

Advancing Permeability Modeling in Fractured and Porous Media: A Bibliometric and Systematic Review (2020–2024)

Waqar Nasir¹, Ijaz Ali², Yaseen Ur Rehman³

¹Petroleum Engineering, Changzhou University, Changzhou 213164, China

²Petroleum Engineering, Changzhou University, Changzhou 213164, China

³Safety Science and Engineering, Changzhou University, Changzhou 213164, China

Email address: waqarnasir098@gmail.com

Abstract—Understanding and better forecasting fluid dynamics and permeability in porous media are vital for developing sustainable management of such resources and enhancing recovery processes related to various oil and gas industries. This systematic literature review (SLR) incorporates meta-analysis and thematic mapping by applying the “PRISMA framework” and “Bibliometrix” to influential authors, leading journals, critical keywords, and thematic trends, respectively. This study explored and analyzed the records published from 2020 to 2024 of 212 documents on the numerical modelling of permeability. The contributions of global institutions, especially from China, on account of the collaborative and interdisciplinary nature. The numerical methods of the lattice Boltzmann method (LBM) and multi-scale modeling have indeed proved reliable to predict permeability, overcoming conventional approaches such as the Kozeny-Carman equation. This study further identifies an upsurge in machine learning techniques applied and their probable refinement of simulation accuracy under such complex fracture and matrix porosity conditions. Despite these huge successes, shortcomings remain in several areas, including over-reliance on idealized models, poor computational capability, and the need to integrate more sustainable processes. This review has pointed out key directions for future efforts toward establishing AI-powered approaches, unifying experimental design, and exploring new methods such as carbon capture, geothermal energy, and next-generation energy storage.

Keywords— Scopus, Bibliometric analysis, Biblioshiny web application, Fracture Porosity, Porous Media, Permeability Prediction Models.

nevertheless, with numerous simplifications used in the model, it was often hard to apply the very same to several complex systems (Chang et al., 2017; Rajagopal, 2007). Fluid flow within porous media is essential in solving numerous problems of petroleum engineering, management of groundwater flow, and environmental sciences. Porous media consist of interconnected void spaces through which the transport of fluids such as water, oil, and gas takes place (Sahimi, 2011; Yusoff et al., 2023). The permeability, an important parameter showing fluid flow, is reasonably necessary to predict among most applications in such materials to have resource optimization in extractive procedures filtration systems for efficiency and even to make variations in environmental hazard mitigation (Sedighi et al., 2023). It is a complex fluid property, pore structure interaction, and combined effects from matrix and fracture porosity (Meakin & Tartakovsky, 2009).

The prediction models for permeability have been among the significant research focuses in this domain (Rodríguez de Castro, 2020). Although traditional models, such as the Kozeny-Carman equation (Carman, 1937); Kozeny (1927), provide essential insight into the process, they usually cannot capture the complexity involved in these heterogeneous and fractured porous systems (Rehman et al., 2024). Recent improvements in machine learning algorithms and Computational Fluid Dynamics (CFD) have enhanced the capability of modelling with much more accuracy in estimating permeability (Elrahmani et al., 2024). These techniques yield much higher resolution of pore-scale dynamics, which bridge the gap between theoretical models and practical applications (Al Balushi et al., 2023).

This study also provides a bibliometric review, outlining the research settings, the highly cited authors, and the influential publications. Bibliometric analysis has, in its development process, joined together the qualitative and quantitative approaches of the discipline: performance analysis, which, as the first step, defines a set of metrics regarding the number of publications and the authors involved, whether it is a single or multi-authored article, citations, h-index, and g-index (Mukhopadhyay et al., 2009). Secondly, science mapping uses citation analysis, co-citation analysis, bibliographic coupling, co-word analysis, and co-authorship to

Abbreviation	Full Form
SLR	Systematic Literature Review
AI	Artificial Intelligence
ML	Machine Learning
CFD	Computational Fluid Dynamics
LBM	Lattice Boltzmann Method
HDR	High Dynamic Range
SCPs	Single-Country Publications
MCPs	Multiple-Country Publications
MCA	Multiple correspondence analysis
CNN	Convolutional Neural Network
KM	Kozeny-Carman
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses

I. INTRODUCTION

Porous media fluid flow has gained importance due to various applications in sciences and engineering. The classic model by Darcy is widely adopted for incompressible fluids' flow;

show the thematic and intellectual structures (Almutairi, 2020). It uses network analysis with measures such as degree centrality clustering techniques supported by Bibliometrix R, VOSviewer, CiteSpace, and Gephi (Johnson et al., 2023). All those methods and techniques have insight into trends in research and the advancement made within permeability prediction and its application in porous media (Hewitt et al., 2016). Most studies on porous media flow showed that pore structure and connectivity impacted the medium's permeability.

Recent numerical models, of which the Lattice Boltzmann Method Bernsdorf (2008), prove proficient in realizing fluid flow over complicated networks of pores and, as such, obtain the relations between microstructural features and macroscopic permeability (Nabipour et al., 2024). In fracture networks, modelled as fracture porosity, an intrinsic constituent part of models explaining fluid transport and flow under various circumstances within unconventional reservoirs and aquifers (Cacace & Jacquey, 2017). There is an increasing need for approaches of fully coupled modelling since the pathways for flow parallel to each other are provided by the fractures, bringing in several interactions with matrix porosity that are relatively complex (Zhang et al., 2019).

The advanced modeling of fracture and matrix porosity conditions and their implications concerning permeability prediction in porous media. From a scientific point of view, this study underlines interdisciplinary approaches- a combination of fluid mechanics, geoscience, and computational modeling that offers an integral insight into fluid transport in porous systems. From the technique viewpoint, the paper addresses numerical modeling techniques such as the lattice Boltzmann method (LBM), CFD, and multiscale modeling approaches. This paper will execute a bibliometric and systematic review emphasizing research developments between 2020 and 2024; therefore, the intellectual structure with key contributors, influential publications, and emerging trends in porous media studies will be analyzed in detail for the first time. The paper further points out that integrating ML techniques with traditional numerical methods is a significant novelty that can be used to enhance model accuracy and computational efficiency.

Therefore, this study critically reviews the related literature to analyze permeability prediction models, fracture porosity, and matrix porosity within geotechnical and geological systems to illustrate the rapid growth in scholarly attention toward these topics. i. An in-depth search was performed using the Scopus database. The search included a keyword phrase: "Permeability Prediction Models, Porous Media, Fracture Porosity, and Matrix Porosity," within a time frame of 2020-2024, which resulted in 212 articles in total. ii. Literature review with emphasis on previously less-covered aspects. This SLR addressed the research questions: i) Which methods have been in vogue to advance the state of the art in permeability prediction and porous media? ii) What is the bibliometric profile, including the most used keywords, the most influential authors, and the key journals that have appeared in the literature? iii) How has research on fracture and matrix porosity conditions evolved during the last decade?

This study was organized into six sections. Section one introduces the researcher's objectives for permeability prediction models and the fracture and matrix porosity interaction. Section two describes the research methodology, explaining the process of SLR and bibliometric analysis. Section three critically reviews the literature, reflecting on identified trends, methodologies, and thematic areas. Section four discusses the criteria and procedures of inclusion and exclusion used for selecting and analyzing the articles composing this research. Section Five contains findings and an analysis of the state of the art regarding the developments, challenges, and gaps in permeability research. Concluding, Section Six proposes possible directions for the future by detailing aspects that, complementing those areas that require further research in permeability prediction and analysis of porous media, are of interest for further investigation. The paper concludes with a long list of references backing this wide-ranged study.

II. METHODOLOGICAL ASPECTS OF THE RESEARCH

This review's different themes are put into thematic sections to lend coherence and comprehensiveness to the narrative. In this study, research is first classified based on the bibliometric insights of high-impact authors, institutions, and journals contributing to the research area. This paper's transition of topics is also reasonably straightforward, with a focused explanation of the principal research areas: interaction of fracture and matrix porosity, permeability prediction, dynamics of fluid flow, and computational developments. An in-depth keyword analysis underpins these themes to track the field's evolution.

The thematic map and intellectual structure analysis show the clustering of research and the co-occurrence of keywords. Each section has concentrated on methods and results, pointing out the novelties of multi-scale and machine learning-based approaches.

2.1. Bibliometric

Section 2 elaborates on the current study, which is focused on a hybrid approach, combining bibliometric analysis with SLR. Bibliometric analysis is an effective method for analyzing different statistical features of research publications and their citation analysis. SLR attempts to investigate a selected research domain in depth and answer specific research questions. SLR differs from other narrative reviews due to its reproducible, scientific, and transparent methodologies (Marathe et al., 2024). The methodology allows for thoroughly collecting all articles and documents relevant to a research topic per predefined inclusion criteria. SLR is an organized and structured method to minimize bias in article searching, shortlisting, and summarization outcomes (Théodon et al.). Bibliometrics performs an analysis of the statistical data regarding published research. The bibliometric method is considered a well-recognized and most widely adapted and implemented procedure, which explores and investigates an enormous quantum of scientific data that will lead towards an evolutionary complexity that may persist within a particular discipline, guide how study domains could

be developed or required (Théodon et al., 2023). Various bibliometric analyses have been done for different purposes, such as understanding collaboration patterns, mapping emerging research trends, and analyzing data on published works (Johnson et al., 2023).

Therefore, identifying and selecting exact and proper search words had a crucial influence on probing this database to glean relevant literature for the specific research work at hand. According to the recent scholarly works on the subject issue, the presented study aims to discover critical criteria required from permeability prediction models about fracture and matrix porosity features (Er & Babadagli, 2010). Based on the importance of identifying only the most applicable articles for conducting the review study, specific search keywords were methodically used: "Permeability Prediction Models," "Porous Media," "Fracture Porosity," and "Matrix Porosity." It undertook a review based on an SLR methodology to synthesize the findings and attempt to answer some of the questions left unanswered by past research (Pan et al., 2004; Rahmanifard & Gates, 2024). The SLR approach is an open, scientific, and reproducible approach, followed here in identifying and searching for studies covering the research domain and its evaluation (Hewitt et al., 2016). The search was performed in the Scopus database, targeting the period between 2020 and 2024 because this database allows for powerful searches and may provide an analysis of bibliographic information. In general, it was found that the terms "Permeability Prediction Models" and "Porous Media" were increasingly present. In contrast, "homogeneous porous media" and "single-phase flow" have been less common in recent works.

The R package tool utilized a complete set of utilities to analyze published bibliographic data precisely. Specifically, Bibliometrix, the open-source tool for science mapping analysis, was used in this paper (Marathe & Sadowski, 2024). It allows robust quantitative analysis in the fields of Scientometrics and Bibliographics. R-studio version 3.6.1 software, developed with the R programming language, has been used to import bibliographic data from databases such as Scopus. Besides allowing accuracy, it was also very convenient. The R programming language and its packages have acquired much relevance in several fields of science to this date. Distribution and archiving are made via the CRAN network project (<https://cran.r-project.org>).

The current work has turned to the Biblioshiny Web application, implemented within the Bibliometrix package, as the most convenient and workable bibliometric analysis system. As stated by official documentation on the platform at (www.bibliometrix.org/biblioshiny/), Biblioshiny can easily be characterized as a non-hardcore analytical device for scientists because it requires only the general, average knowledge from the users (Baiyegunhi et al., 2022). These publicly available tools enable scholars worldwide to adore the privileges of deep academic analytics without extreme technical problems. Complementary tools were used to complement the clustering of publications with Mendeley and VOSviewer, visually enhancing the depth and clarity of the analysis.

This study organized the bibliometric analysis into three hierarchical knowledge structures: conceptual, intellectual, and social. First, network analysis, factorial analysis, and thematic mapping were employed to construct the conceptual structure to detect thematic trends and research clusters. Second, historiography and network analysis have been used to explore the intellectual structure of the evolution of scholarly contributions and prominent authors. Third, the social structure was analyzed using various techniques of an association network, which determined the collaboration pattern in authors, institutions, and countries. These combined methods give a distinct perception of general patterns and voids within the previously published literature. Besides, it was possible to introduce hierarchical metrics at the source, author, and document levels, allowing systematic search in bibliographic data that enables meaningful insights and visualizations to enhance knowledge on permeability prediction and porous media research.

2.2. Data collection

It is also a crucial preliminary step in a systematic literature review: identifying an appropriate database from which bibliographic records are collected (Chedik et al., 2024). The decision to use the Scopus database in this study is based on the fact that it contains the most extensive collection of peer-reviewed literature and, therefore, gained international acclaim among researchers. This renowned database from Elsevier BV provides more than 16,981 titles in the number of high-impact research works across various disciplines (Elsevier.com).

This study followed the PRISMA methodology, which insinuates a systematic and transparent way of data collection to identify and fill the research gaps. The process followed significant steps: formulating a strategy for the search, setting clearly defined inclusion and exclusion criteria, and carrying out a rigorous selection and evaluation of the research output (Aziz et al., 2024; Kumar et al., 2024). Initial filtering targeted journal articles to maintain the consistency and quality of the contribution, while the restriction to English and Chinese ensured accessibility for the researchers conducting the review. Figure 1 shows the PRISMA methodology and framework used in this study.

The search was performed in two phases: first, the Scopus database was searched within all fields from 2020 to 2024. Based on the specific inclusion and exclusion criteria, the search retrieved 16,981 documents. A further limitation of the retrieved documents to journal articles and conference proceedings was done to ensure the scholarly rigor of the search output. In addition, the publication stage was limited to the Final, which ensured that only complete studies were represented. The search was refined further to keep with the research focus and accessibility, basing it on documents in English and Chinese. The keywords will include "Porous Media," "Permeability," "Fracture," and "Numerical Models"; therefore, applying filters to keep only relevant studies will be effective. It, thus, sets a strong foundation for further bibliometric and systematic analysis thanks to such profound filtering.

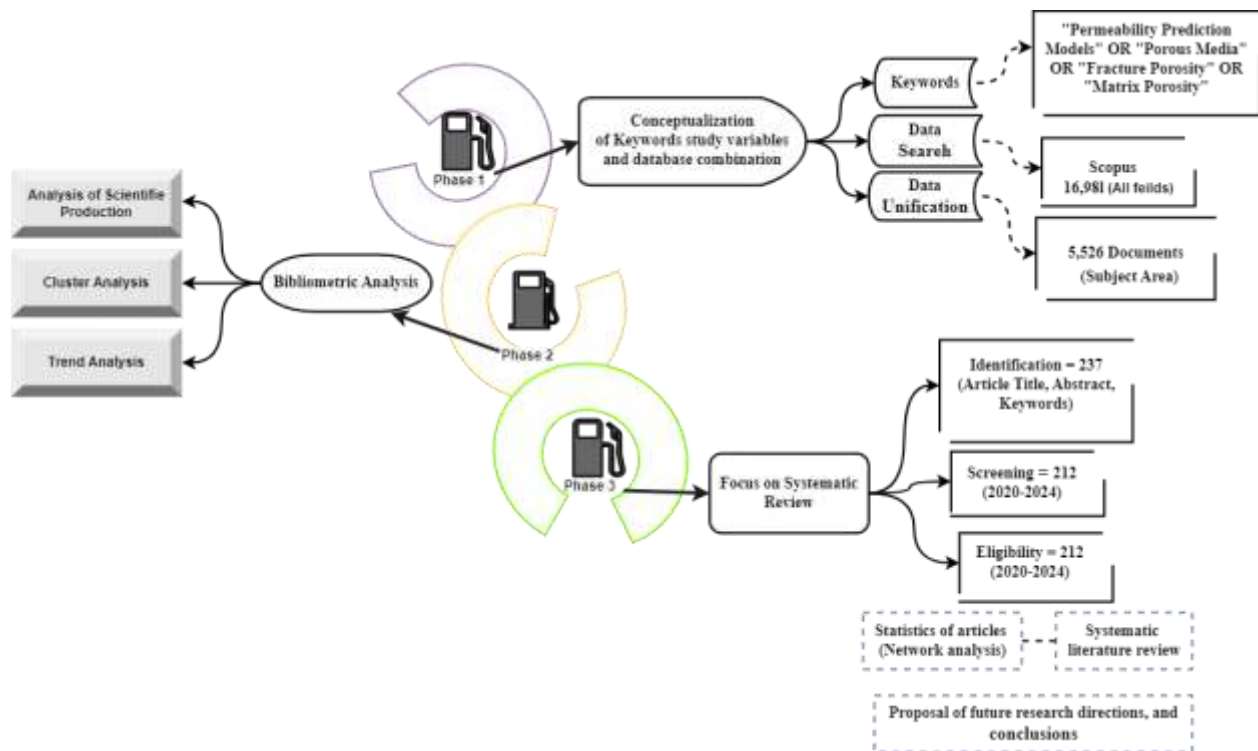


Fig. 1. Prisma flow diagram

In the second filtering step, the dataset from Scopus was refined to focus on high-quality and relevant publications, narrowing the total number of documents to 5,526. This step targeted works in engineering, excluding other subject areas, and restricted the document type to peer-reviewed journal articles for academic rigour. Besides, publications were limited to 5,230 English and 297 Chinese articles for accessibility and interpretability. Major contributors included countries like China with 2,921 articles, the United States with 631 articles, and Iran with 318 articles. This dataset offers a refined and focused foundation that underpins studies of permeability, porous media, and numerical modeling in the engineering domain with a guarantee of impactful and relevant literature.

The third filtration step followed this: during this phase, the search in the Scopus database was refined to the article title, abstract, and keywords to make it as specific as possible in targeting the documents that would fall directly into the purpose of the research objectives. This resulted in a reduced dataset of 237 records. The other inclusion criterion was the language, which needed to be in English for homogeneity and easiness of analysis. The subject areas were further limited to engineering so that the data extracted would fall within the technical scope of the study. These extra refinements helped filter studies relevant to permeability, porous media, and numerical modelling. In the last step, the dataset was cleaned by excluding non-English publications and documents outside the engineering discipline. The importance of the publications was analyzed based on title, objectives, methodology, and results for an in-depth analysis of their contribution to the research area. The current study focused on trustworthy

document repositories based on various factors, including the authors' affiliations, country of origin, citations, and other related information that may provide a proper assessment of quality and quantity. The search results have been refined to a focused collection of articles to reduce the considerable extent to which the Scopus database avails. In this regard, only publications in the English language and from the subject areas relevant to the study were considered. A title, abstract, and keyword appraisal identified 212 articles matching the predefined criteria, which were exported in Bibtext file format to analyse and use in this study.

2.2.1. Literature review (Section 3)

2.2.1.1 Permeability Prediction Models

Permeability is one of the most critical parameters in geosciences; it controls fluid transport within a porous medium (Rehman et al., 2024). Many models are developed, from empirical equations to advanced machine learning methods, due to the challenge of accurate prediction. Among different models, the Carman-Kozeny equation is one of the conventional models widely applied in the permeability prediction for granular porous media (Schulz et al., 2019). This equation has huge limitations when applied to highly heterogeneous and fractured media. Recent studies emphasise the trend of shifting towards ML models for more flexibility to give higher accuracy by learning from massive datasets (J. Chen et al., 2022). Physical models were compared against ML algorithms; it was determined that ML models, when trained on the physical properties of the media, resulted in much better permeability predictions (Li et al., 2018). The ML models to adapt and learn from a wide range of input data, such as mineralogy and grain size, to improve their predictive

power significantly (Rehman et al., 2024). Permeability predictions in such formations have been modelled successfully using more advanced models, including deep-learning approaches for unconventional reservoirs and fine-grained sediments (Srisutthiyakorn & Mavko, 2017).

ML in permeability prediction has confronted the challenges posed by porous media; it has also considerably increased its predictive capabilities in a far broader range of geological conditions (Movahedi et al., 2024). ML algorithms for permeability estimation using the routine core analysis data from the UK Continental Shelf, and it was concluded that the ML models could achieve a high accuracy degree compared to traditional methods (Khan et al., 2024). Recent advancements in digital rock technology and ML techniques have shown great promise regarding real-time permeability estimation with significantly reduced computational time/cost. Applied 3D CNNs in anisotropic rocks to estimate the permeability, showing good prediction accuracy (Fu et al., 2023). In contrast, their computational time was highly reduced compared to traditional approaches. These applications support the high, transformative potential of ML toward enhanced permeability predictions, bringing efficient, scalable, and precise solutions for such complex subsurface systems (Elmorsy et al., 2022).

2.2.1.2 Porous Media

PM is vital in many engineering, geotechnical, and scientific applications since it influences materials' fluid transport, heat transfer, and chemical reactions (L. Chen et al., 2022). Current research has targeted the understanding of particle and fluid behaviors within porous media in environmental engineering, geotechnical science, and energy production (Yan et al., 2022). The behaviour of particles in drying porous media has been reviewed to show how the deposition of particles affects porosity, hence changing the characteristics of the materials (Gens, 2010). The development of more efficient porous materials. It facilitates consideration of how porous materials play roles in transport mechanisms for pollutants/fluids in various applications relating to filtration in water treatment systems and enhanced oil recovery in reservoirs and pharmaceutical fields (Maggay et al., 2021). Besides, nanoparticle tracking was applied to study complex transport dynamics within porous media, thus revealing the fundamental processes that control diffusion, retention, and accessibility in such materials (Pham & Papavassiliou, 2017).

Besides, porous media has critical applications in aerospace and fluid machinery for drag-reduction. Other experimental studies have shown that by bringing different pore densities into the light in porous materials, porous media seriously influences the flow dynamics and friction drag reduction to attain better aerodynamic efficiency (Liu et al., 2020). It is especially valuable for airfoil applications, given the decrease in strength of the vortices and shear stresses caused by the presence of the porous medium leads to improved performance (Ahlawat et al., 2024). This type of study holds importance due to its role in optimising materials for energy-efficient technologies (Tian et al., 2023) Porous media have been used in combustion systems to increase heat

transfer efficiency and flame stability and reduce emissions, further illustrating their use in sustainable energy applications.

2.2.1.3 Fracture Porosity

Fracture Porosity is an essential factor in many geological formations, particularly in reservoirs or aquifers and in fractured rock systems; it plays a significant role in the determination of permeability and characteristics of fluid flow (Mazzullo, 2004). The fluid passes, enhancing the permeability of otherwise relatively impermeable materials. These may range from small microcracks to large fault systems, and their geometry, connectivity, and distribution significantly impact the material's fluid transport properties (Lei et al., 2021). In petroleum engineering, fracture porosity is essential in producing unconventional resources, such as shale gas and tight oil (Ma, 2016). Advanced modelling methods include computational fluid dynamics and lattice Boltzmann methods, which have been applied to fluid flow simulation through fractured porous media, how fractures interact with matrix porosity and, consequently, the interaction that occurs with overall permeability (Meakin & Tartakovsky, 2009). Besides, fracture networks are usually an integral part of reservoir simulation models for predicting fluid behaviour with the extraction view; thus, fracture network geometry is essential in maximizing resource recovery (Boutt et al., 2007).

Recent research has also explored the role of fracture porosity in geothermal energy systems, especially in hot, dry rock reservoirs (Chaaban et al., 2022). Indeed, the presence of a fracture network greatly enhances heat exchange efficiency in HDR and makes it an attractive option for renewable energy production (Golparvar et al., 2018). Fracture geometry complexity and its interaction with fluid flow are still challenging to comprehend, as fractures can present highly irregular and anisotropic features that complicate modelling efforts. Fractures evolve during processes like hydraulic fracturing and how this affects long-term fluid flow behaviour in fractured reservoirs. This also goes hand in hand with improving imaging techniques such as X-ray tomography and digital rock physics for better characterization of fracture networks, giving rise to even better models that can predict fluid behaviour (Viswanathan et al., 2022). Knowledge of this type is essential for mining, oil and gas extraction, and water management (Katende, 2022) Managing fluid flow through fractured porous media is a concern for optimising their efficiency and causing minimal environmental damage.

2.2.1.4 Matrix Porosity

Matrix porosity is essential in understanding reservoir rocks and materials' storage and flow properties. Some recent advances have been made in matrix porosity characterization, especially for complex materials such as shale and ceramic composites (Qian et al., 2024). The influence of matrix components and diagenetic processes on pore properties in shale from the Lower Cambrian period in South China (Jia & Xian, 2022). The matrix heterogeneity thus plays a vital role in pore development and connectivity; also, these various lithofacies show sharp variations in pore size and poor connectivity (Yang et al., 2022). This work pointed out that matrix composition, combined with the corresponding diagenetic processes of compaction and cementation, directly

controls the material's porosity and permeability and significantly impacts fluid flow and resource recovery (Weiqiang et al., 2020).

Porosity is a common problem in metal matrix composites, like SiC-reinforced aluminium, arising from the nature of the manufacturing process while being able to alter their mechanical properties significantly (Chen et al., 2020). The porosity of the matrix has been investigated concerning its role in the elastic modulus of these composites. It was revealed that the distribution and size of pores in the material can strongly influence its capability of stress transfer within it (Wang & Monetta, 2023). The position of pores, especially those far from reinforcing particles, was observed to have more significant effects on the effective elastic modulus of the material. These findings show that the correct prediction of matrix porosity is essential in material properties and enhancing composite materials' performance in engineering applications (Dalaq et al., 2016). The nature of the matrix porosity study presented herein is necessary for improving models dealing with fluid flow through porous media and for giving insight into the effects of matrix porosity in complex systems.

III. RESULTS

3.1. Performance Analyses

Section 4 develops the bibliometric analysis findings, divided into two sub-areas. This study encompasses a comprehensive descriptive analysis that examines significant authors, top journals, contributing organisations, and the most often-used terms in titles and keywords.

3.2. Descriptive Analysis

Descriptive analysis was done to obtain data on the field's basic and structural research features. Specific analysis entailed the distribution of authors' affiliations, international collaborations of authors, publication sources, and bibliometric features of the documents. Furthermore, the fact that journal articles and conference proceedings, which comprised approximately 20% of the reviewed documents, were considered gave the study a broader perspective on the emergent research trends. While the percentage is minor, conference papers contributed highly and provided insight into local permeability and porous media research developments.

Fig. 2, "Annual Scientific Production," reflects the stable growth of research output from 2020 to 2024, with a sharp increase in 2024, which can be marked as a peak for scientific activity. This increase demonstrates greater interest academically and industrially in understanding permeability and porous media due to impelling advances in computational modelling and its applications.

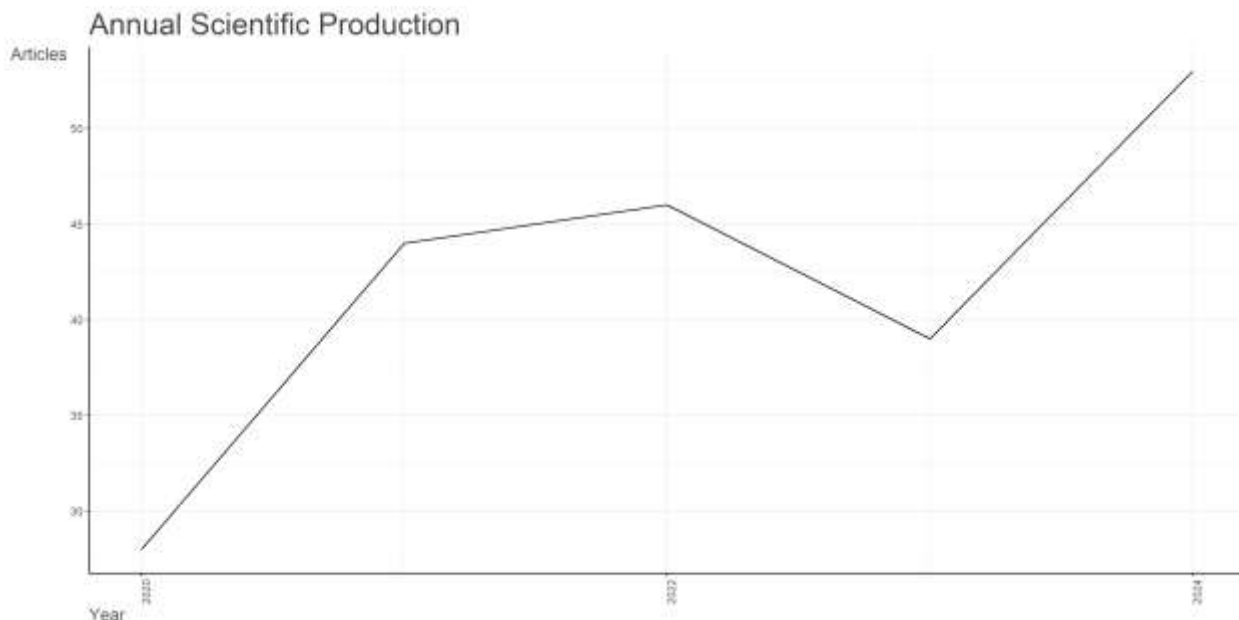


Fig. 2. Annual scientific production.

Fig. 3, on "Average Citations per Year," however, shows a fall for the same period, probably due to the spreading caused by the increasing number of published documents and concentrated works on the most recent ones. These trends underscore the need for impactful, high-quality research to meet emerging challenges and remain relevant in this growing field.

3.3. Authors influence

Figure 4 shows the "Most Relevant Authors" in permeability prediction and porous media research. It can be interpreted from this figure that the most prolific author has contributed up to 11 documents, showing the significant impact of this author in leading the domain. He is followed by other contributors with 9, 8, and 7 papers, respectively, reflecting their active interest and regular scholarly contributions in the field. The contributors of 6 and 5 documents are equally important in helping reshape the

landscape with their valuable insights and fostering collaboration across interdisciplinary topics. This distribution reflects intense concentration among a few leading contributors, which is essential to drive innovation and lay

foundational knowledge. The presence of multiple authors with varying levels of contribution underlines the collaborative and expanding nature of research in the area.

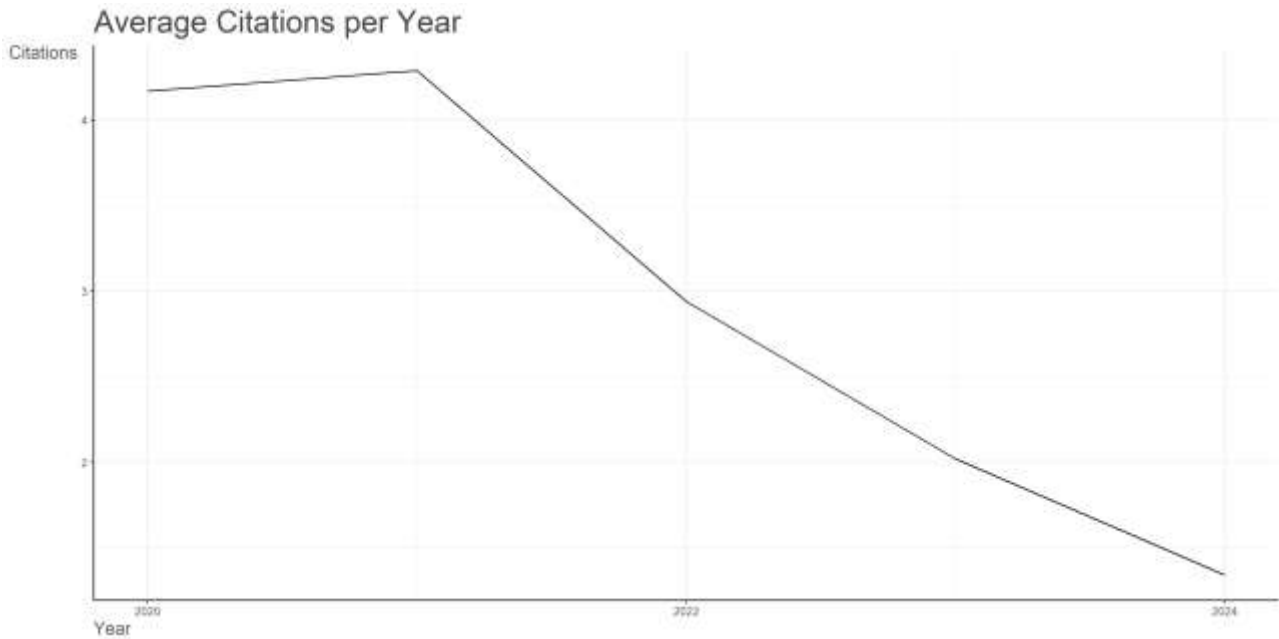


Fig. 3. Evolution of papers per year.

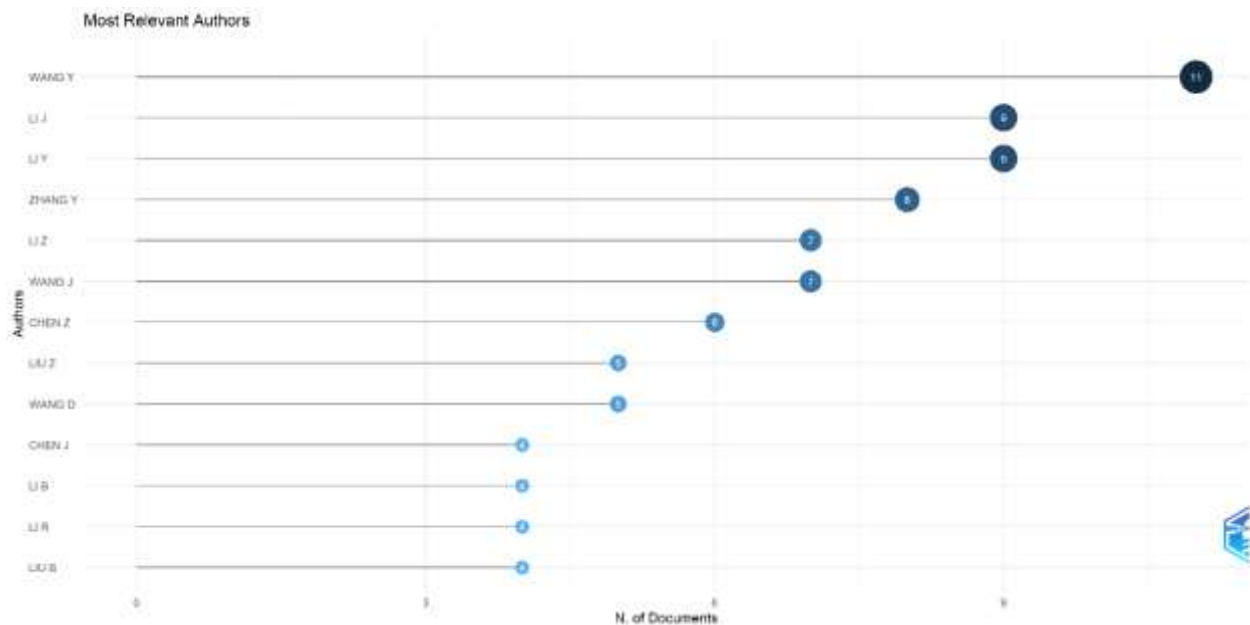


Fig. 4. Most relevant authors per fractionalised N of authored documents.

3.4. Affiliation Statistics

The analysis of the most relevant affiliations in permeability prediction and porous media research shows a significant concentration of contributions by a few key institutions. The leading contributor is Tsinghua University, which has 11 articles, thus demonstrating its dominant contribution to advancing research in this area. It is closely followed by the China University of Mining and Technology

and Tianjin University, with 9 and 7 articles underlining China's high position in this area.

Other notable institutions are Southeast University, with 6 articles, and a cluster of universities, such as Shanghai Jiao Tong University and Xi'an University of Architecture and Technology, each contributing 5 articles. These contributions reflect intense interdisciplinary research commitment, especially in the Chinese academic landscape, and notable participation by global institutions in advancing scientific

understanding related to fluid dynamics and porous media Figure 5-7.

The analysis of global scientific production in the research on permeability prediction and porous media shows the significant contribution of several countries. According to the data, the leading position belongs to China, with the overwhelming contribution of 253 documents, reflecting its strong emphasis on developing research in this domain. The United States follows it with 31 documents showcasing the continued impact of that country on global research trends.

Other major contributors include Iran with 26, India with 22, the United Kingdom with 17, and Canada with 15; all these numbers bear witness to the increasing interest and investment in this domain. Further contributions come from Germany, Italy, Australia, and Japan, which underpin broad international cooperation and variety in research. The diversity in contributions from developed and developing countries also underlines the collaborative potential for addressing universal challenges in porous media studies.

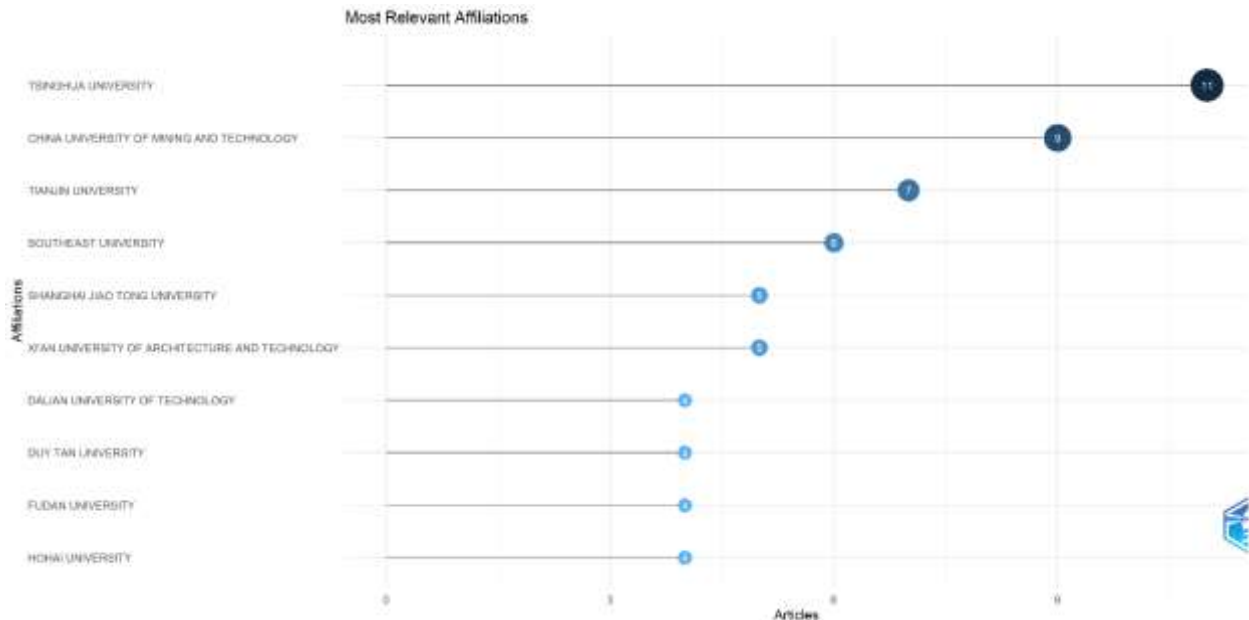


Fig. 5. Most relevant affiliations.

Country Scientific Production

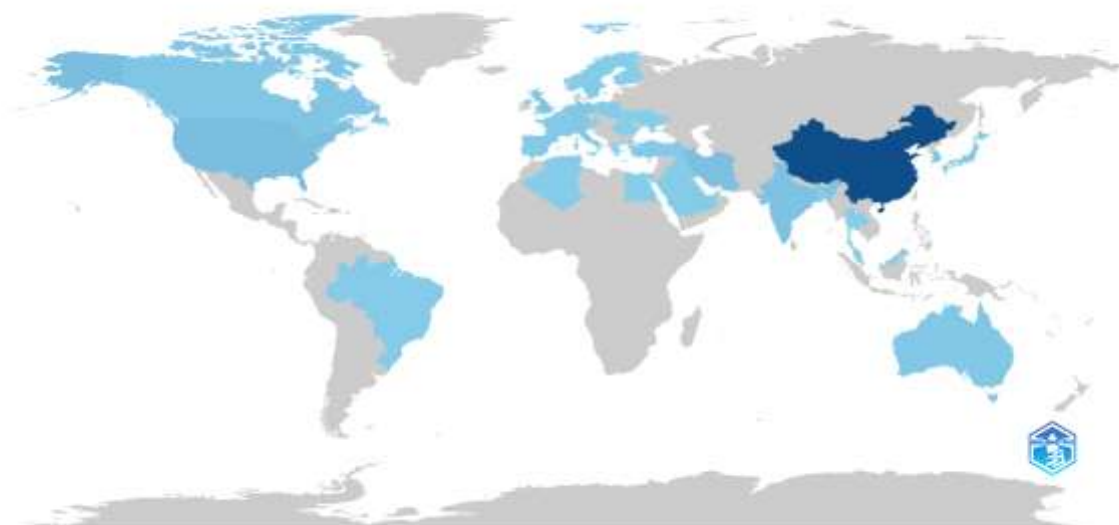


Fig. 6. Scientific production countries.

The contribution of the corresponding authors in the country contribution analysis reflects the dominant position taken by China, leading with 100 articles, which amounts to

47.6%. The color intensity of each country in the chart refers to the number of publications contributed by each country Figure 7. China is the darkest, having taken the lead with 100

publications dominated by single-country publications. The United States comes second with 13 publications, with a stronger emphasis on multi-country collaborations. India and Iran have 10 publications each, showing moderate intensity, highlighting their national research efforts. Lighter shades, meaning fewer publications, represent countries like Canada, the United Kingdom, and Germany; however, their approach is very balanced due to the mix of SCPs and MCPs, reflecting their consistent participation in advancing the field.

3.5. Most relevant sources

Analysis of the most relevant sources indicates that the leading publication, with 15 articles, is the primary platform for disseminating research in this domain Figure 8. Other sources contributed significantly, with seven articles reflecting

their active role in the field. A few journals with contributions ranging from 6 to 5 articles further show the diversity of publication platforms involved in this area. This distribution underlines the concentration of impactful studies within a few core journals yet simultaneously points to the interdisciplinary reach of research into fluid dynamics and thermal engineering in several specialized outlets.

This table displays Bradford's Law, in which the journals have been categorized as "Zone 1," representing all core sources of the most output (Figure 9). The International Journal of Heat and Mass Transfer, with its 15 articles, represents evidence of the leading influence in publishing a subject.

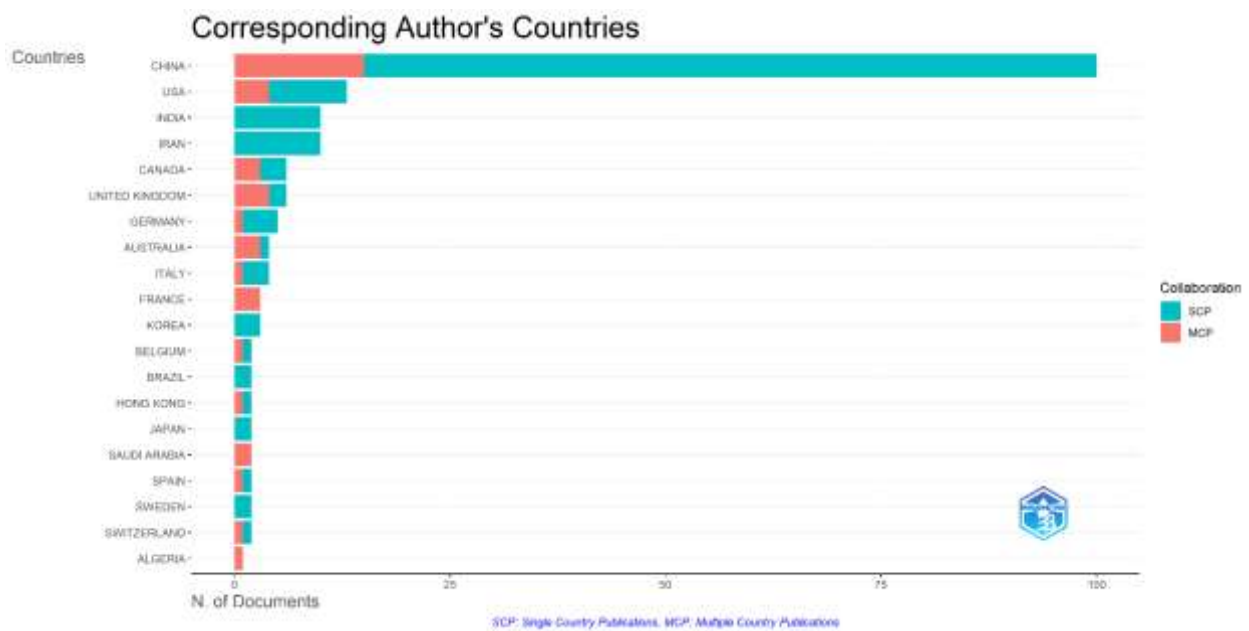


Fig. 7. Corresponding author's country.

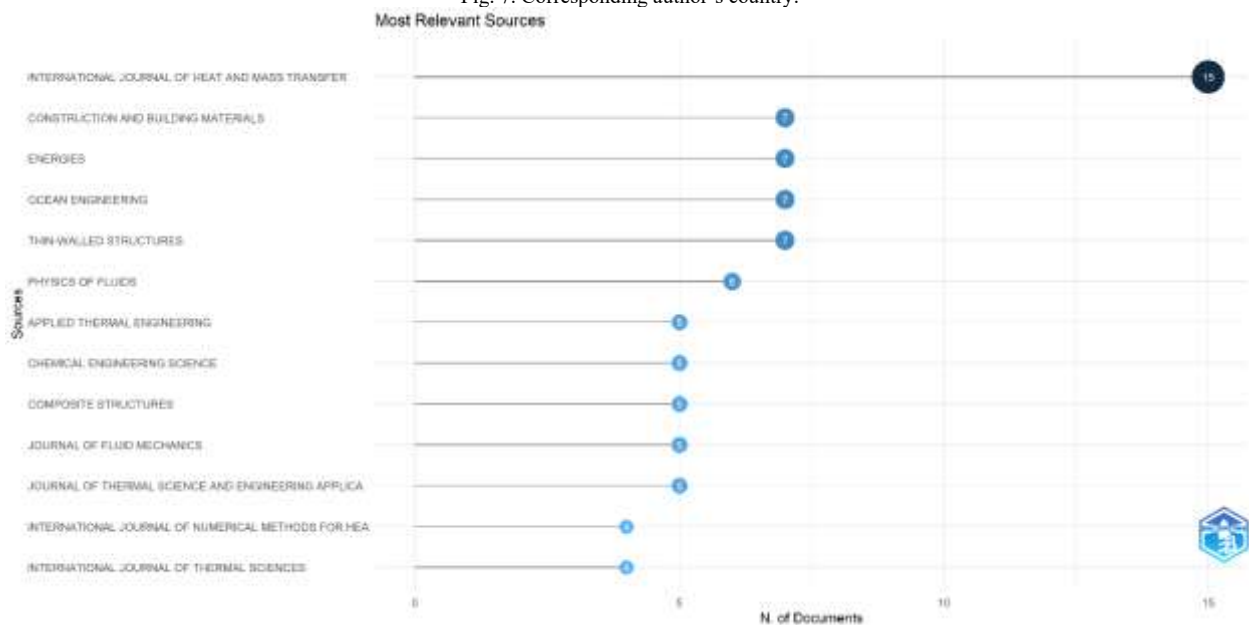


Fig. 8. Top ten leading sources

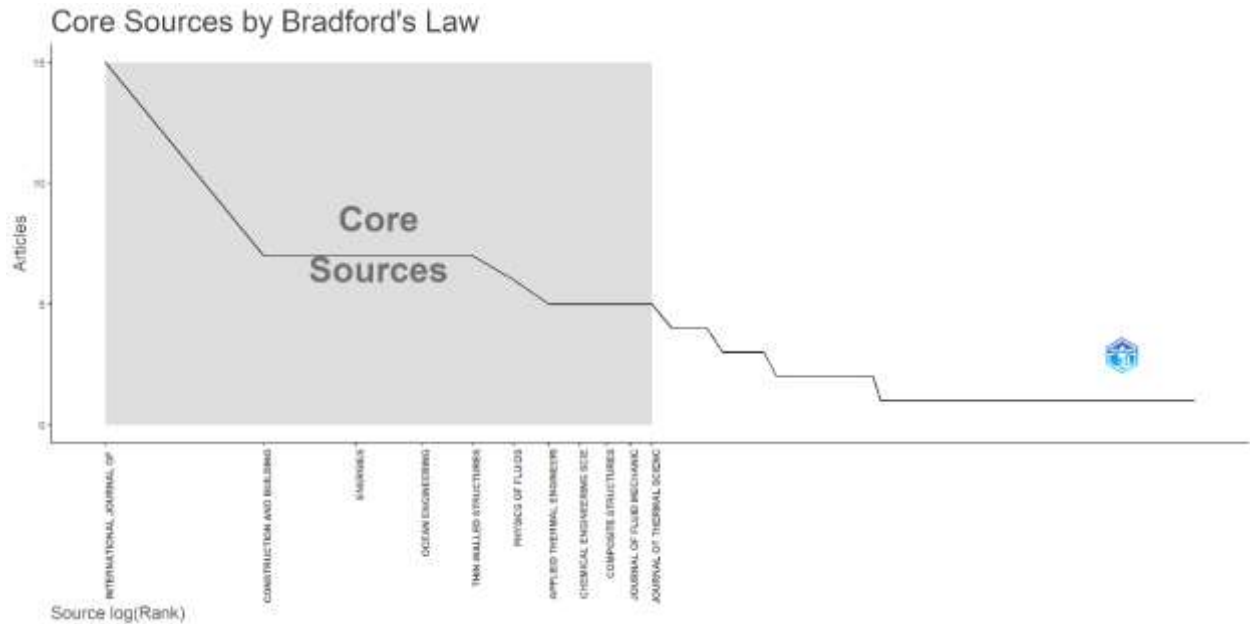


Fig. 9. Source clustering through Bradford's law.

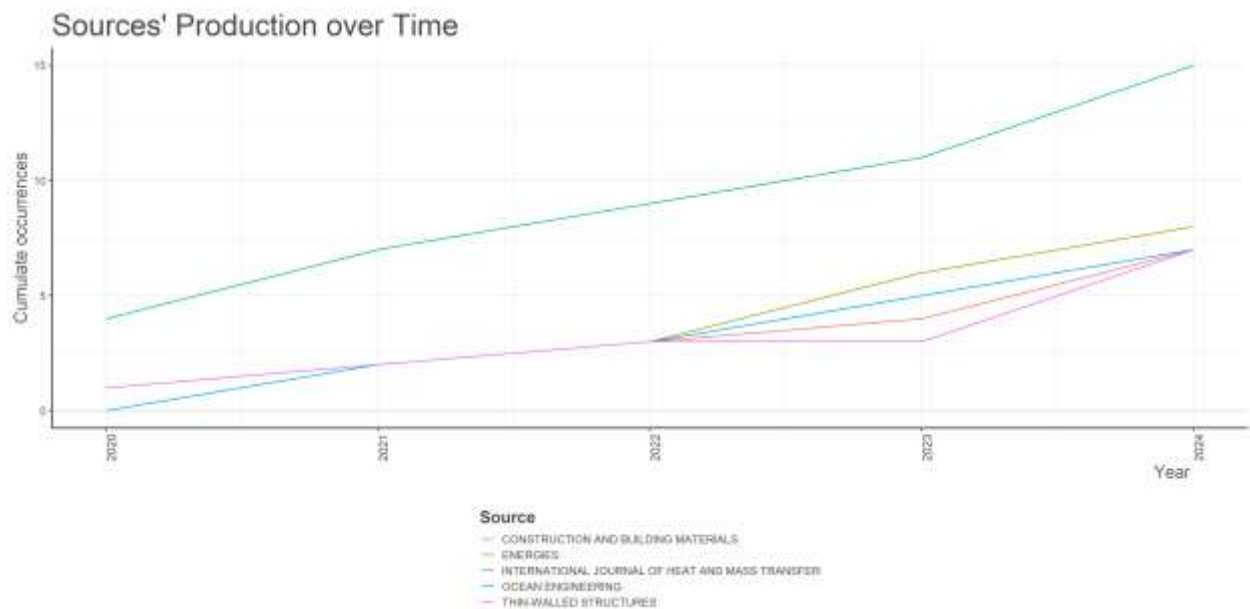


Fig.10. Source growth.

The graph of cumulative frequencies shows the concentration; therefore, all those journals also, like Construction and Building Materials and Energies, though providing merely a few or single articles as contributions, were put as core sources.

Graph 10 illustrates the cumulative production across key sources from 2020-2024. The International Journal of Heat and Mass Transfer has shown an increasing trend in the number of articles, with 4 articles in 2020 to 15 by 2024, making it the most productive. Other sources, such as Energies and Construction and Building Materials, also present stable growth, which reflects increasing attention within their respective fields. Ocean Engineering and Thin-Walled Structures have maintained a moderate but steady

contribution, reaching 7 articles in 2024. These dynamics testify to the temporal development of research activities across diverse but interrelated disciplines.

H-index is an index that tries to estimate the productivity and impact of a journal according to its citations. Indeed, it calculates the number of articles receiving at least h citations each. According to Glänzel (2006) "the m-index is defined as the quotient of the h-index by the number of years since first publication, while another metric called the g-index is an improved variant of the latter which calculates this accumulated citation effect. Table 1 presents the ten best sources and their respective contributions to the field. The International Journal of Heat and Mass Transfer tops the list with an h-index of 8 and an m-index of 1.333, indicating its

prominence in research impact and publication productivity. Other vital journals, such as Chemical Engineering Science and Applied Thermal Engineering, exhibit robust metrics, with respective h-indices of 5 and 4, indicating considerable consistency in the scholarship output.

This table's overall picture is that such journals have contributed immensely to the academic output and impacted the field.

In Figure 11, the words cloud and table represent the most frequent terms within the research of porous media; it is clear why "porosity" is the most present word, having appeared 118 times. Other significant terms are "porous materials," with 82 appearances; "porous medium," with 70; and "numerical models," with 41. This points toward the great use of computational methodologies. Works gave the development of simulation methods, such as "computer simulation" and

"computational fluid dynamics," gaining more and more importance from 2020 to 2024, highlighting state-of-the-art improvements concerning modelling and comprehension of porous structure in recent years.

This agrees with the increased interest in your research field in applying new techniques to study porosity in the context of fluid flow and material sciences.

3.6. Top cited documents

The analysis of the most cited countries reveals that China stands tall with 1,011 citations, while its contributions to this area are so vast that this score underestimates the weight of the contributions of China in the area Figure 12. Iran comes in second among the most cited countries with 250 citations, reflecting a high impact on research output.

Table 1: Source Local impact by h-index and its generalizations.

Source	h index	g index	m index	TC	NP	PY_start
International journal of heat and mass transfer	8	12	1.333	166	15	2020
Chemical engineering science	5	5	0.833	70	5	2020
Composite structures	5	5	1	191	5	2021
Applied thermal engineering	4	5	0.667	209	5	2020
Construction and building materials	4	7	0.8	77	7	2021
International journal of thermal sciences	4	4	0.8	60	4	2021
Ocean engineering	4	7	0.8	112	7	2021
Physics of fluids	4	6	1	60	6	2022
Thin-walled structures	4	7	0.667	126	7	2020
Chemical engineering journal	3	3	0.6	56	3	2021

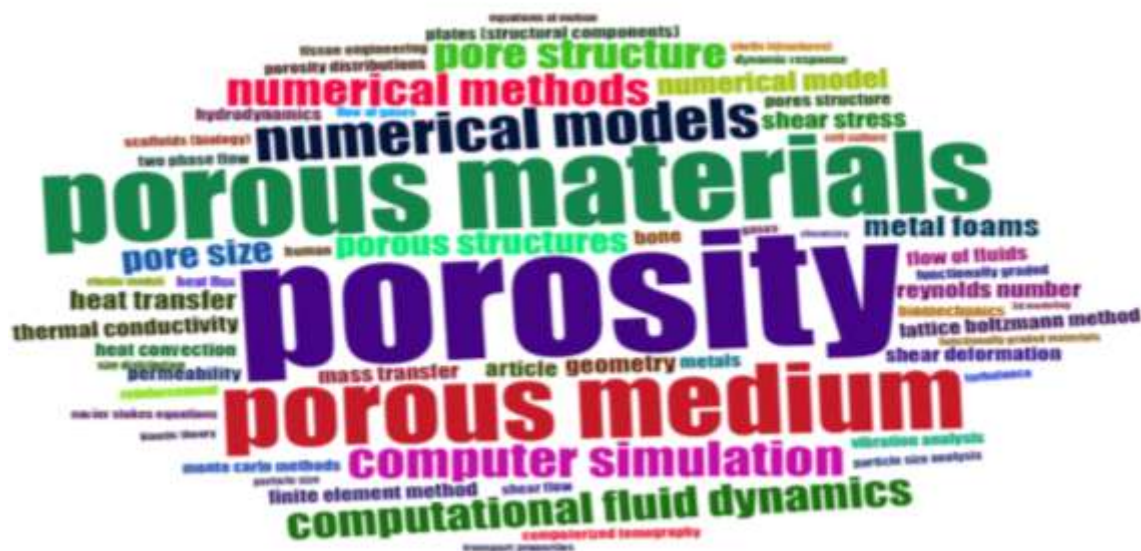


Fig.11. Most relevant words.

The United Kingdom and the USA, which closely follow with 185 citations, stress their strong position in knowledge development. India, with 125 citations, illustrates the growing influence of its research output, while Belgium and Germany, with 72 and 62 citations, further underpin Europe's contribution. Other notable countries like Canada, Algeria, and Spain contribute 51, 50, and 45 citations to highlight a

balanced global effort in driving innovation and scholarly discourse in the domain.

Table 2 represents the most cited papers worldwide. The leading paper is that of Ghahremannezhad et al. (2020), with 131 citations with a very high yearly citation rate of 21.83, indicating that the paper has an immense impact on the field. Niblett et al. (2020) with 99 citations, and the paper of Shahgholian-Ghahfarokhi et al. (2021), with 98 citations,

which reflects their relevance and influence. The highest TC per Year, 28, is Belabed et al. (2024), which shows rapid growth in citations for this very recent publication.

3.7. Keywords statistics

The most frequent keywords are porosity, porous materials, and porous medium, with porosity first, with 118 mentions in Table 3 and Figure 11. Numerical models come

next with (41 Occurrences), and computational fluid dynamics follows with (31 Occurrences), showing that the majority of the research about porous structure is computational and modeling. These keywords reflect the central themes and methodologies in this research field. Word pairs will be used using the co-occurrence function, as outlined in Table 3.

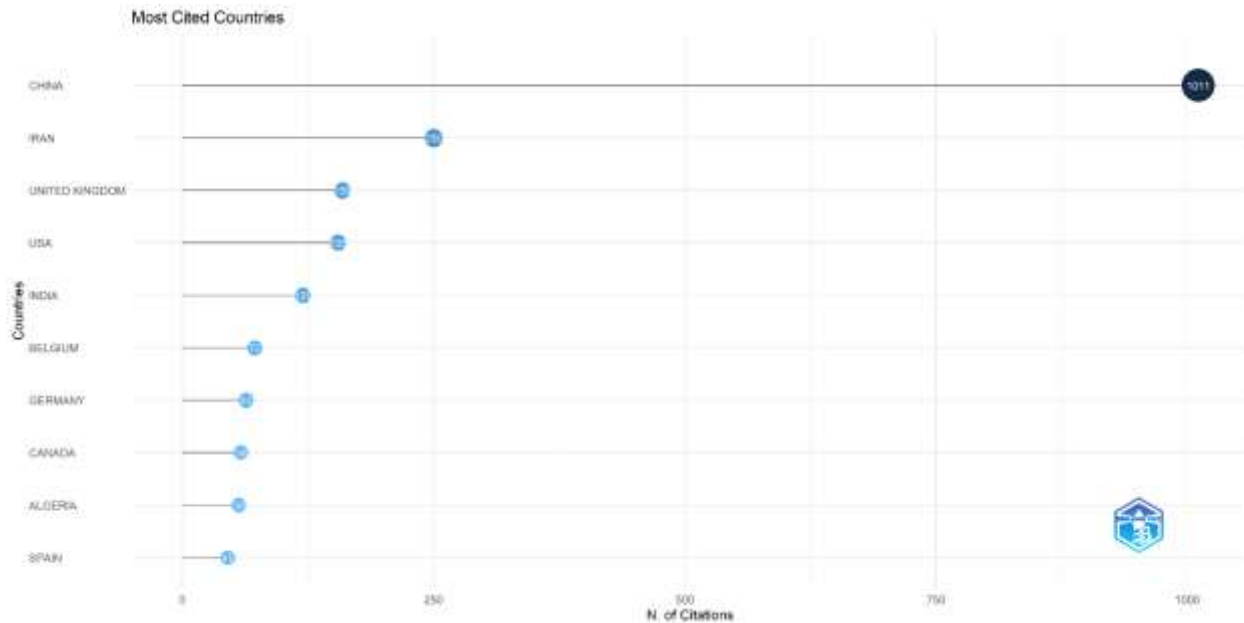


Fig. 12. Most cited countries.

Table 2: Top cited documents.

Paper	Total Citations	TC per Year
Ghahremanezhad et al. (2020)	131	21.83
Niblett et al. (2020)	99	16.50
Shahgholian-Ghahfarokhi et al. (2021)	98	19.60
Zamponi et al. (2020)	71	11.83
Li et al. (2021)	63	12.60
Hajmohammad et al. (2021)	62	12.40
Belabed et al. (2024)	56	28.00
Fu et al. (2020)	53	8.83
Noori et al. (2021)	47	9.40
Zhang et al. (2022)	45	11.25

Table 3: Title words by occurrences.

Words	Occurrences
Porosity	118
Porous materials	82
Porous medium	70
Numerical models	41
Computer simulation	35
Numerical methods	32
Computational fluid dynamics	31
Pore structure	30
Pore size	25
Porous structures	24

3.8. Mapping conceptual structure

3.8.1. Factorial analysis

The bibliometric analysis applied factorial R techniques to conceptualize a framework and visual outline of the thematic structure of this study. In that respect, a conceptual framework

represented in Fig. 13 was created using linguistic elements: keywords and words provided by the authors and representing their co-occurrence patterns. The closeness of positioning of two words would suggest the co-occurrence of the terms in question over many documents as relevant to a specific theme.

This review focuses on critical themes such as porosity, computational fluid dynamics, and numerical modeling. Fig. 13 gives an overview of the importance of terms like "porosity," "porous medium," and "numerical models" within the research landscape and their interconnectedness within the study corpus.

The conceptual structure word map is generated using the multiple correspondence analysis (MCA) technique, which relies on keywords, as seen in Fig. 14. MCA further refines the conceptual structure into distinct clusters of thematic relevance. Three clear thematic clusters emerge in the most critical research areas in porous media and computational techniques. The red cluster concerns material and structural properties; terms present there are "functionally graded materials," "porosity distributions," and "dynamic response." This cluster is related to engineering and structural analysis of the advanced material; some of the keywords, like "shear deformation," "reinforcement," and "metal foams," refer, in fact, to studies referring to the mechanical behavior and adaptability of materials in different conditions. It reflects the good attention given to understanding the structural composition and optimization of materials for a wide variety of applications in engineering.

The blue cluster is dominated by the terms "numerical models," "finite element method," and "computational fluid dynamics" and therefore represents computational and analytical methodologies. This cluster underlines the strong presence of simulations and numerical approaches in studying porous media. It covers the analysis of heat transfer, particle size, and transport properties, emphasizing the application of computational tools to solve complex physical phenomena. The green cluster focuses on biological and biomechanical applications, such as "permeability," "biomechanics," and "scaffolds." The systems analyzed are biological, such as tissue engineering and bone modeling, and fluid flow dynamics in a biological context.

3.8.2. Thematic map

The thematic analysis of the figure grouped the research themes in a four-quadrant scale of relevance (centrality) and development (density) in Figure 15. The motor themes in the upper-right quadrant are well-developed and highly relevant. Examples include "computational fluid dynamics," "flow of fluids," and "shear stress," all falling into this quadrant and indicating core value in driving the research in porous media and fluid dynamics. Such themes are crucial and constitute high academic activity with strong interdisciplinary applications.



Fig. 13. Word tree map of high-frequency keywords in the sustainability field

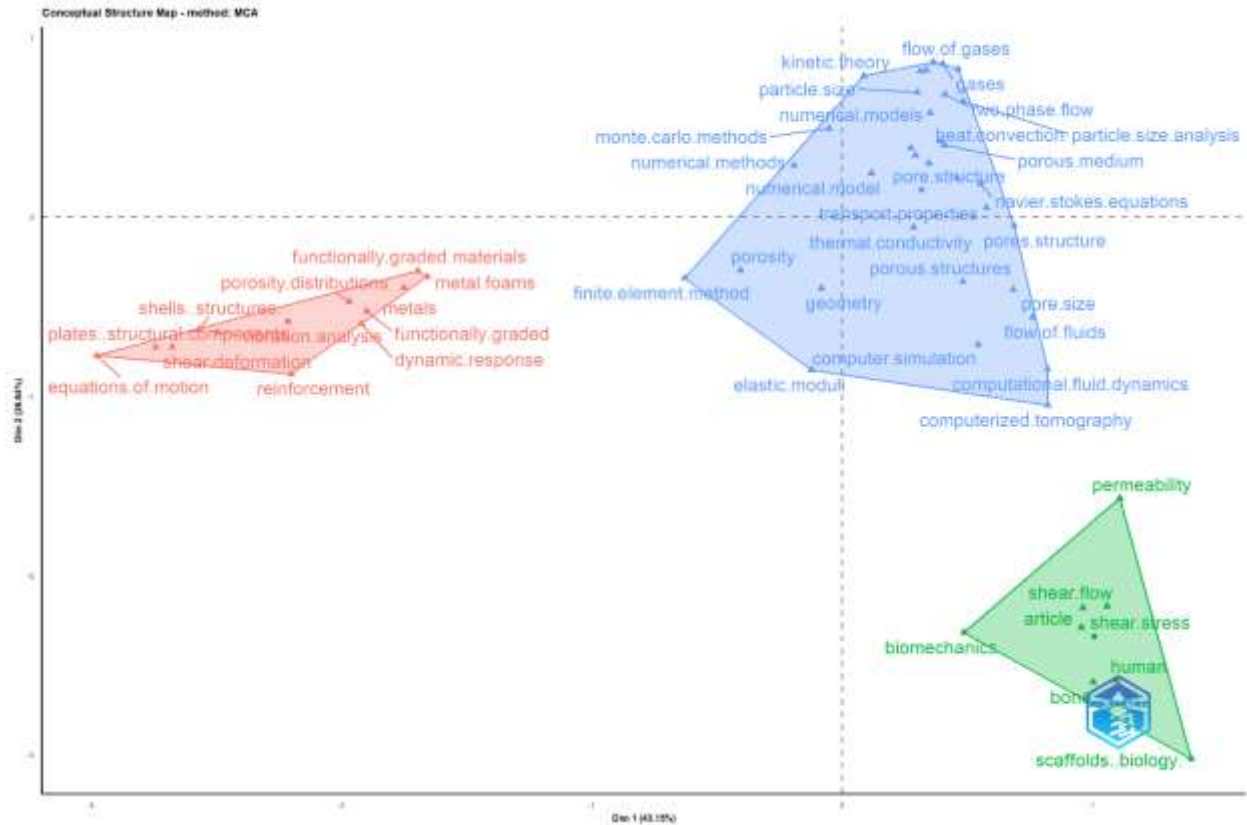


Fig. 14. Conceptual structure map.

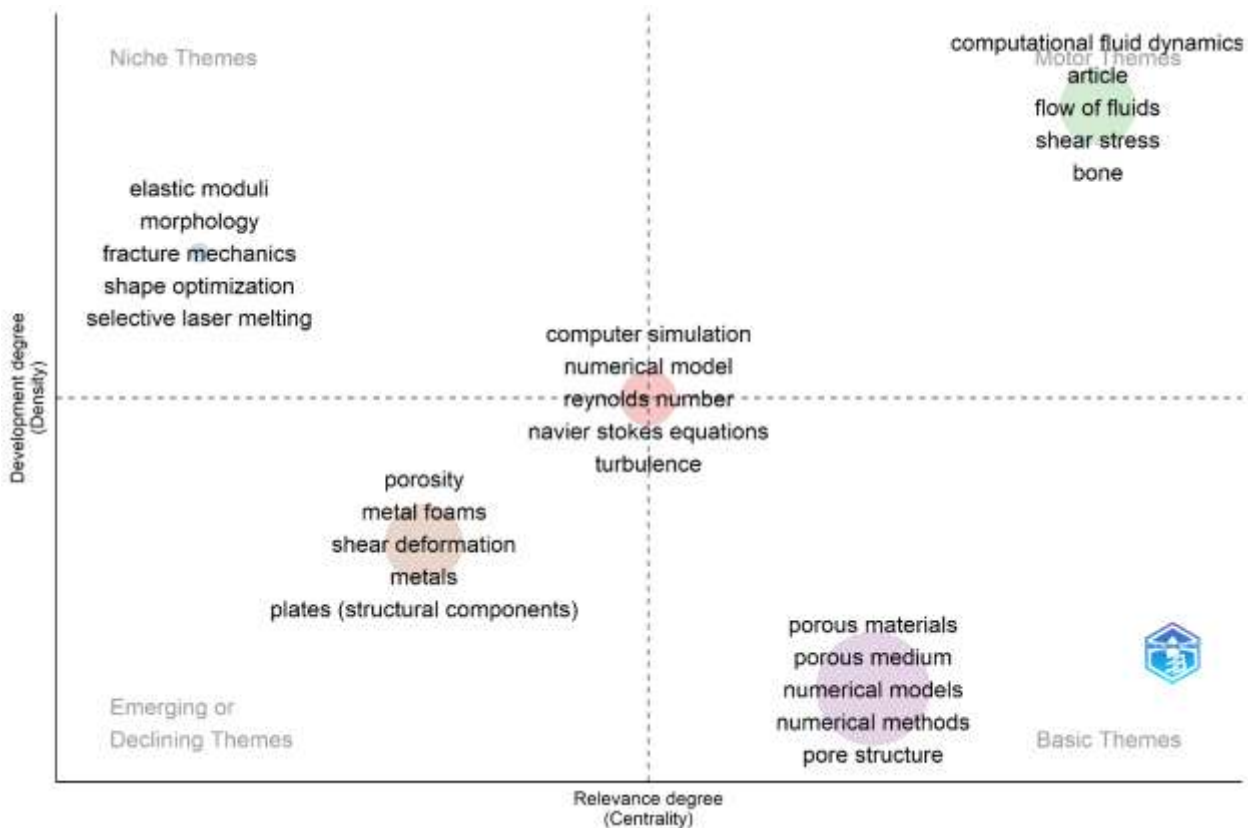


Fig. 15. Thematic map of research topics based on the author's keywords.

The basic themes in the lower-right quadrant are "porous materials," "porous medium," and "numerical methods," which are foundational concepts central to the field but less developed in terms of their thematic sophistication. These themes are the structural bases for ongoing research, often feeding into work in more advanced areas. The upper-left quadrant displays "niche themes" that represent highly developed but less central issues, standing for their importance in more narrow research contexts. Finally, the lower-left quadrant shows emerging or declining themes that are less developed and less relevant; it includes "porosity," "metal foams," and "shear deformation" as such topics, which may stand either for underexplored opportunities or for topics with waning research interest.

3.8.3 Intellectual structure co-occurrence network

This section elaborates on the lexical linkages of diversifying our knowledge with different subjects through keyword networks. This paper considers one of the essential environmental themes analyzed through co-word network analysis about the innovation performance regarding time and territory. Word networks were mapped on a two-dimensional thematic map based on the measured centrality and density. The "Biblioshinyapp" software has been used in the elaboration because it allows an efficient and transparent visualization of the structure of the co-occurrence network in figure 16.

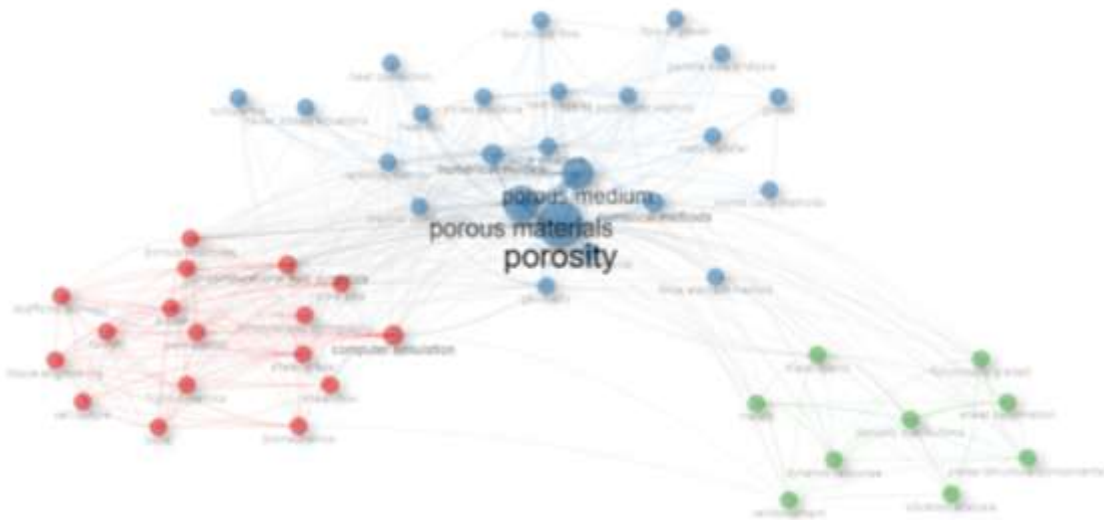


Fig. 16. Co-occurrence Network.

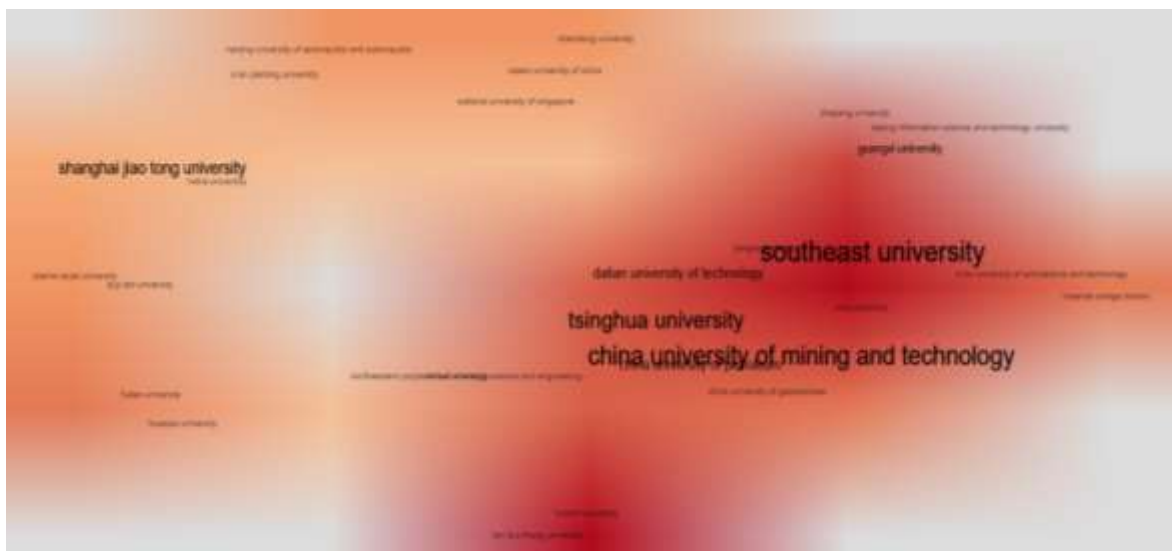


Fig.17. Network of Institutional Collaboration

This co-occurrence network underlines the interrelation between essential research concepts and themes developed within porous media. The central terms, hence dominating in

this network, are "porosity," "porous materials," and "porous medium," thus representing the very foundation of the research domain. Computational and numerical methods are

depicted in the blue nodes, showing strong connections with fluid dynamics, heat transfer, and pore structure analysis. Red clusters highlight biological and biomechanical applications, placing permeability, tissue engineering, and shear stress into larger biological. The green cluster represents structural and material-themed topics: metal foams, reinforcement, and structural components indicate an interdisciplinary approach that cuts across computational, biological, and engineering themes in porous media research.

3.8.4 Social Structure

Social structure analysis looks into the collaborative network of institutions and countries contributing to the research within the field. The first visualization shows the

institutional collaboration network, in which Southeast University, China University of Mining and Technology, and Tsinghua University emerge as leading knowledge production and collaboration centers Figure 17. These universities are at the core, representing their great contribution and influence within the field. Other institutions, like Shanghai Jiao Tong University and Dalian University of Technology, are scattered but part of this global interconnected network that fosters collaboration and cooperation to help further human knowledge in general.

The second visualization is about international collaboration between countries, with China as the hub of the global research network Figure 18.

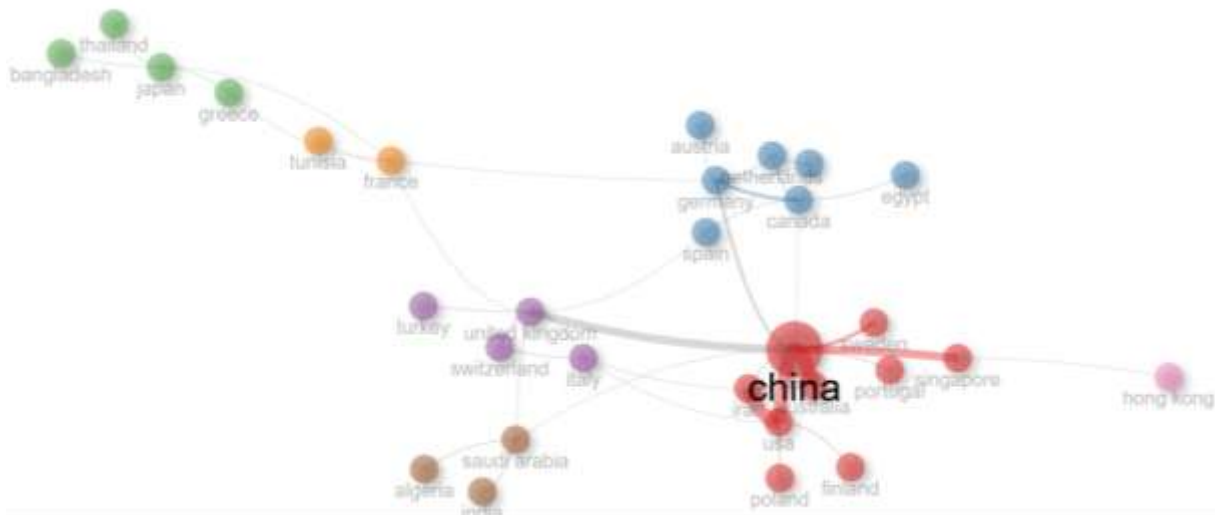


Fig. 18. International Collaboration Network

This would suggest that it is highly interconnected with other seminal nations, such as the United States, Germany, and the United Kingdom, considering its pivotal role in creating a unified international partnership. Contrasts such as Japan, France, and India also provide peripheral contributions, but the interconnections are much more regional. The above analysis can be used to emphasize institutional and international cooperation at the heart of the development of this field by providing a range of perspectives and shared knowledge.

IV. DISCUSSION

How has research on fracture and matrix porosity conditions evolved in the last decade? During the past few years, research on fracture and matrix porosity conditions has moved upwards over the last decade due to better modeling techniques, more powerful computational tools, and increased cross-disciplinary interactions. It has been marked by the integration of ML models and CFD, evolution characterized by a more accurate prediction with a deeper understanding of fluid flow and transport mechanisms within complex porous media systems (Johnson et al.). The study SLR the critical aspects of permeability prediction, fracture porosity, and matrix porosity. The results indicated that fracture porosity has recently gained significant attention due to its potential to

enhance fluid transport in unconventional reservoirs and geothermal applications (Darwent, 2022).

On the other hand, matrix porosity studies have now been developed in the direction of their interaction with fractures, highlighting the contribution of matrix porosity to overall permeability and fluid retention properties. Such developments emphasize the transition from conventional empirical approaches toward computational and data-driven techniques for superior modeling accuracy and scalability. This, in turn, was further testified to by the bibliometric analysis, in which China became the leading contributing nation in quantity. Major contributors at the institutional level included Southeast University and Tsinghua University. The most apparent evidence underlining the importance of international collaboration, particularly involving China with major global research epicenters, came out through social structure analysis. Thematic clustering pointed toward innovative materials, numerical models, and environmental sustainability within a multidisciplinary expanding field illustrated by the conceptual structure maps.

The bibliometric and SLR complete fracture and matrix porosity research showed several significant findings. Permeability modeling through numerical simulations has seen the most significant development, especially after introducing LBM and CFD techniques. Prediction of fluid

flows within complex porous media using machine learning has emerged as a promising arena for higher accuracy and efficiency (Joodat et al., 2018). It also underlined that China is the leading contributor to publications and collaboration, thus documenting the role played by that country in advancing this field.

Different challenges are yet to be overcome, such as the inability of traditional permeability models, such as Kozeny-Carman, to capture realistic flow physics and high-resolution simulations with CPU-intensive computations. Interdisciplinary collaborations that addressed geology and engineering with the multi-faceted environmental sciences were identified as a crucial strategy for further innovation. Such multi-scale applications of sustainability principles also include emerging yet underexplored areas of integration in applications like geothermal energy, enhanced oil recovery, carbon sequestration, and more. This perspective underlines the practical applications of porous media studies in sustainable engineering and resource management.

4.1. Future research

The results of this study point to several promising ways that future research on fracture and matrix porosity might take. First, the potential of advanced ML and AI methods integrated into the simulation of porous systems, particularly under different fracture and matrix porosity conditions, stands very high. The same could be immensely useful in improving the accuracy and efficiency of existing predictive models. Second, those dealing with developing multi-scale modeling approaches that link micro-scale and macro-scale dynamics in porous media need a deeper understanding of how fractures interact with matrix porosity in influencing fluid flow. Besides this, nurturing an interdisciplinary approach among the engineering, geology, and environmental science disciplines will be crucial in meeting the challenges related to sustainable resource extraction and fluid dynamics. Future research should also be directed to show how porosity studies can be related to new fields such as carbon capture, energy storage, and geothermal energy systems, further extending the scope of this critical research.

4.2. Limitations of existing research

Despite these advances, critical limitations remain regarding fracture and matrix porosity. Most of the studies are based on idealized models or laboratory conditions that cannot represent the complexities of real porous media. Besides, there is an acute scarcity of standardization regarding experimental methodologies, data collection, and model validation—a factor that restricts comparability among the various studies and hampers reproducibility. Other limitations include a minimal emphasis on sustainability issues concerning porosity-related research, primarily environmental and energy issues. High-level computational tools in the form of CFD and ML are scarcely used because of the high computational cost and technical skill needed. Such issues must be addressed to enhance the practical application of porosity research and further develop its industrial and environmental relevance.

V. CONCLUSION

This paper critically reviews the current state of fracture and matrix porosity studies, underlining the advances in permeability prediction, computational modeling, and interaction of fractures with the matrix. The past decade has made considerable progress by developing numerical modeling techniques and interdisciplinary approaches that have advanced the understanding of fluid flow and transport mechanisms in porous media. This approach utilized the PRISMA framework and Bibliometrix for Meta-analysis and thematic analysis to identify China.

Besides these advances, some critical challenges must be overcome, including a lack of standard methodologies, high computational requirements, and limited integration with sustainability principles. When these gaps are mended, will porosity research have practical applications in solving real-life problems of sustainable engineering and resource management? Future efforts should focus on adopting advanced computational tools, enhancing multiscale modeling, and incorporating sustainability frameworks to foster continued innovation and broaden the impact of this dynamic field.

The paper first identified a well-structured framework involving a focused research topic, selecting relevant databases, and establishing key analytical tools and methodologies. Initial analysis has focused on citation distributions as a means by which to answer the research question of how fracture and matrix porosity studies have evolved. These contributions of leading authors and their respective institutions brought to the fore the leading institutions, especially those in China, which appeared to be the leading contributors, together with several other active nations. The study also listed permeability, fracture porosity, and matrix porosity as key terms, indicating that significant themes of the critical fluid flow modeling and analysis of porous media were being focused upon. Influential contributions came from prominent journals that have shaped this field.

International Journal of Heat and Mass Transfer and Applied Thermal Engineering featured key articles that placed them in the lead among major contributors to this field. It identifies the highly cited papers, computational models, and bibliometric methods of analysis that give information on co-author networks of influence. Such insights will help to integrate methods across disciplinary divides, most noticeably in fluid dynamics, energy storage, and resource management, and underline a continued emphasis on innovation through computation and frameworks, foregrounding sustainability in building both the theoretical and practical understandings of the porosity-related phenomena with implications for useful strategies driving forward research and applications.

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