded to include non-peer-reviewed publications to broaden the study's scope. By means of VOSviewer software, the bibliometric analysis was conducted to visualize key connections, focusing our research on four primary topics: exploration, drilling, reservoir, and production and injection stages, supplemented by a statistical

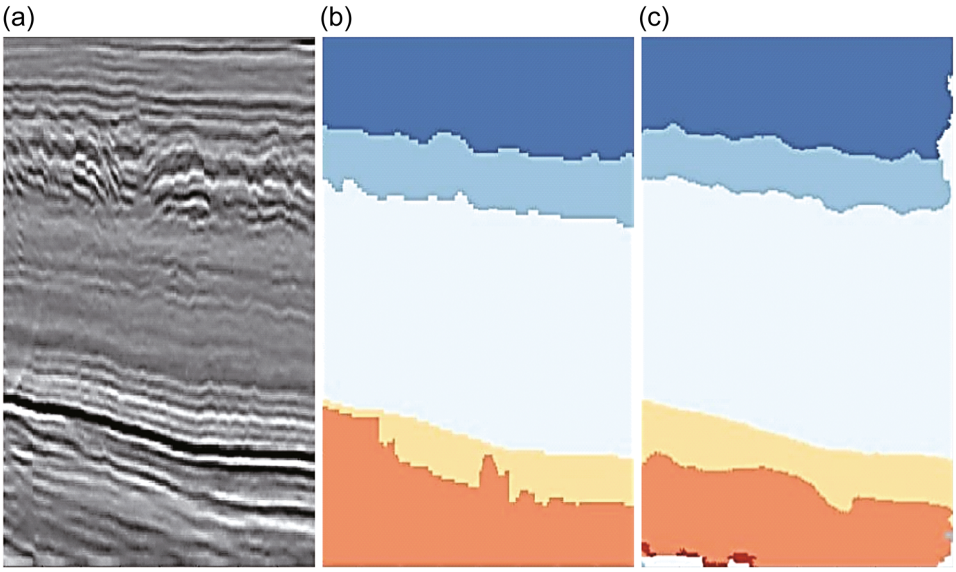

FIGURE 1 Comparative visualization of AI-assisted seismic facies detection: (a) original seismic section, (b) expert-interpreted seismic horizons, and (c) AI-predicted seismic horizons, demonstrating the accuracy of AI predictions in geothermal exploration. (Nasim et al., 2022).

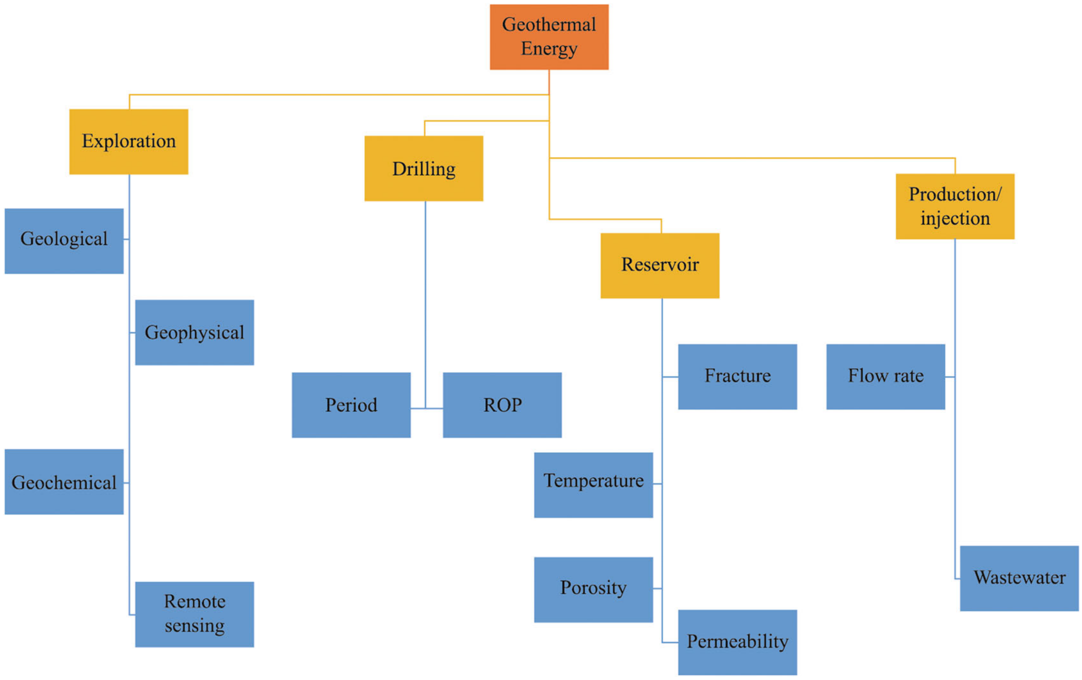

FIGURE 2 Visualization of systematic research categorization in machine learning applications across the geothermal sector, encompassing exploration, drilling, reservoir, and production/injection stages. ROP, rotation of penetration.

analysis to derive meaningful insights. This methodology ensures a thorough exploration of AI's application in geothermal energy development. Figure 2 provides a graphical representation of the various research topics and their respective subcategories within the geothermal sector. This visualization aids in understanding the categorization utilized in the study and highlights specific areas of focus within each research topic.

9 | ADVANCEMENTS IN GEOTHERMAL ENERGY: INSIGHTS FROM RECENT LITERATURE

9.1 | Integrating AI and ML/DL techniques in geothermal energy research: Approaches and key insights

In exploring the advancements of AI in geothermal energy, the analysis identified key fields and terms through a data set, as visually represented by the word cloud in Figure 3. This analysis spans exploration, reservoir characterization, engineering, and production, highlighting AI's extensive use for fracture characterization, heat mapping, and more. The research, significantly conducted in geothermally active regions like China and Iceland, uses AI models like ANNs and CNNs for diverse purposes from drilling times estimation to forecasting geothermal properties. Table 3 further delves into ML/DL techniques applied across these study topics, indicating ANNs as a predominant approach in the sector. These findings showcase AI's role in enhancing exploration, reservoir characterization, drilling operations, and production efficiency, marking a substantial contribution to sustainable geothermal energy development.

9.2 | Insights into publication trends and growing interest in AI applications in the geothermal sector

Figures 4 and 5 provide insights into the publication trends and the growing interest in AI applications in geothermal energy development. Figure 4 illustrates the annual publication count over time. It shows a recurring steady increase every 5 years, specifically between 2019 and 2022. The analysis is based on the data from Google Scholar and Scopus databases, which are widely used for academic publications. The increasing trend in publication counts indicates a growing interest in the application of AI in geothermal energy research and development. This suggests that researchers and professionals in the field are recognizing the potential of AI techniques and their impact on geothermal energy exploration, production, and optimization.

Figure 5 highlights the trends in AI application in geothermal energy development over the past 5 years, showcasing the recent growth in publications related to AI in the geothermal sector. The upward trend in the number of papers published indicates an increasing emphasis on AI technologies for geothermal research and development. This reflects the recent advancements in AI and ML techniques, along with the availability of large datasets and computational resources, which have facilitated the application of AI in the geothermal industry. The figure uses horizontal strips to represent the density or concentration of publications within specific ranges over this period. This visualization method provides a clear understanding of the overall trend and emphasizes the concentration of research efforts in the geothermal industry without depicting individual data points for each year, highlighting the density and distribution of publications.

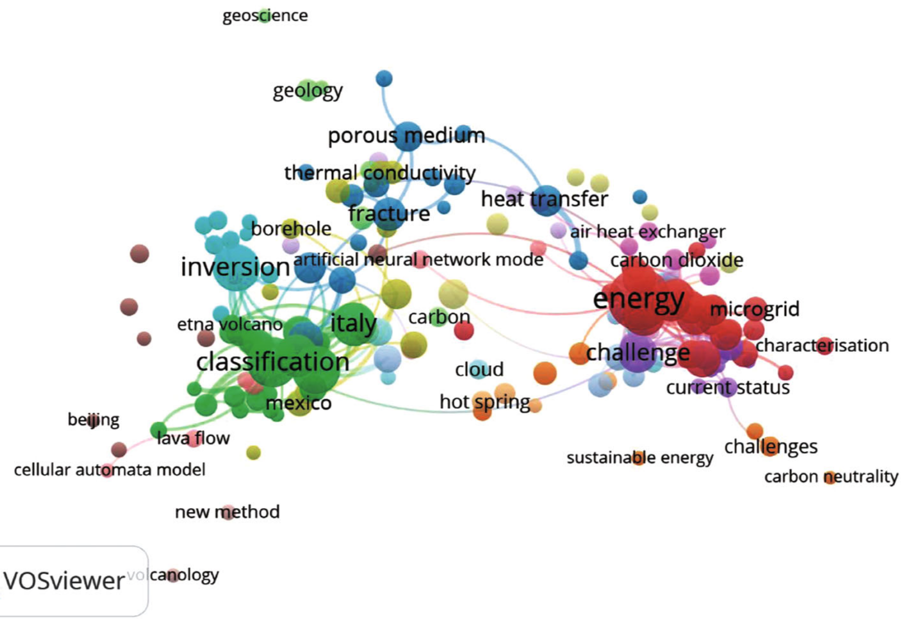

FIGURE 3 Word cloud visualization derived from a comprehensive analysis of geothermal publications in the Scopus database, highlighting key research areas and terms associated with artificial intelligence advancements in geothermal energy (extracted from the Scopus database).

TABLE 3 ML and DL approaches used in different areas.

Subject of study	ML/DL approach (s)	The issue(s) being treated	References
Exploration (remote sensing, geology, and geosciences)	CNN, DNN, and KNN	Transformation of data analysis; interpreting of gravity anomalies; play fairway analyses; prospective interpretation. 3D seismic activity identification and localization, velocity modeling inverting using 3D seismic data, and study of variations in the seismicity spectrum.	Ahmmed and Vesselinov (2021), Bortnik and Camporeale (2021), Siler et al. (2021), Zhou (2021), Mishra (2022), Dramsch (2019), Aminzadeh et al. (2022), Kute et al. (2021)
Drilling	ANN	Estimating penetration depth (ROP). Estimation of static formation temperatures (SFTs).	Diaz and Kim (2020); Yuswandari el al. (2019), Fathaddin et al. (2023), Ben Aoun and Madarász (2022), Bassam et al. (2010)
Reservoir characterization and engineering	ANN, DNN, KNN, and RNN	Fractures characterization, reservoir temp predictions using gas-phase fluid components, analysis of small-scale discrete fractures, reservoir thermal categorization, artificial permeability distributions predictions, and fault diagnosis. Development of well site, calculation of pressures and temperature decline, forecasting of temp in geothermal reservoirs, forecast of production entropy, forecast modeling of tracer returns, vertically permeability profiling.	Gudmundsdottir and Horne (2020), Suzuki et al. (2021), Zhou et al. (2021), Porkhial et al. (2015), Pérez-Zárate et al. (2019), Juliusson and Horne (2010), Aydin and Temizel (2022), Al-Fakih, Ibrahim et al. (2023), Kumar et al. (2022), Szczepaniuk and Szczepaniuk (2022), Lai et al. (2020), Ying et al. (2023)
Production	ANN and DNN	Estimation of incomplete data sets and expected product flow rates, forecasting of geothermal well heat flux.	Bassam et al. (2015), Shi et al. (2021), Pandey and Singh (2021), Zhou et al. (2019), Kshirsager and Sanghavi (2022), Xue et al. (2019), Park et al. (2018), Bilgiç et al. (2023)

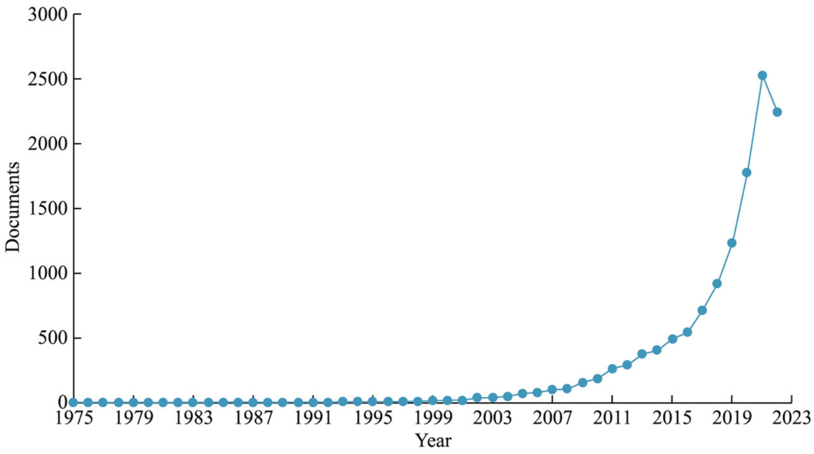

FIGURE 4 Annual trend of artificial intelligence-related publications in geothermal energy from Scopus database, illustrating a significant increase in interest and research output from 1975 to 2023.

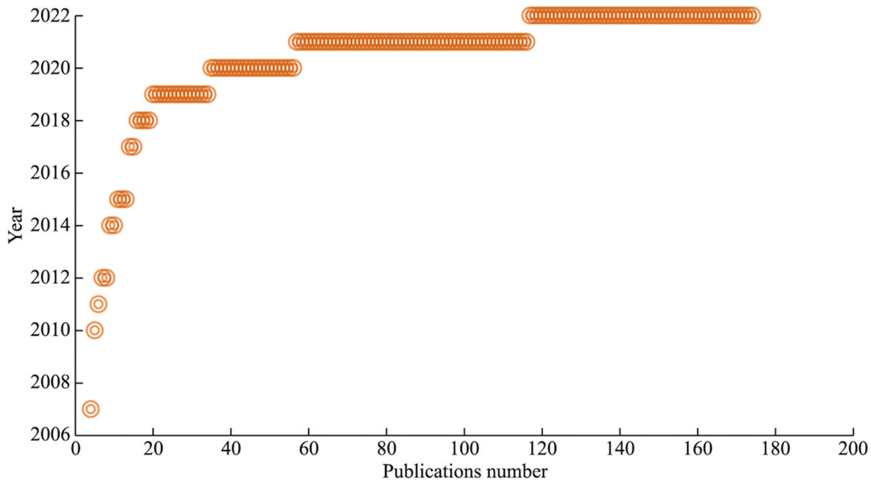

FIGURE 5 Five-year publication trend in artificial intelligence for geothermal energy, highlighting a surge in research, especially from 2019 to 2022, as captured by Google Scholar and Scopus databases.

Both Figures 4 and 5 indicate a significant and increasing interest in the application of AI in geothermal energy development. The recurring steady increase in publication count and the upward trend in recent years reflect the growing recognition of AI's potential to enhance various aspects of geothermal exploration, reservoir characterization, drilling, production optimization, and more. These trends signify the active engagement of researchers, professionals, and stakeholders in advancing the use of AI in the geothermal sector.

9.3 | Publication distribution in country and document type

Figure 6 shows international rankings of geothermal nations based on publication numbers. The graph illustrates the top three nations, the United States, China, and Italy, in terms of geothermal literature references. The United States has the highest number of references, followed closely by China in second place and Italy in third place. These rankings align with the geothermal production rates of the United States and China, indicating their prominent positions in academic and professional geothermal research and development activities and signifying their significant presence in the field and their strong engagement with geothermal studies.

Figure 7 presents the number of document publications on ML in the geothermal sector. It also provides a breakup of the journal articles, conference papers, reviews, books, and other publication types. The chart also showcases the growing interest and research activities in applying ML techniques to subsurface geothermal resource development.

9.4 | Frequency of AI tools used in the geothermal energy sector and top authors

This study has proved that AI tools are extremely successful and active in all areas of geothermal energy. Special among these tools are ANN, RNN, and CNN, as shown in Figure 8 (Okoroafor et al., 2022).

Despite publication volume being the most relevant indicator, author centrality is also essential in understanding the research landscape (Bavelas, 1948). Figure 9

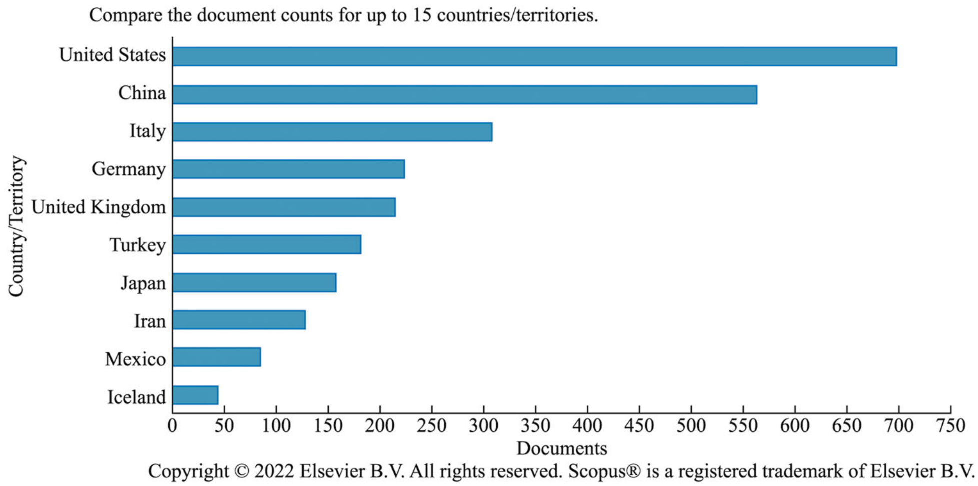

FIGURE 6 International rankings by publication count in the geothermal sector, highlighting the United States, China, and Italy as the leading contributors (data sourced from Scopus).

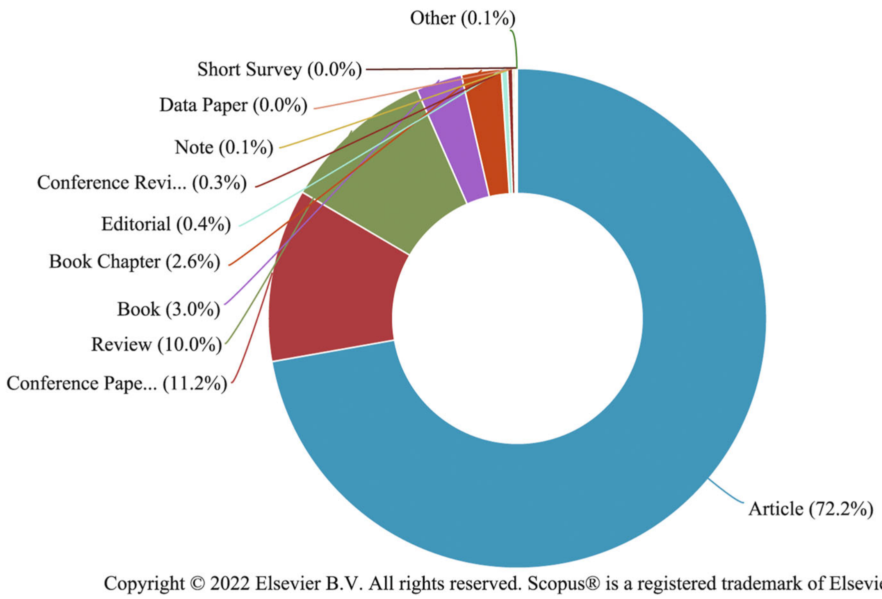

FIGURE 7 Distribution of publication types in machine learning research within the geothermal sector, highlighting the predominance of journal articles (data sourced from Scopus).

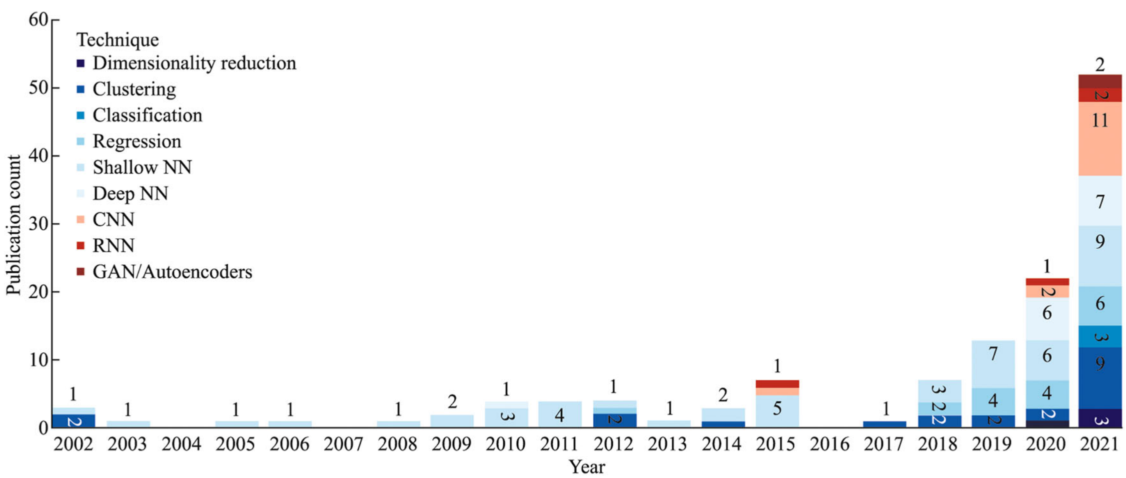

FIGURE 8 Trends in publication counts of machine learning methods in subsurface geothermal energy research over the past 20 years, with a focus on ANN, RNN, and CNN techniques. (Okoroafor et al., 2022).

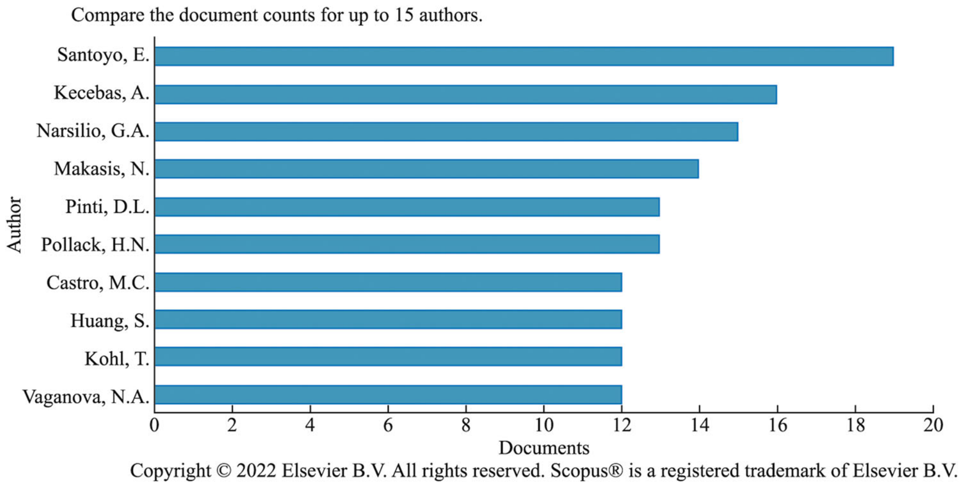

FIGURE 9 The top 10 authors in geothermal research by publication count, illustrating their influence and connectivity within the research community based on degree and betweenness centrality metrics (data sourced from Scopus).

showcases the rankings of the top 10 authors based on publication numbers, highlighting their degree centrality and betweenness centrality ratings. Degree centrality represents the number of connections an author has with other authors, indicating their overall influence and prominence within the geothermal research community. On the other hand, betweenness centrality measures the extent to which an author acts as a bridge between different groups of researchers or facilitates information flow. These centrality metrics provide valuable insights into the network of authors and can help identify key figures and facilitate connections within the geothermal research community. As shown in the figure, the top four authors with the highest centrality metrics are E. Santoyo, A. Keçebaş, G. A. Narsilio, and N. Makasis. Their high centrality scores suggest that they have a significant presence and play pivotal roles in connecting various researchers within the geothermal domain. The centrality estimates of the author network graph offer valuable information for determining the shortest paths between authors and fostering collaborations within the geothermal research community. It is important to note that the data used for these rankings was extracted from the Scopus database.

10 | CONCLUSIONS

This study identified a significant growth in the application of ML and DL in geothermal resource development, emphasizing developments observed from 2019 and projecting trends up to 2024. The comprehensive literature review underscored an exponential increase in AI-focused research, highlighting DL as a key area of innovation. As is observed, reservoir engineering and exploration are at the forefront of AI technology implementation, significantly enhancing performance and risk management. Moreover, the contributions of countries like the United States, China, and Italy highlight a global movement toward adopting AI in geothermal energy. The study underlines the critical need for further AI integration in drilling and production, confronting data accessibility and educational challenges. It points to future research directions, emphasizing refining AI models for specific geothermal applications and expanding their use in less-explored domains to fully leverage AI's potential for sustainable and innovative geothermal resource development.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest that could potentially influence or bias the outcomes and interpretations presented in this study. This research was conducted with a primary focus on advancing knowledge and understanding in the field of geothermal energy, specifically in the application of machine learning and deep learning. The authors have not received any financial support or incentives from any organization, commercial entity, or other parties that could have a direct or indirect interest in the findings or the publication of this work. Furthermore, the authors have not been involved in any activities or affiliations that could be perceived as conflicting with the impartial and unbiased presentation of the research results. The commitment to transparency and the integrity of the research process is paramount to the authors, and they are dedicated to upholding the highest ethical standards in their scholarly work.

DATA AVAILABILITY STATEMENT

The data used in this study are based on existing literature, publicly available information, and datasets from the Scopus and Google Scholar databases. All data sources are appropriately cited within the manuscript. There are no additional datasets or supplementary data associated with this research.

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