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REVIEW

Worldwide research progress and trends on geothermal water–rock interaction experiments: a comprehensive bibliometric analysis

D. Yáñez-Dávila[1] · E. Santoyo[2] · G. Santos-Raga[1]

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Abstract
The present work reports a novel methodological and comprehensive bibliometric analysis on past and present research advances carried out on geothermal water–rock interaction experiments from 1963 to 2022. The novel bibliometric analysis enabled the most representative bibliometric indicators on the research subject to be obtained. Published articles, preferred publication journals, research leaderships (authors, networking groups, institutions, and countries), and future research trends were also collected from a comprehensive searching carried out in indexed databases (Web of Science and Scopus). Up to our knowledge, this bibliometric information will benefit the worldwide geothermal community by providing a deeper insight of water/rock interaction lab experiments carried out up to date. The bibliometric analysis suggests relevant research areas such as geochemistry, thermodynamics, enhanced geothermal systems, carbon dioxide capture, and hydrothermal alteration as the main key research findings. These research areas were identified as the main bibliometric hotspots which have a strong potential to be used for the experimental design of new and improved water–rock interaction studies to address some crucial problems present in the geothermal prospection and exploitation. Among these problems stand out the study of hydrothermal, superhot and enhanced geothermal systems, the chemical fractionation of major and trace elements, the hydrothermal alteration, the calibration of solute and gas geothermometers, the scaling and corrosion problems, the carbon capture and storage, the evaluation of environmental issues, among others. Details of this comprehensive bibliometric analysis, including some statistical and text mining and mapping tools are fully outlined.

Keywords Geothermal energy · Hydrothermal and hot-dry rock systems · Geothermal prospection and exploitation · Text mining · Statistics

Introduction

In the upcoming years, the worldwide energy demand will be increasing due to the population growth, the fossil fuel depletion, and the environmental impacts caused by their use (Soltani et al. 2019). The energy demand and the mitigation of environmental impacts are expected to be solved by using sustainable renewable energy sources (Adekoya et al. 2021). In this context, geothermal energy is a clean and renewable energy source that can be sustainable exploited for electricity generation with base-load specifications, and with levelized generation costs similar to fossil fuel technologies (IRENA, JRC 2021). The current installed capacity of geothermal power and thermal (direct uses) have been estimated to be 15.9 GWh (Huttrer 2020) and 107.7 GWt (Lund and Toth 2021), respectively. According to the International Energy Agency (IEA), the annual electricity generation from geothermal resources for 2050 will be increased up to ~ 1,400 TWh/y, and the thermal energy from direct uses to ~ 1,600 TWh/y, which may come from the exploitation of hydrothermal and enhanced geothermal systems (International Energy Agency 2011; Yusupov and Almaktar 2021).

These promissory energy scenarios will demand the solution of scientific-technological problems, and challenges that must be faced by a geothermal prospection and exploitation with less risks (Soltani et al. 2021). Updated roadmaps for

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✉ E. Santoyo
esg@ier.unam.mx

[1] Posgrado en Ingeniería (Energía), Instituto de Energías Renovables, Universidad Nacional Autónoma de México, Privada Xochicalco S/N Centro, 62580 Temixco, Morelos, México

[2] Instituto de Energías Renovables, Universidad Nacional Autónoma de México, Privada Xochicalco S/N Centro, 62580 Temixco, Morelos, México

geothermal energy projects have been proposed by the IEA (International Energy Agency 2011), and the European Commission (Pinzuti et al. 2019), where the following technological and research priorities have been outlined: (i) the reliable assessment of geothermal resources using geoscientific and geographical information system databases (Zhang et al. 2020b); (ii) the development of integrated conceptual models of both hydrothermal and hot-dry rock (HDR) systems for estimating their heat and power potential with confidence (Aghahosseini and Breyer 2020); (iii) the development of suitable engineering operations for a safety and economical access to deep geothermal resources (e.g., advanced drilling, improved downhole instrumentation, well monitoring, among others; International Energy Agency 2011); (iv) the characterization and solution of technical problems associated with the use and transport of geothermal fluids inside power plant installations (wells, pipes, separators, etc.): (Kioka and Nakagawa 2021); (v) the optimized life cycle assessment, and the proposal of new sustainability indicators and inventories for a better identification and reduction of environmental, economic and social impacts that will affect new geothermal projects (Tomasini-Montenegro et al. 2017; Tian et al. 2020); (vi) the proposal of public policy and regulations for a better deployment of future commercial geothermal projects (Schroeder et al. 2015; Wang et al. 2020); among others.

To face out some of these problems (e.g., i, ii, iv, and v), experimental, field and theoretical studies of water–rock interaction (WRI) processes are considered as a crucial research task for addressing some issues such as: (1) the elucidation of kinetic mechanisms of rock-mineral dissolution and precipitation (e.g., Brantley et al. 2008; Zhang et al. 2015); (2) the fractionation of minerals, and major/trace elements in rocks and fluids (e.g., Perry and Gysi 2020; Santos-Raga et al. 2021); (3) the determination of the effective reactive surface of rock or mineral samples, and the chemical affinity of interacting aqueous solutions (e.g., Schmidt et al. 2017, 2018, 2019; Okamoto et al. 2017); (4) the thermodynamic calibration of geothermometers (solutes, gases, and mineralogical) for a better estimation of deep equilibrium temperatures in geothermal systems (e.g., Pérez-Zárate et al. 2015; Harvey et al. 2017; Stober and Bucher 2021; Stober et al. 2022a); (5) the elucidation of water–rock interaction processes under geothermal field conditions (e.g., Bucher and Stober 2002, 2019; Stober and Bucher 2004; Stober et al. 2016, 2022b); (6) the development of novel extraction technologies for non-toxic critical metals (e.g. lithium and rare-earth elements) from geothermal brines (e.g., Osvald et al. 2019; Warren 2021); (6) the geochemical modelling of the CO_2 capture and storage in geothermal systems (e.g., Galeczka et al. 2014; Marieni et al. 2020); and (7) the search for innovated technical solutions for solving the ancient scaling and corrosion problems (e.g., Bai et al. 2012b; Zhang et al. 2020a).

To address most of these geothermal investigations, it makes so necessary to carry out an updated and comprehensive bibliometric analysis on the historical applications of WRI experiments carried out at lab conditions (from 1963 to 2022). This literature review is required to highlight the main research contributions or Published Articles (PA) reported in the worldwide geothermal literature, as well as to identify early and emerging research topics, major knowledge gaps, research leaderships (authors, networking groups, institutions, and countries), and future research trends and challenges to be achieved for the solution of above described problems. A systematic literature review and bibliometric analysis are gaining popularity among a wide variety of sciences as screening and effective tools for obtaining the current *state-of-art* of any research topic (Carrión-Mero et al. 2020). Bibliometric analyses (BA) are suggested as suitable text mining tools to obtain a better understanding of research patterns and trends, or studies positioned to gain in-depth insight into any research topic (Bezak et al. 2021; Qin et al. 2022). BA is recommended as a first searching approach to summarize and synthesize large volumes of scientific data published in the literature, which is generally carried out using world-leading and competing citation databases (e.g., Web of Science, Scopus, Scholar Google, among others): Donthu et al. 2021; Martín-Martín et al. 2021.

The aim of the present BA work was conducted to identify key research aspects of the geothermal WRI experiments (WRI-E) carried out in lab studies for which the following questions were formulated: (i) What are the main articles published in peer-review journals on the WRI-E subject?; (ii) What is the temporal evolution and the current state of development of the geothermal WRI-E works?; (iii) What are the main worldwide institutions and researchers leaders in conducting geothermal WRI-E?; (iv) What are the main peer-review journals where the WRI experimental works have been published?; (v) What are the most important research areas of the WRI experimental works, and the most cited articles on these WRI experimental applications?; and (vi) What are the main research hotspots towards the conduction of WRI-E for addressing geothermal applications?.

An integrated methodology of BA for mapping the cumulative scientific knowledge on the WRI-E research subject, and its future development has been also proposed for the prospection and exploitation of geothermal resources. Details of this novel methodological and comprehensive BA is fully outlined. To report the present study, the research work was organized in the following sections: (1) A brief introduction of on the research subject: Geothermal WRI-E; (2) A description of an integrated methodology of BA for mapping the cumulative scientific knowledge on the research subject; (3) Results and discussion, where the main findings and research gaps of this study were described; and (4) Conclusions of the BA where the future development of the geothermal WRI-E are reported with emphasis to the geothermal prospection and exploitation applications.

Methodology

A schematic diagram showing the bibliometric analysis methodology (BAM) used in the present investigation is shown in Fig. 1.

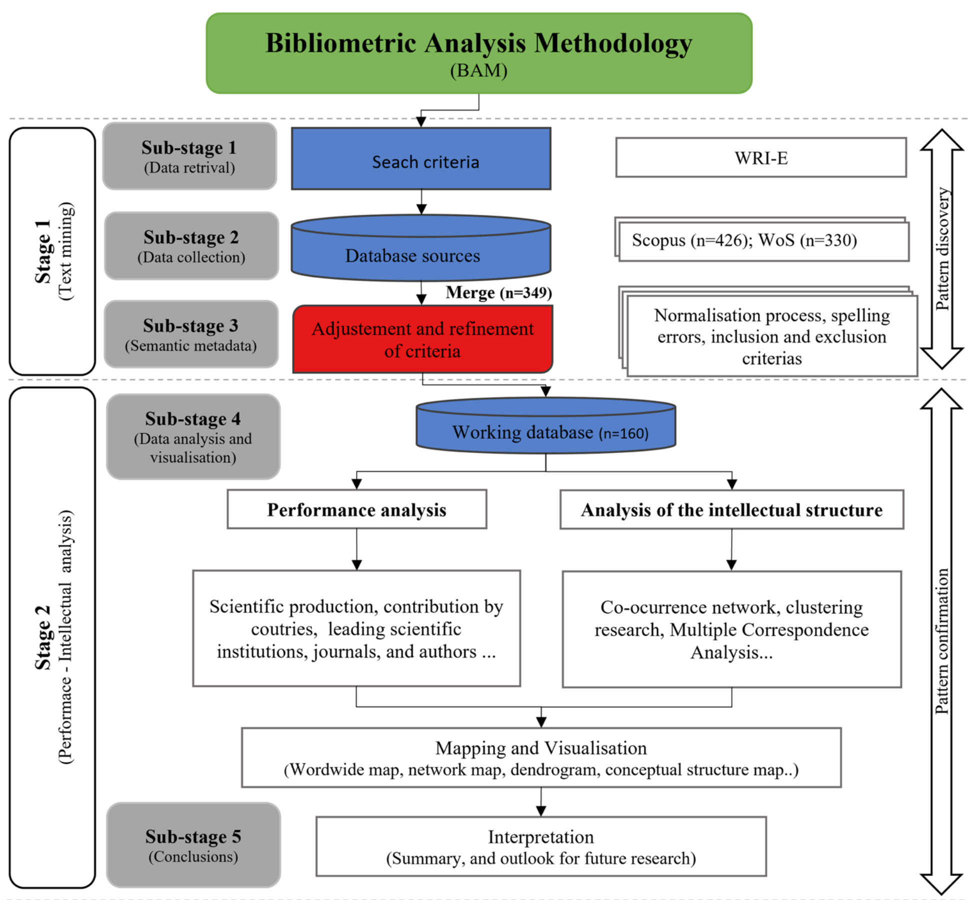
The methodology was based on previous BA studies reported in the literature to minimize bias and errors in the mapping of cumulative scientific studies (e.g., Zupic and Cater 2015; Aria and Cuccurullo 2017; Carrión-Mero et al. 2020; Donthu et al. 2021; Goh and See 2021; Qin et al. 2022). According to these authors, the methodology must be divided into two evaluation stages: Text Mining (TeM) and Performance-Intellectual Analysis (PeIA). The TeM stage is used to find out the most representative patterns of scientific productivity within citation bibliometric (CB) databases (Fig. 1), which typically involves three major sub-stages: (1) the data retrieval through a general searching criterion based on the research subject under evaluation; (2) the bibliometric data collection through a state-of-art compilation from indexed CB databases using suitable keywords and specific time periods; and (3) the semantic metadata process through a fine adjustment and refinement of the searching criteria.

The PeIA stage is used to validate the patterns of scientific productivity within the CB databases by involving the following consecutive sub-stages (Fig. 1): (4) the data analysis and visualization, which includes the performance and intellectual structure analysis of the CB databases for mapping and envisioning the temporal evolution of the articles published on the research subject; and (5) the conclusions and an outlook for future research.

Stage 1: Text Mining

TeM techniques are usually recommended to transform unstructured texts into normalized and structured data for using in BA methodologies. This phase also allows new information sometimes excluded in previous bibliographic databases to be more efficiently collected and accessed (Baraibar-Diez et al. 2020).

Fig. 1 Improved flow diagram showing the methodology developed for the present bibliometric analysis. Modified after: Zupic and Cater (2015); Aria and Cuccurullo (2017); Carrión-Mero et al. (2020); Donthu et al. (2021); Goh and See (2021); and Qin et al. (2022)



Data retrieval (Sub-stage 1)

Before to carry out the BA methodology, a descriptive knowledge on the research subject under evaluation must be defined as a general searching criterion, which will allow representative scientific publications to be identified and compiled.

Bibliometric data collection (Sub-stage 2)

The bibliometric data collection on the research subject must be defined for a given time period, including the selection of the most suitable indexed CB databases, preferentially those that may provide citation records from peer-reviewed journals. Among some available databases, the Web of Science©, Scopus®, and Google Scholar may be used as a powerful text-mining searching tools or engines (Martín-Martín et al. 2018).

A complete subscription to the Web of Science© (WoS) database provides scientific citation records (published in nearly 21,894 peer-review journals and some conference proceedings of recognized prestigious) since 1900 and to date (Vera-Baceta et al. 2019). Scopus® is also an indexed CB database that may be accessed through a subscription fee which offers a shorter period (1966 – to date), but the citation records may be obtained from a larger number of peer review journals (over 25,000), conference proceedings, and books (Martín-Martín et al. 2021).

On the other hand, Google Scholar is an open-source Web search engine that may afford updated scholarly literature (Harzing and Alakangas 2016). Google Scholar searches for citation records a wider variety of academic sources (e.g., peer-reviewed and not-peer review journals, academic books, conference papers, theses, among others). However, some of the publications referred by Google Scholar are not always peer-reviewed materials that may include less rigorous scrutinized publications than those provided by peer-reviewed databases (e.g., WoS and Scopus). Moreover, Google Scholar cannot provide an advanced search that relies on specific keywords or expert metadata, limiting its searching results. After selecting the CB databases, suitable Boolean strings (keywords with syntax variants) must be defined to fulfil the searching processes of scientific publications on the research subject, and to complete the bibliometric data collection process. The CB databases also provide information on the historical evolution of citations recorded by the publications, including some bibliometric indicators such as authors, peer-review journals, networking research groups, universities, countries, publication years, etc.

Semantic metadata (Sub-stage 3)

A semi-automatic adjustment and refinement is required to obtain a normalization of the bibliometric data, a checking for spelling and typographical errors, and the application of inclusion and exclusion criteria. The bibliometric data normalization is required to facilitate the correct allocation of the scientific production reported in the CB databases by including a detailed identification of addresses (e.g., author´s data, journal titles, and standardized affiliation): Morillo et al., 2013. A checking for spelling and typographical errors is also needed to avoid bias problems due to the wrong use of abbreviation standards (e.g., author´s data, journal titles, institutions, or affiliations), differences in USA versus UK language spelling, and transliteration differences (Hood and Wilson 2003). Inclusion and exclusion criteria of selected topics are also required as filtering tasks for refining the bibliometric collection of PA on the research subject, which may be achieved either by applying Boolean string of keywords or by analysis of the article title or abstract (Carrión-Mero et al. 2020). A bibliometric collection of PA is generated by using either an Excel spreadsheet or a computer R-programme, and defined as the final version of the working database.

Stage 2: Performance—Intellectual Analysis

Data analysis and visualization (Sub-stage 4)

If the working database is generated in Excel format as a M.xlsx file, the records obtained from the semantic metadata (sub-stage 2.1.3) are exported into the Bibliometrix package (from R-studio) both for conducting the BA, and to complete the science mapping analysis (Aria and Cuccurullo 2017). A Bibliometrix *R*-package was used for the data construction and exploration using analytical methods for the performance analysis on the research subject. Information on scientific production, prominent authors, preferred peer-review journals, world-wide institutions, most cited articles, and major contributions by country require to be compiled. According to Shafique (2012) and Zupic and Cater (2015), an analysis of the intellectual structure is conducted by using the searching results on the research subject to determine: (i) the scientific knowledge domain; (ii) the major cross-disciplinary research areas; (iii) the dominant research topics; and (iv) the schematic pattern of interrelationships among research topics.

To carry out the examination of the scientific knowledge domain (i), a co-occurrence network or bibliometric map is created by using either KeyWords Plus® or author's keywords. According to the terminology recommended by WoS, KeyWords plus® are defined as words or phrases that commonly appear in the title of the references included in PA, which usually do not appear in the article´s title. Based upon a searching algorithm, the use of KeyWords Plus® enhances the power of the cited references by using a strategic search across different topics that have been cited as references (Garfield 1990). To conduct the cross-disciplinary research areas (ii), a network analysis based on WoS research areas and research specific areas is evaluated by following the methodology suggested by Viebahn (2018), which looks for the identification of interrelation networks (*Fx.y*) among categories (*x*) and research areas (*y*). As this analysis is only based on WoS searching parameters, the PA compiled from the WoS searching process are used to perform the analysis. To perform the analysis of the dominant research topics (iii), a multiple correspondence analysis (MCA) is required. A conceptual structure map is created by using an exploratory factor analysis method among independent bibliometric or categorical variables such as research subject categories, author keywords, keywords Plus, article titles or abstracts (Cobo et al. 2011). To reduce the dimensionality of data in any categorical variable, a complete disjunctive coding of these variables is suggested (Cuccurullo et al. 2016). The MCA is recommended as an exploratory data analysis both to examine the interconnection among a set of categorical variables, and to identify hidden clusters that may provide additional information on the research subject (Blasius and Greenacre 2006; Cuccurullo et al. 2016). To complete the analysis of the intellectual structure (iv), the pattern of interrelationships among research topics is created using hierarchical dendrograms from the MCA clustering results. Hierarchical dendrograms and selected categorical variables are then used to validate the MCA conceptual structure map. In the hierarchical dendrograms, the term-level similarity is determined for revealing a disparity among research topics (Forina et al. 2002).

Conclusion (Sub-stage 5) and future research

After completing the data analysis, a geospatial analysis based on two-dimensional maps, dendrograms, and social networks are carried out. In concordance with Aria and Cuccurullo (2017), the geospatial analysis will be used to address the questions formulated in the introduction section**.**

Results and Discussion

Following the methodology shown in Fig. 1, the presentation of results and discussion have been organized in the following two sections:

Stage 1: TeM

Data retrieval (Sub-stage 1)

To select the most suitable supervised keywords for the present BA, an integrated analysis of a comprehensive search strategy was carried out. With these purposes, a methodology based on the well-known PICO format (Morton et al., 2011), and a coupled text mining procedure were efficiently used (Santoyo-Castelazo et al., 2022). To facilitate the selection of supervised keywords, the following technical evidence questions were formulated on the research subject (geothermal WRI-E):

- What are the fractionation coefficients that exhibit the major and trace elements of fluids to explain their mobility inside the geothermal systems?
- What are the novel technologies used for the extraction of non-toxic critical metals (e.g., lithium and rare-earth elements) from geothermal brines?
- What are the geochemical models used for the development and calibration of new solute, gas and mineralogical geothermometers, and the estimation of deep equilibrium temperatures?
- What are the kinetic mechanisms of rock-mineral dissolution and precipitation processes present in power plant installations (e.g., wells, pipes, separators, etc.) and rock-formations?
- What are the geochemical models used for the CO_2 capture and storage in geothermal systems, and the reduction of environmental, economic, and social impacts for sustainable projects?

These technical questions were used by the PICO format to define the following parameters: (i) Population or problem: WRI-E; (ii) Interventions, causes or factors: scientific-technological geothermal applications; (iii) Comparison and/or study settings: Technical methods for conducting geothermal WRI-E; and (iv) Outcomes: Current state of development for the geothermal WRI-E. The following inclusion/exclusion criteria were also defined: Language: English; Document type: article, reviews, and conference papers; Time period: March 1963 to February 2022; and Specific condition: Geothermal WRI-E carried out in lab reactors (batch or flow-through type). By considering these parameters, the PICO format was structured as a first part of the search strategy (Table 1).

On the other hand, the text mining procedure was used both to identify the most relevant articles' keywords and to address the historical literature advances on the geothermal WRI-E subject. The aim of this text mining was used to extract unstructured information and text data collection by analyzing the full text of the most representative articles published on the research subject. These articles were selected by using the following criteria:

1. Earlier reviews published on the research subject. Because these reviews have been scarcely reported in the literature, three short reviews were used as repre-

sentative sources (i.e., Arnórsson and Stefansson, 1999; Ngothai et al., 2011; Wu and Li, 2020); and

2. The top five articles published in the literature for the period 1963–2022, which have the highest number of citing records (i.e., Mottl and Holland, 1978; Gislason and Oelkers 2003; Seyfried and Mottl, 1982; Ellis and Mahon 1964; and Ellis and Mahon 1967).

To perform the text mining, a Python script was programmed for counting the frequency of words (or keywords) related to the research subject, which was used through the following steps: (1) To export the articles from a PDF to a text format; (2) To perform a clean analysis of the text body in each article by using the article title, abstract, author keywords, introduction, methodology, results, and conclusions; and (3) To analyze the most relevant articles' keywords identified from the counting of the word frequency by a participatory analysis of two technical searchers and a senior researcher with a high experience on geochemistry of geothermal systems. This type of text body extraction was recommended by Morton et al. (2011), Saha et al. (2016), and Zhu and Cole (2022). By integrating the PICO format and the text mining, the following eighteen supervised keywords were selected:

P: Water/rock interaction experiments;
I: Hydrothermal fluids; Geothermal; Active Hydrothermal Systems; Enhanced Geothermal Systems; Hot Dry Rock; Hot springs;
C: Batch reactor; Flow through reactor; and
O: Mineral; Solubility (Dissolution); Temperature; Thermodynamic; Kinetics; Chemical Fractionation; Mineral equilibria; Pressure; and Precipitation.

Bibliometric data collection (Sub-stage 2)

Considering the advantages afforded by the available CB databases, the WoS and Scopus were selected as searching tools. Suitable Boolean strings (keywords and syntax variants) were defined for searching articles according to the nomenclature of these databases, and used both to find out citation records on the WRI-E subject, and to minimize duplicated records. This process was conducted on 6th of February 2022 by two technical searchers to avoid bias based on the following constraint Boolean strings: *{TITLE-ABS-KEY (water AND rock interaction AND experiments) AND TITLE-ABS-KEY (geothermal) OR TITLE-ABS-KEY (mineral AND mineral equilibrium AND kinetics AND hydrothermal systems active AND enhanced geothermal systems AND hot dry systems AND hydrothermal activity AND chemical fractionation AND hot-springs AND temperatures AND solubility AND precipitation AND thermodynamic AND pressures AND hydrothermal fluids AND batch reactor AND flow-through reactor AND flux reactor)}*.

As WoS and Scopus use different syntaxes to carry out the search of keywords, the following searching strings were separately applied:

Table 1 Summarized results obtained from the integrated analysis of the search strategy and selection of supervised keywords by applying the PICO format methodology and the text mining

Selected Supervised Keywords				Literature sources used in the text mining (NCR)
P (WFC)	I (WFC)	C (WFC)	O (WFC)	
Water/rock interaction experiments (439)	Hydrothermal fluids (242)	Batch reactor (60)	Mineral (1,341)	R1 Arnórsson and Stefánsson 1999 (71)
	Geothermal (212)	Flow through reactor (49)	Solubility (Dissolution) (900)	R2 Ngothai et al., 2011 (10)
	Active Hydrothermal Systems (212)		Temperature (761)	R3 Wu and Li, 2020 (29)
	Enhanced Geothermal Systems (144)		Thermodynamic (350)	A1 Mottl and Holland, 1978 (543)
	Hot Dry Rock (122)		Kinetics (295)	A2 Ellis and Mahon 1964 (443)
	Hot springs (100)		Chemical Fractionation (256)	A3 Seyfried and Mottl, 1982 (437)
			Mineral equilibria (199)	A4 Gislason and Oelkers 2003 (436)
			Pressure (145)	A5 Ellis and Mahon 1967 (366)
			Precipitation (64)	

WFC: Word Frequency Count (Text Mining Indicator); NCR: Number of Citing Records; Type of Documents: R – Reviews; A – Articles (top five articles published on the research subject with the highest number of citing records)

1) *WoS: TS = (water rock interaction geothermal experiments) OR TS = (water/rock interaction geothermal experiment) OR TS = (water rock interaction geothermal experiments mineral equilibrium) OR TS = (water rock interaction geothermal experiments mineral) OR TS = (water rock interaction geothermal experiment kinetics) OR TS = (water rock interaction experiment hydrothermal systems) OR TS = (water rock interaction experiments hydrothermal system active) OR TS = (water rock interaction experiments enhanced geothermal system) OR TS = (water rock interaction experiments hot dry system) OR TS = (water rock interaction experiments fractionation) OR TS = (water rock interaction experiments hot-springs) OR TS = (water rock interaction experiments geothermal temperatures) OR TS = (water rock interaction geothermal experiments solubility) OR TS = (water rock interaction geothermal experiments thermodynamic) OR TS = (water rock interaction geothermal experiments pressures) OR TS = (water rock interaction geothermal experiments hydrothermal fluids) OR TS = (water rock interaction geothermal experiments kinetics) OR TS = (water rock interaction geothermal experiments batch) OR TS = (water rock interaction geothermal flow through reactor); and*
2) *Scopus: (TITLE-ABS-KEY (water AND rock AND interaction AND experiments) AND TITLE-ABS-KEY (geothermal) OR TITLE-ABS-KEY (enhanced AND geothermal AND systems) OR TITLE-ABS-KEY (mineral AND equilibrium) OR TITLE-ABS-KEY (mineral) OR TITLE-ABS-KEY (mineral AND solubility) OR TITLE-ABS-KEY (pressures) OR TITLE-ABS-KEY (hydrothermal AND systems) OR TITLE-ABS-KEY (active AND hydrothermal and systems) OR TITLE-ABS-KEY (hot AND dry AND rock) OR TITLE-ABS-KEY (chemical AND fractionation) OR TITLE-ABS-KEY (hot-springs) OR TITLE-ABS-KEY (thermodynamic) OR TITLE-ABS-KEY (batch AND reactor) OR TITLE-ABS-KEY (flow-through AND reactor) OR TITLE-ABS-KEY (mineral AND equilibria) OR TITLE-ABS-KEY (flux AND reactor) AND TITLE-ABS-KEY (temperatures)).*

These syntaxes were described to provide to the journal readers the criteria used to reproduce the WoS and Scopus searching results. These instructions allowed the scope of the research subject to be concentrated on a primary statistical sample of 756 PA, from which Scopus and WoS reported 426 and 330 PA, respectively. To avoid the use of duplicated publications obtained from the WoS and Scopus, the primary bibliographic sample was filtered to obtain a current status of the geothermal WRI-E research subject by including historical and future tendencies of publications on these investigations.

With these purposes, the present BA considered a merged searching process among the results provided by the WoS and Scopus databases using an efficient method suggested by Echchakoui (2020). The merging process was carried out using a R computer code, which was developed by Echchakoui (2020). The merging process involved the following algorithmic steps: (i) the conversion of the citation records obtained from WoS and Scopus to Endnote® bibliography files (*.bib); (ii) the conversion of both bibliography files (Scopus.bib and WoS.bib) to "bibtex" files using Rstudio (or R), and the bibliometrix package; (iii) the formatting of the WoS and Scopus bibtex files to have the same tag fields, which was performed through a Word VBA macro; and (iv) the merging of the two databases for removing duplicates, which was carried out after converting the WoS and Scopus bib files to Excel files (WOS.xlsx and Scopus.xlsx) in Rstudio. The removal of duplicated references between Scopus and WoS was finally achieved using a VBA Excel code, which was also reported by the author. After applying this merging procedure, a secondary statistical sample of 349 PA was obtained.

Semantic metadata (Sub-stage 3)

As the merging database of 349 PA was created by using the eighteen supervised keywords, a final manual refinement was used to obtain exclusively the state-of-the-art of the experimental works of WRI carried out at laboratory level for studying the geothermal systems (i.e., field and theoretical works on WRI processes conducted for other geothermal applications were excluded). This specific task was conducted by an expert on geochemistry of geothermal systems to fulfil the strict condition. The final refinement was also carried out for data normalization and spelling errors. To satisfy the strict condition of geothermal WRI-E works, the following searching criteria was successfully applied to the merging database (or secondary statistical sample) using an Excel spreadsheet: {include (keyword, "batch", "flow-through", "reactor", "experiments") AND limit-to (doctype: "article", "reviews", "conference proceedings") AND limit-to ("geothermal")}. As a result of this refinement, a tertiary statistical sample of 160 PA was obtained from which 143 articles were published in peer-review journals (including the three reviews), and only 17 full text articles were reported in some conference proceedings. This tertiary statistical sample was defined as the final working database for carrying out this BA study (M.bib or M.xlsx files).

To complete the scope of the present BA, all these PA have been listed in the Table 1S of the supplementary material, which may be used as a fundamental literature for addressing past and latest studies on the geothermal WRI-E research subject. The supplementary Table 1S has been saved in a R program format for validating or updating the BA processing.

Stage 2: PeIA

As a part of the PeIA, the results of the sub-stage 4 (data analysis and visualization) are briefly discussed in this section (see Fig. 1). This sub-stage included the following analyses: (3.2.1) A performance analysis through the BA on the geothermal WRI-E subject; and (3.2.2) An analysis of the intellectual structure using a clustering and multicriteria analysis based on the main bibliometric indicators of the research subject (Table 2).

Performance analysis (Sub-stage 4: Data analysis and visualization)

Bibliometric analysis to evaluate the global scientific production The performance analysis was performed based on the scientific production generated on the geothermal WRI-E subject using the 160 PA reported between 1963 and 2022 (Figs. 2A-B).

A statistical cumulative frequency plot of these PA is shown in Fig. 2A, where the intersection red dashed line represents the most significant inflection point of the exponential curve (Sinclair 1974; Andreo-Martínez et al. 2020; Carrión-Mero et al. 2020). The exponential curve shown in Fig. 2A describes the growth in the study of the WRI-E subject with time, which mathematically may be expressed through the following exponential function (Price 1963):

$$F(t) = ae^{bt} \quad (1)$$

where *F(t)* represents the sample size at a given time *t*; *a* is the initial sample size; and *b* is the continuous growth rate, which is related to the percentage by which the sample size increases per year. This percentage was calculated by using the Eq. (2):

$$R = 100\left(e^{b} - 1\right) \quad (2)$$

where the variable *R* represents the annual growth rate for any science field compared with the earlier year. Considering the Eqs. (1) and (2), the annual growth rate of scientific production for the geothermal WRI-E subject was calculated as ~ 8.3% (1963–2022), which is equivalent to an average publication of ~ 2.7 articles per year. Another useful bibliometric indicator related to this exponential growth is given by the doubling time (i.e., the fixed period in which the sample size of the scientific literature publications has been duplicated), which was determined as ~ 8.7 years by using the Eq. (3) recommended by Tague et al. (1981):

$$D = \frac{ln2}{b} \quad (3)$$

The variability of the number of PA with time is represented in Fig. 2B using the well-known Price's law phases (Price 1963). The Price´s phase 1 is defined as the "forerunners" zone, whereas phase 2 is commonly referred as the "growth" zone. The red dashed line in Fig. 2B represents the time boundary between these two phases, which was estimated from the inflection point of the cumulative frequency plot (Fig. 2A). The Price´s phase 1 was described for the time period boundary between 1963 and 2007, where 48 articles were published. These PA represent a 30% with respect to the total number of articles (n = 160) which were published for the entire time period (1963 to 2022). The citation records (or scientific impact) found for these 48 PA were ~ 2,864, which represent about 61% of the total number of citation records reached by the 160 articles (4,704). The papers published by Mottl and Holland (1978) and Gislason and Oelkers (2003) are the most cited articles reported for the time period of the "forerunners" zone (1963 – 2007) with 383 and 312 citations, respectively. The first article was published with the title "Chemical exchange during hydrothermal alteration of basalt by seawater 1 experimental results for major and minor components of seawater", which shows an impact factor of ~ 8.7 citations per year. The second article entitled "Mechanism rates and consequences of basaltic glass dissolution an experimental study of the dissolution rates of basaltic glass as a function of pH and temperature", reached a higher impact factor of ~ 16.4 citations per year. A listing of the PA of the Price´s phase 1 are included in Table 2S of the supplementary material, including the main author's keywords and the total number of citations.

On the other hand, the Price´s phase 2 was identified for a time period between 2008 and 2022, where the scientific production exhibits a higher exponential increase of 112

Table 2 Summary of bibliometric indicators found in Scopus and Web of Science databases on the research subject of WRI-E and geothermal applications (Time period 1963 – 2022)

Main information about data	
Time period	1963—2022
Journals	63
Articles	160
Average citations per articles	29.4
Articles contents	
Author's Keywords	446
Keywords Plus	1022
Authors	
Authors	517
Authors of single-authored articles	5
Authors of multi-authored articles	512
Articles per year	2.67
Authors collaborations	
Articles per Author	0.31
Authors per Article	3.23
Co-Authors per Article	4.08
Collaboration Index	3.3

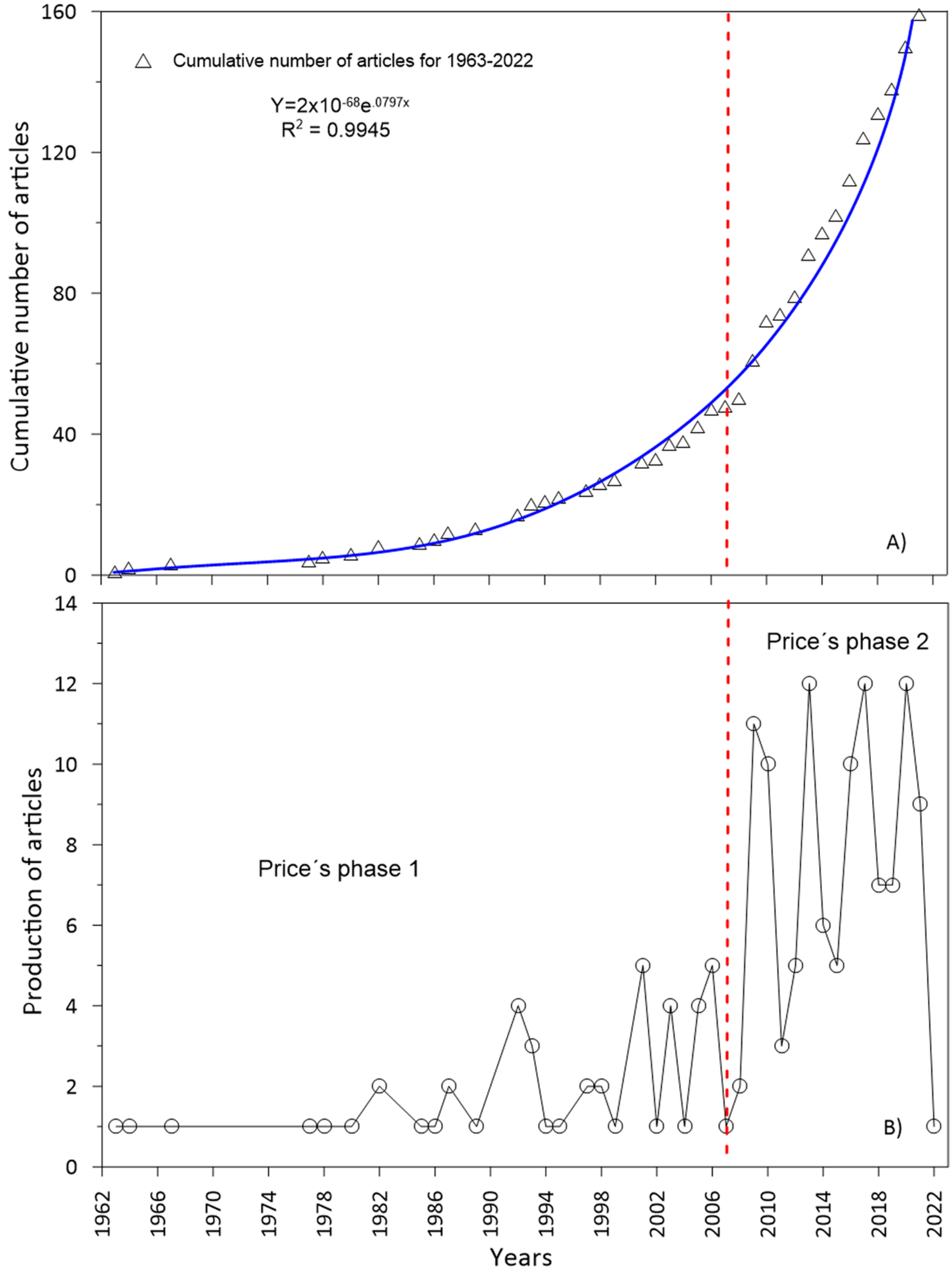


Fig. 2 Plots of the scientific production reported on WRI-E articles: [A] Exponential growth behavior describing the correlation among the number of articles per year; [b] Scientific productivity of WRI-E articles associated with geothermal applications, where the Price´s phase 1 is defined as "forerunners zone" on the research and Price´s phase 2 is defined as "growth zone" started substantially in 2007

PA representing 70% with respect to the total number of publications (n = 160). The citation records found for these articles were ~ 1,840, which nearly represent a 39% of the total number of citation records. The papers published by Daval et al. (2009) and Gudbrandsson et al. (2011) are the most cited articles reported for the period 2008 – 2022 with 158 and 102 citations, respectively. The first article was published on the "Carbonation of Ca-bearing silicates the case of wollastonite experimental investigations and kinetic modelling", which has reached an impact factor of ~ 12.1 citations per year, whereas the second paper published on "An experimental study of crystalline basalt dissolution from $2 \leq pH \leq 11$ and temperatures from 5 to 75 °C", which exhibits a lower impact factor of ~ 9.3 citations per year. A listing of the PA of the Price´s phase 2 are included in Table 3S of the supplementary material, including the main author's keywords and the total number of citations.

Bibliometric analysis to evaluate the productivity of articles per country A worldwide distribution of articles published in peer-review journals and conference proceedings is shown in Fig. 3. After revising the information of author affiliations and origin countries, the contribution of PA per country was quantified for the global time period (1963

– 2022), which is also shown in Fig. 3. The percentage of collaboration among researchers and institutions from different countries was also inferred, where the stronger links of collaboration were achieved for the pairs USA – China (9%) and Iceland – France (15%). A lower collaboration links were observed for other country pairs (3%). It was also found that the research subject under evaluation has been studied in only 26 countries (Fig. 3). The top ten countries leading the publication of articles and their citation records are attributed to: (i) USA, ranked with a total publication of 32 articles out of 160 PA, which roughly represents a contribution of 20% and 1,282 citations; (ii) France with 27 PA (~17%) and 768 citations; (iii) Japan with 23 PA (~14%) and 386 citations; (iv and v) China and Germany by 15 PA (~9%) with 98 and 158 citations respectively; (vi) Iceland with 7 PA (~4%) and 452 citations; (vii and viii) Australia and Italy by 5 PA (~3%) with 128 and 59 citations respectively; and (ix and x) Canada and UK by 4 PA (~2.5%) with 112 and 93 citations respectively. Other countries such as Korea, Mexico, Netherlands, New Zealand, Belgium, Estonia, Hungary, Israel, Norway and Panama have a lower productivity with an integrated contribution of nearly ~9%. Among these countries, Korea and The Netherlands stand out by the publication of only one article but with a high research impact given by the number of citations achieved of 94 and 76, respectively.

Bibliometric analysis to evaluate the productivity of articles per institution A total number of 232 institutions were identified as the representative sample, from which ~40% showed crossed collaborations among these institutions. A summary of the top ten institutions leading the productivity of PA on the geothermal WRI-E subject is presented in Table 3. Tohoku University (Japan) and the University of Iceland (Iceland) are leading the publication of 17 articles (each one) with a contribution of ~11% (17/160), followed by China University of Petroleum (China) with 6.5% (10/160), the University Toulouse (France) with ~5% (8/160), among other six institutions.

A schematic network diagram showing the most productive collaboration clusters among research institutions is shown in Fig. 4. Six clusters of collaboration were identified, where Iceland, Toulouse (France), and McGill universities were recognized as the most relevant clusters. The other five clusters were found for the following alliances: (i) China University of Petroleum (China) and the

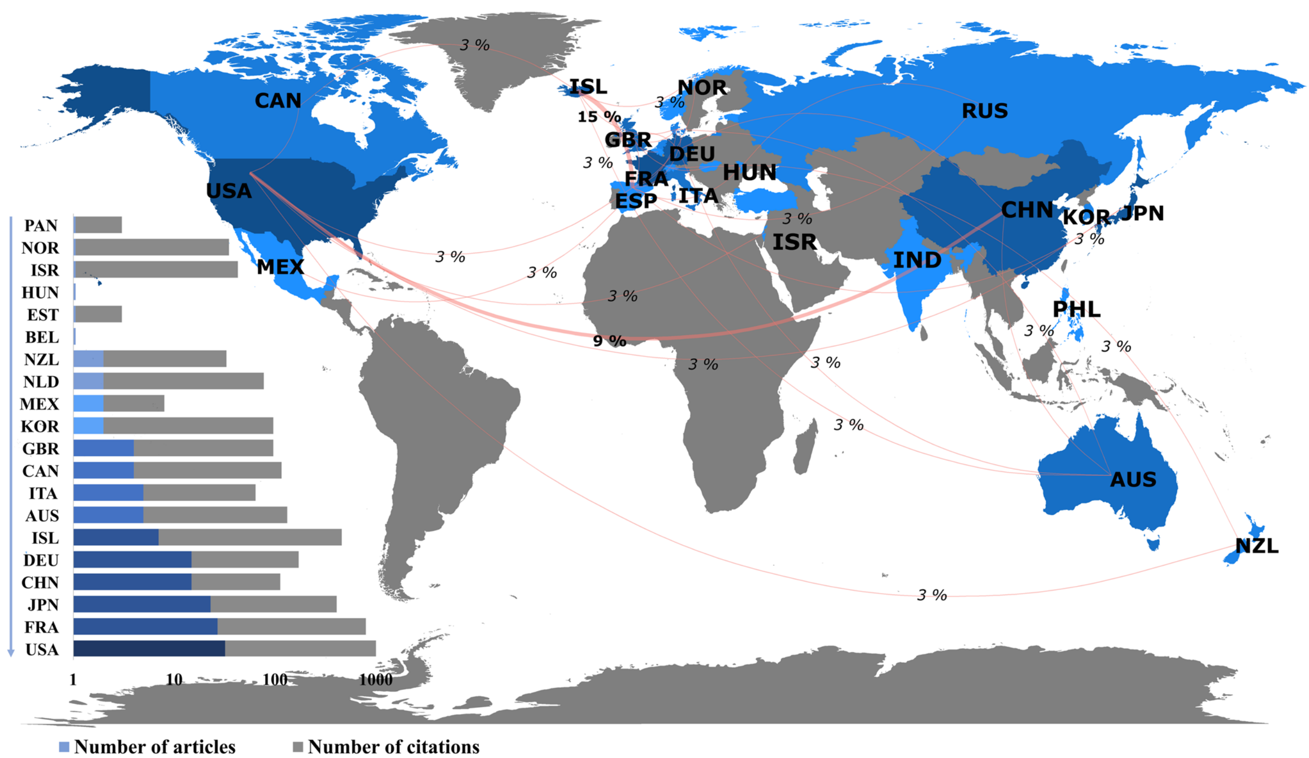


Fig. 3 Worldwide distribution of articles reported in peer-review journals, reviews, and conference proceedings on WRI-E focussed on geothermal applications (1963–2021). The thickness of the red line indicates the high percentage of collaboration. The name of the countries is abbreviated using the international convention suggested by ISO-3166 international standard. The logarithmic scale of the number of citations ranges from 1 to 1000, and it is overlapped with the number of published articles

University of Minnesota (USA); (ii) Kyoto University and Mitsubishi Materials Techno Corporation, as an excellent example of Japanese collaboration between academia and industry (Japan); (iii) Hiroshima University and Tohoku University (Japan); (iv) Stanford University and University of California, Berkeley in USA; and (v) the Bureau de Recherches Géologiques et Minieres and the University of Lorraine in France. The strength of the collaboration clusters depended on factors such as the geographical distance, language of the authors, the sharing or access to experimental infrastructures, among others (Melin and Persson 1996).

Bibliometric analysis to evaluate the productivity of PA in peer-review journals After revising the 160 PA, it was found that 63 peer-review journals were used as main publication sites. These PA received ~ 4,704 citations from 1963 to 2022. Table 4 shows the top-ten peer-review journals preferred by the authors to publish articles on the research subject. These journals covered about ~ 57% of the total number of publications in the last 59 years. The most cited articles per journal are listed in Table 4. From the scientific impact point of view, 911 citations were reached by ten articles (10/160), which roughly represents a ~ 19% of the total number of ~ 4,704 citations. Four of these highly cited articles were published in the forerunners zone of the Price´s phase 1, whereas the six remaining articles were published in the Price´s phase 2: Fig. 2B.

Based on Bradford´s law (suggested as an evaluation metric of the journal productivity), Geochimica et Cosmochimica Acta (29), Chemical Geology (18), and Applied Geochemistry (11) fulfilled the productivity condition of ≥ 11 PA, which enabled these journals to be grouped in

Table 3 Leading global institutions by productivity of articles published on the research subject of WRI-E on geothermal applications (Time period 1963 – 2022)

Institutions	Countries	Articles	AT W (%)
Tohoku University	Japan	17	4.01
University of Iceland	Iceland	15	3.54
China University of Petroleum	China	10	2.36
University Toulouse	France	8	1.89
Institute Mineral Resources	United States	6	1.42
Institute of Geosciences and Resources	Italy	6	1.42
University California Berkeley	United States	6	1.42
University of Lorraine	France	5	1.18
Jilin University	China	4	0.94
Kyoto University	Japan	4	0.94

AT W (%) Articles weighted with respect the total number of publications by institutions

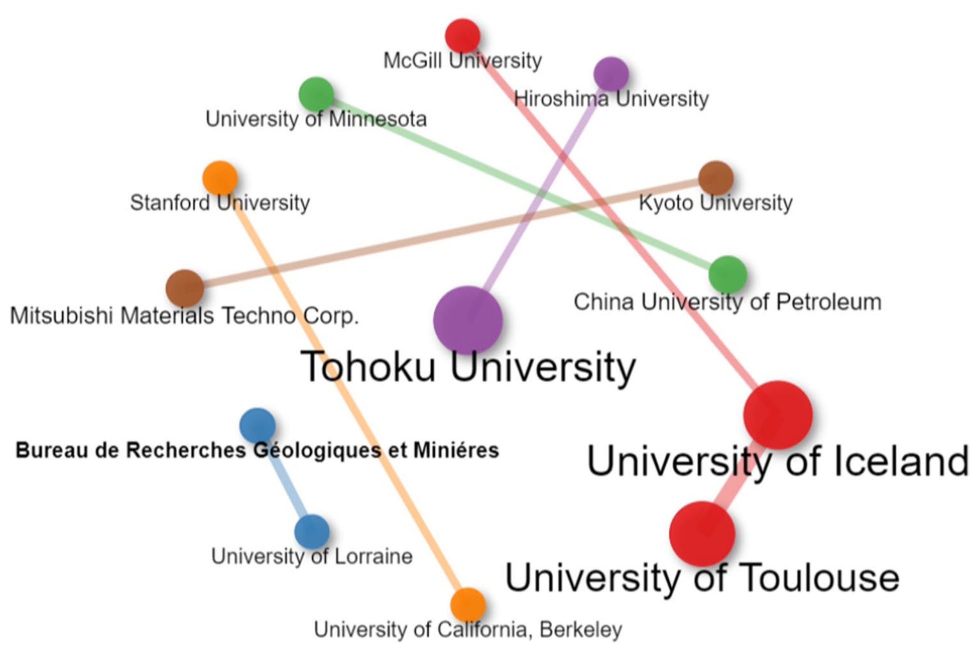


Fig. 4 In the schematic network diagram showing six main cluster of the most productive collaboration between institutions identified from this bibliometric analysis

Table 4 List of the top ten peer-review journals used for the publication of articles on the WRI-E for geothermal applications (Time period 1963–2022)

ID	Peer-review Journals (ISSN; JIF, JIF-Quartile)	Articles (#)	*h*-index	Total citations	TC (%)	The most cited article of the journal	TC	TC (%)	Authors
1	Geochimica et Cosmochimica Acta (ISSN: 0016–7037; JIF: 5.010; JIF-Q1)	29	19	2,371	50.4	Chemical exchange during hydrothermal alteration of basalt by seawater -I. Experimental results for major and minor components of seawater	383	8.1	Mottl and Holland 1978
2	Chemical Geology (ISSN: 0009–2541; JIF: 4.015; JIF-Q1)	18	13	784	16.7	Carbonation of Ca-bearing silicates the case of wollastonite experimental investigations and kinetic modelling	158	3.4	Daval et al. 2009
3	Applied Geochemistry (ISSN: 0883–2927; JIF: 3.207; JIF-Q2)	11	8	225	4.8	Dissolution of Columbia River basalt under mildly acidic conditions as a function of temperature experimental results relevant to the geological sequestration of carbon dioxide	54	1.1	Schaef and Mcgrail 2009
4	Geothermics (ISSN:0375–6505; JIF: 3.806; Q2)	10	6	13	0.3	Geochemical interpretation of long-term variations in rare earth element concentrations in acidic hot spring waters from the Tamagawa geothermal area Japan	45	1.0	Sanada et al. 2006
5	Geothermal Resources Council -Transactions (ISSN: 102,935,933; SJR: 024)	6	3	150	3.2	Laboratory scale study of fluid-rock interaction in the EGS in cooper Basin South Australia	5	0.1	Kuncoro et al. 2010
6	Geofluids (ISSN: 1468–8115; JIF: 2.176; JIF-Q3)	5	4	42	0.9	On modelling of chemical stimulation of an enhanced geothermal system using a high pH solution with chelating agent	23	0.5	Xu et al. 2009
7	Contributions To Mineralogy and Petrology (ISSN: 0010–7999; JIF: 4.076; JIF-Q1)	3	3	133	2.8	An experimental investigation of high temperature interactions between seawater and rhyolite andesite basalt and peridotite	82	1.7	Hajash and Chandler 1982
8	Environmental Earth Sciences (ISSN: 1866–6280; JIF: 2.784; JIF-Q3)	3	2	67	1.4	Geomechanical and geochemical effects on sandstones caused by the reaction with supercritical CO2 an experimental approach to in situ conditions in deep geological reservoirs	62	1.3	Marbler et al. 2013
9	Geochemical Journal (ISSN: 0016–7002; JIF: 1.561; JIF-Q3)	3	2	148	3.1	Batch dissolution of granite and biotite in water implication for fluorine geochemistry in groundwater	94	2.0	Chae et al. 2006
10	Geothermal Energy (ISSN: 2195–9706; JIF: 2.800; JIF-Q3)	3	3	13	0.3	The potential of coupled carbon storage and geothermal extraction in a CO2 enhanced geothermal system a review	5	0.1	Wu and Li 2020

TC = Total citations; ISSN = International Standard Serial Number; JIF = Journal Impact Factor; SJR* = SCImago Journal Rank the "core" zone of the Bradford diagram with a contribution of 36% from the total number of PA (Fig. 5). Other 14 journals (with a contribution of 34.4%) were grouped in the intermediate zone of Bradford's law (i.e., satisfying the productivity condition: $2 \leq PA \leq 10$). The remaining 46 journals (which were used for the publication of 52 articles) were grouped in the outlying zone (Fig. 5).

Bibliometric analysis to evaluate the productivity of PA per authors After analyzing the 160 PA, it was found that most of these articles were mostly published by collaboration groups ranging from 2 to 16 co-authors per article, among which a total number of 517 authors were counted. Table 5 summarizes the top ten collaboration groups of authors leading a total number of 56 PA on the geothermal WRI-E research subject during the last 59 years (1963 – 2022). The collaboration group of "Gislason et al." (from the University of Iceland, Iceland) and "Ueda et al." (from the University of Toyama, Japan) led with 8 PA per group for a time period of 32 and 14 years, respectively. Up to February 2022, these PA received a total number of 810 citation records from which 723 correspond to the articles published by Gislason's group, and 87 to the Ueda's group. Among the most cited articles published by these groups stand out the papers entitled "Basaltic glass dissolution rates as a function of aqueous aluminum, silica, and oxalic acid" and "Experimental studies of CO_2-rock interaction at elevated temperatures under hydrothermal conditions", which were published by Gislason and Oelkers (2003) and Ueda et al. (2005), respectively. The first article has reached 312 citation records, whereas the second one has accumulated 52 citations. Other collaboration groups of authors with some bibliometric indicators are also listed in Table 5. The well-known *h*-index (referred to the PA on the geothermal WRI-E subject) is also reported in the same Table 5.

A schematic Sankey diagram showing the journal preferences used by these top ten groups of authors is shown in Fig. 6. From the scientific impact point of view, the author groups "Gislason et al." and "Oelkers et al." (with an *h*-index of 7 and 6, respectively) preferred to publish in journals of high impact factor such as Geochemical et Cosmochimica Acta, Applied Geochemistry and Chemical Geology, which according to Bradford´s law are placed in the core zone. The group of authors led by "Ueda et al." generally chosen journals of lower impact factor (*h*-index of 4). Other authors have selected journals located in the intermediate zone of the Bradford´s law, for which the *h*-index ranged from 3 to 4. In the same figure, it is also observed the author collaboration among countries, where the articles published by "Gislason et al." were written by co-authors from Iceland, France and USA, whereas the papers reported by "Oelkers et al." and "Ueda et al." were written by co-authors from France, Iceland, Germany, and UK, and from Japan and China, respectively.

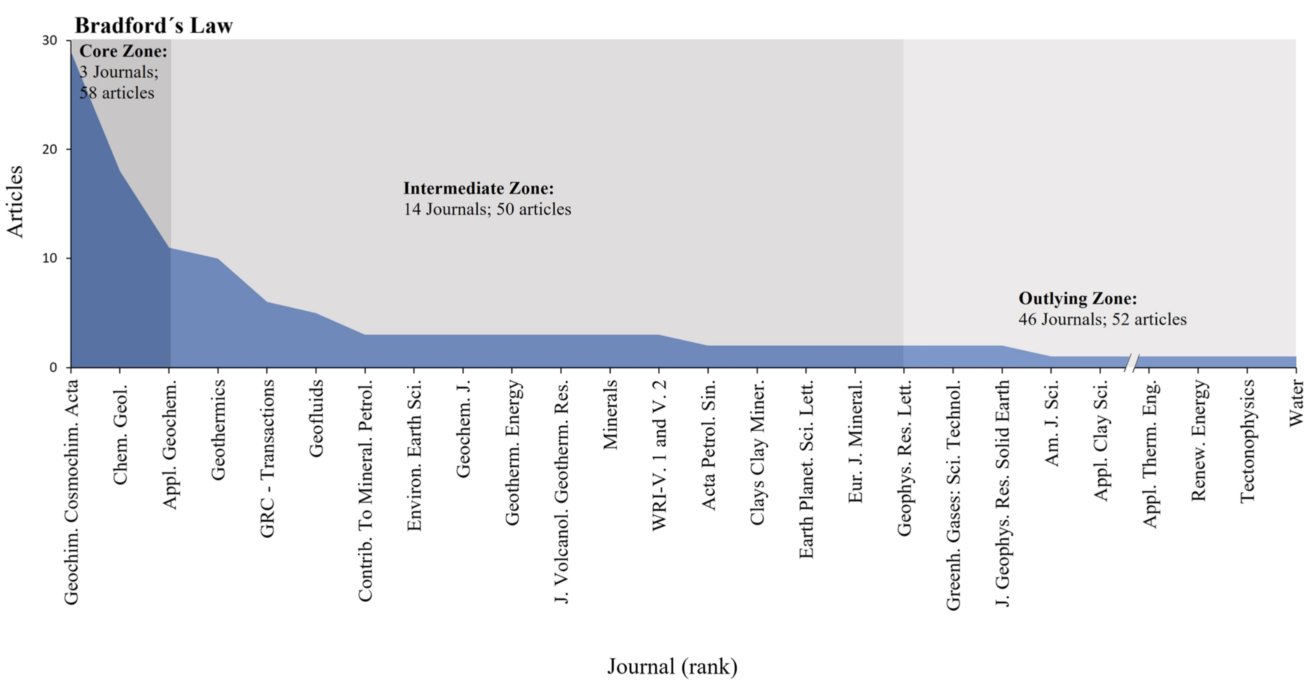
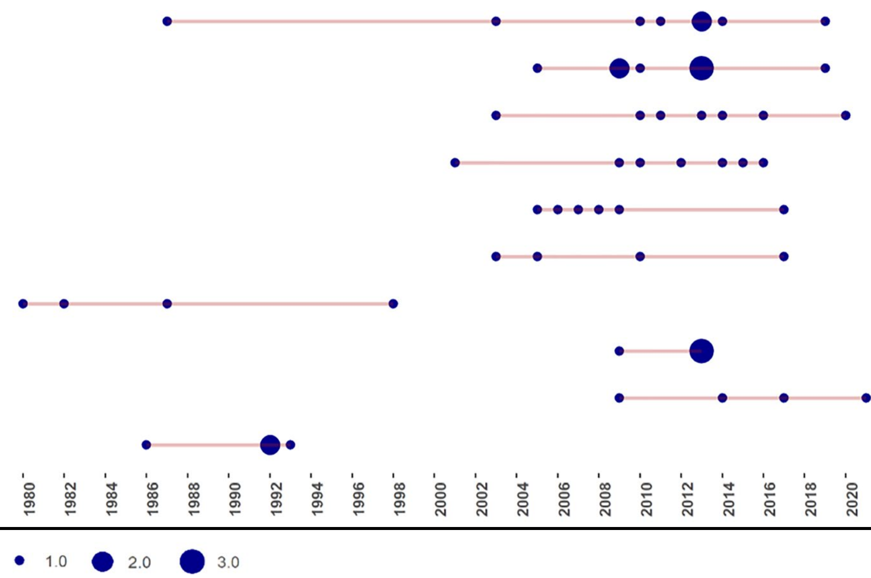


Fig. 5 Zones for journals covering the topic of WRI-E focussed on geothermal applications (1963–2021) by Branford's law. Showing the core, intermediate, and outlying zones

Table 5 Leading global researchers' groups by number of scientific journals published on the research subject of WRI-E on geothermal applications

Top ten collaboration groups by leader authors

Outstanding Author	Productivity over time of WRI-E	Affiliations
S. Gislason		University of Iceland
A. Ueda		University of Toyama
E. Oelkers		Université de Toulouse
T. Xu		Jilin University
N. Tsuchiya		Tohoku University
B. Fritz		Université de Strasbourg
A. Hajash		Texas A&M University
T. Matsuoka		Kyoto University
H. Milsch		GeoForschungsZentrum
D. Savage		British Geological Survey



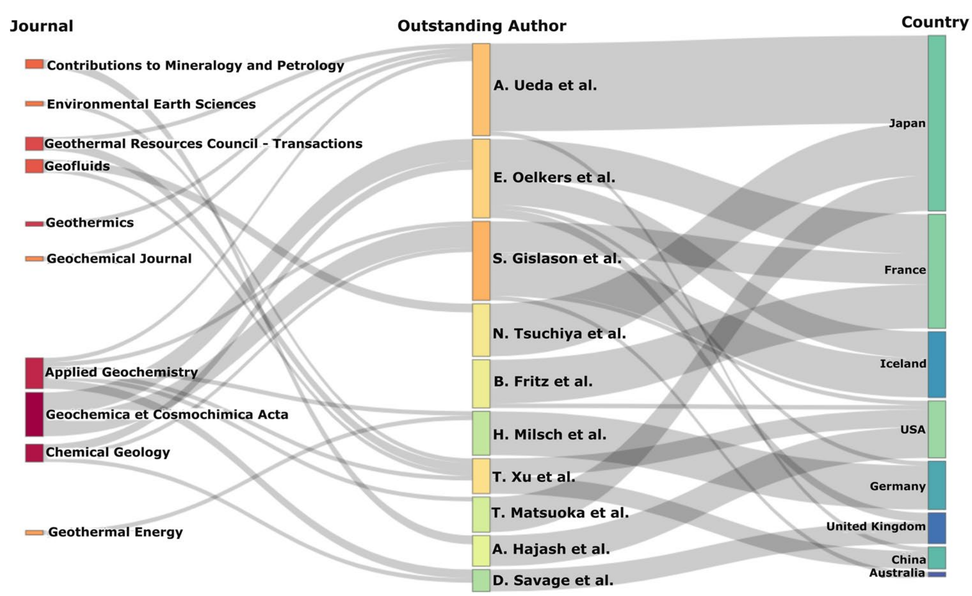


Fig. 6 Sankey diagram showing the peer-review journal preferences used by the top ten authors to publish their articles on the WRI-E research subject (geothermal applications)

Analysis of the intellectual structure (sub-stage 4: Data analysis and visualization)

To analyze the scientific knowledge domain, a co-occurrence network or bibliometric map was created by using KeyWords Plus® (Fig. 7). To analyze the working database, 1,022 KeyWords Plus® were used. A network covering twenty-three interconnected KeyWords Plus® was generated. Three major clusters of KeyWords Plus® (Dissolution, Geothermal Fields and High Temperature) were identified as a first search approach of the intellectual structure analysis. The size of these clusters (nodes and connections represented by colors in Fig. 7) enabled the identification of the main KeyWords Plus® nodes that centralized connections among other related KeyWords Plus®. In the co-occurrence map, the nodes represent the KeyWords Plus®, whereas the circle sizes, the number of times that appear in the 160 PA. The link connection shows the KeyWords Plus® relationships among nodes, whereas the thickness of these connections represents the strength of these relationships (Van Eck and Waltman 2014). The biggest cluster identified was < Dissolution >, mostly represented by rock or mineral dissolution studies, which were strongly interconnected and referenced with KeyWords Plus® related to experimental works, water–rock interaction, geochemistry, carbon dioxide, carbon sequestration, calcite, temperature, and hydrothermal alteration.

The second-size cluster was < Geothermal Fields > which exhibits a less degree of interconnection with KeyWords Plus® related to granite, silica, geothermal systems, geothermal energy, EGS, and permeability, and a less size of reference among the 160 PA. The third smaller cluster recognized was < High Temperature > which shows a lesser degree of interconnection with KeyWords Plus® related to minerals, kinetics, reaction kinetics, pH, and dissolution kinetics, and a lesser size of reference (and schematically represented by the smaller size of the circles). According to these bibliometric indicators, the future research on geothermal WRI-E studies is well founded on an integrated framework given by the clusters and keywords most frequently used in the publications, which are proposed to address some scientific and technical issues of the worldwide geothermal community. After a comprehensive analysis of the co-occurrence network (Fig. 7), together with a deep geothermal expertise analysis of the most relevant clusters and nodes, some important gaps and findings may be identified, which are summarized in the Table 6:

Network analysis per WoS categories and research areas To conduct the cross-disciplinary research areas, a network scheme based on WoS research areas was created by using only 111 PA out of 160 compiled in the working database. These 111 PA were grouped based on the identification of interrelation networks (*Fx.y*) and connections between categories (*x*) and research areas (*y*) using an open-source software (Gephi): Bastian et al. 2009. Seven central clusters (CC) of categories and research areas were identified and represented as continuous lines in Fig. 8. These CC were characterized by 111 nodes and 1,884 link connections (Fig. 8), which were grouped by ranking from the larger to the smaller number of PA, and according to the WoS categories classified as: CC1: Geochemistry & Geophysics; CC2: Geology; and CC3: Energy & Fuels; CC4: Geothermal energy; CC5: Geochemistry; CC6: Mineralogy; CC7: Engineering. The 111 nodes differ in size and may overlap to a certain extent with other categories or CC.

CC1—Geochemistry & Geophysical This cluster grouped the larger number of PA (n = 26), and was mostly related with investigation works on dissolution–precipitation of minerals under hydrothermal conditions. Among these studies stand out the two early works published by Ellis and Mahon (1964, 1967), which addressed geothermal WRI-E works with volcanic rocks and greywacke at 150–350 °C and 400 – 600° C temperature intervals, respectively. According to the CC1 classification, the two high-impact journals used to publish geothermal WRI-E studies were Geochemical et Cosmochimica Acta (10 PA; ~ 41%) and Chemical Geology (3 PA; ~ 25%).

CC2 – Geology This cluster grouped 23 PA related to the research subject, which specifically addressed experimental and *in-situ* geothermal field studies by considering different rock and fluid samples. Among these studies stand out the

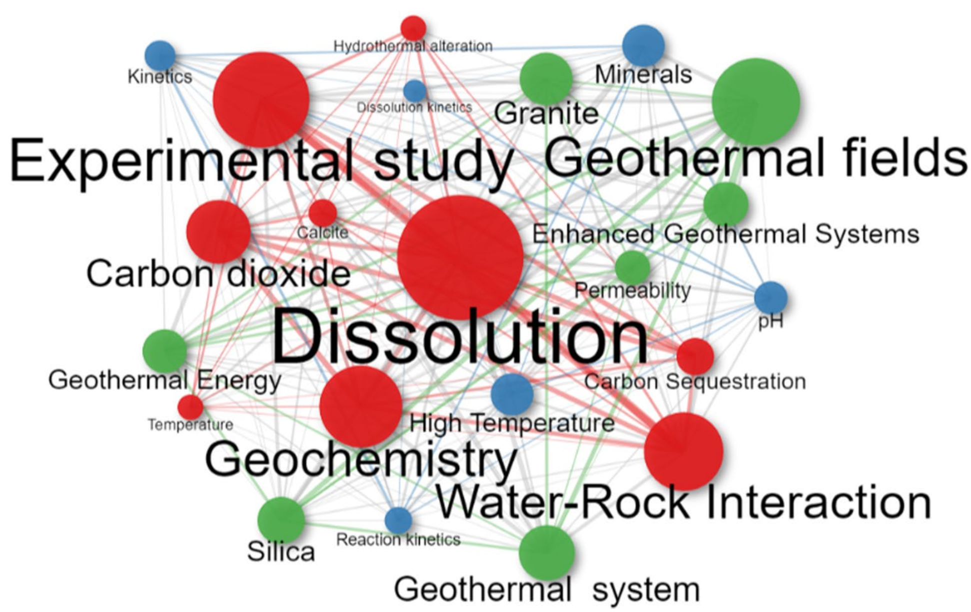


Fig. 7 A schematic co-occurrence bibliometric map showing the most representative author keywords and grouped in three major keyword clusters: Dissolution (in red colour network), High temperatures (in blue colour), Geothermal fields (in green colour)

Table 6 Some important gaps and findings of the research subject of WRI-E on geothermal applications

ID	Major KeyWords Plus® Clusters	Major research or knowledge area	Major findings	Scientific and technical gaps	Application fields
1	Dissolution	- Mineral dissolution and precipitation	- Elemental mobility by WRI process - Pathfinder elements in geothermal exploration	- Partition coefficients for studying different geological settings - Precise mass-balances to evaluate the effective mobility of major and trace elements	- Decoding of fluid-rock interaction processes and geochemical signatures by involving major and trace element analyses (water and gases)
		- Mineral deposition (silica and calcite)	- The kinetics in the rate at silica dissolves	- Dissolution rates as a function of rock and fluid properties (composition, mineralogy, superficial area, temperature, and pressure)	- Development of thermodynamic computer models for evaluating laboratory and field experiments
		- Carbon dioxide and carbon sequestration	- CO_2 sequestration and modelling in basalts rocks	- CO_2 sequestration processes in different geological settings	- Evaluation of the potential carbon sequestration in geothermal systems
2	Geothermal fields	- Technology of geothermal wells	- WRI-E for developing prediction models of deposition kinetic processes	- Effective scaling control for producer and reinjection wells	- Evaluation of scaling issues and blockage risks for geothermal wells and rock-formations
		- Permeability and fracture properties	- Integrated studies of thermal, hydrological, mechanical and chemical effects	- Effective fracturing control either to maintain or increase permeability	- Enhanced geothermal systems
3	High temperature	- Rock (minerals) and fluids	- Rare earth elements mobility	- Molecular simulation (substitution patterns)	- Study of the preferential partition of REE in different geological settings, thermodynamic conditions, and at an atomic scale
			- Calibration of geothermometers	- Improved and more effective solute and gas geothermometers and uncertainties	- Reliable prediction of deep equilibrium temperatures in geothermal systems
		- Fluid physicochemical properties (pH)	- High-enthalpy systems studies	- Supercritical thermodynamic systems for studying the interaction of acid fluids and rocks - High-quality thermodynamic data at a wider interval of geothermal temperature and pressure conditions	- Geochemical and thermodynamic studies for the evaluation of super-hot geothermal systems

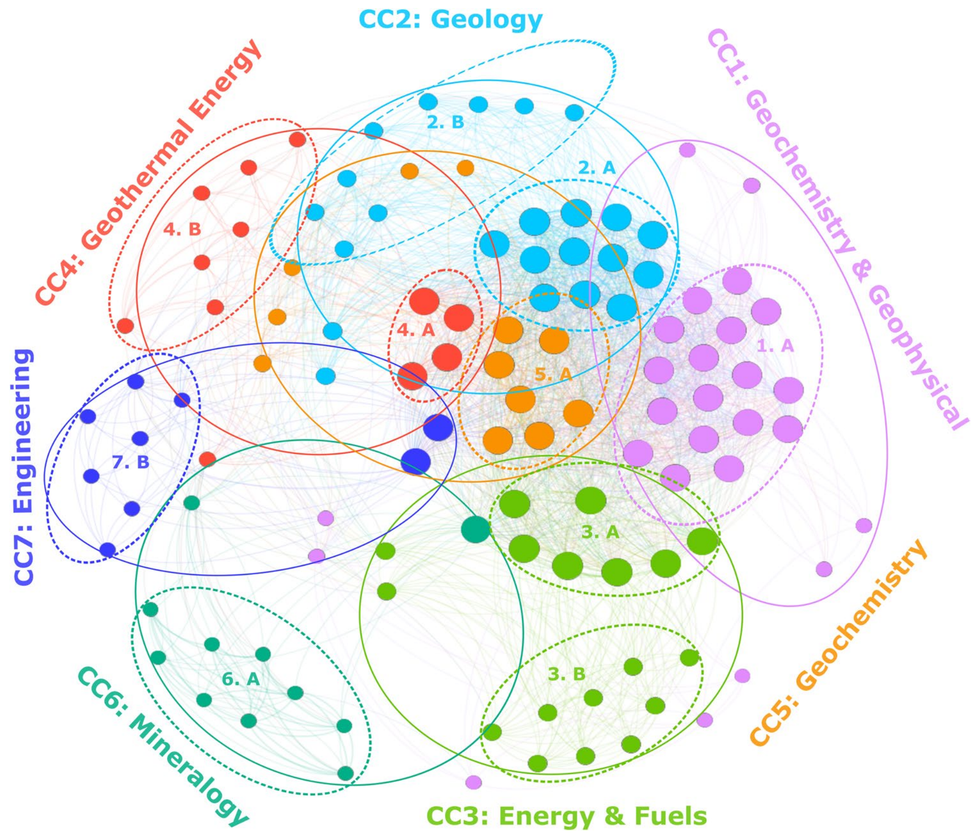


Fig. 8 Schematic representation of the overall paper network using research areas reported by Scopus and WoS, its six central clusters with 160 nodes and 6227 aristae, connections between nodes are shown. CC1—Geochemistry & Geophysical; CC2—Geology; CC3—Energy & Fuels; CC4—Geothermal Energy; CC5—Geochemistry; CC6—Mineralogy; CC7—Engineering

works reported by Savage et al. (1993) and Pollet-Villard et al. (2017), which were related to the experimental evaluation of granite reactions with stream water, and the experimental study of dissolution kinetics of K-feldspars, respectively. Key peer review journals such as the Journal of Volcanology and Geothermal Research (3 PA; ~ 13%) and Geofluids (2 PA; ~ 9%) were generally preferred by the CC2 (Geology) cluster.

CC3—Energy & Fuels This cluster grouped 18 PA on a wider variety of research topics such as carbon dioxide (Daval et al. 2009), carbon sequestration and dissolution of CO_2 (Gysi & Stefansson, 2012), all in connection to the research subject. These PA were related to WRI-E works conducted at thermodynamic conditions relevant to geologic CO_2 sequestration in subsurface environments (T = 90 °C and pCO_2 = 25 MPa), including experiments and theoretical modelling of CO_2 sequestration under hydrothermal basalt alteration conditions, respectively. Key journals such as Geothermal Energy (2 PA; ~ 11%) and Energy Procedia (2 PA; ~ 11%) were generally selected for the publication of the WRI-E studies of this cluster classification (CC3).

CC4—Geothermal energy This cluster was grouped by 12 PA dealing with several research topics such as geothermometry (Pope et al. 1987), and the element mobility Mate Osvald et al. (2018), which were focused on the calibration of quartz, Na–K, Na–K-Ca geothermometers, and the mobility effects of some fluid components for the extraction of metals from geothermal systems, respectively. Key journals such as Applied Geochemistry (2 PA; ~ 16%), and Geothermics (1 PA; ~ 8%) were selected for the publication of the WRI-E studies in this cluster classification (CC4).

CC5—Geochemistry This cluster grouped 12 PA mainly focused on the chemical exchange, reaction mechanisms, reaction rates, and mineral dissolution topics. Among these studies stand out the investigation reported by Gislason and Oelkers (2003), which addressed an experimental work for the study of the dissolution rates of basaltic glass as function of pH and temperature. Key journals such as Geochemical et Cosmochimica Acta (5 PA; ~ 41%) and the Earth and Planetary Science Letters (1 PA; ~ 8%) were generally selected by the authors of these WRI-E studies in the CC5 cluster.

CC6 – Mineralogy This cluster grouped 11 PA covering research topics mainly related to solubility, dissolution, and the effect of secondary minerals for the study of water–rock interaction processes. Among these geothermal WRI-E works stand out the studies reported by Arnórsson and

Stefánsson (1999) and Guichet and Zuddas (2003), which were based on the assessment of feldspar solubility constants in water at a temperature interval from 0 to 350 °C, and vapor saturation pressures, and the effect of secondary minerals on electrokinetic phenomena during WRI at temperatures ranging from 20 to 80 °C, respectively. Key journals such as Minerals (2 PA; ~ 18%) and Contributions to Mineralogy and Petrology (1 PA; ~ 9%) were generally selected for the studies of the CC6 cluster.

CC7 – Engineering This cluster grouped 9 PA on geothermal WRI-E studies performed at sub- and supercritical conditions of pressure and temperature, and generally carried out in HDR geothermal systems. Among these investigations stand out those WRI-E works reported by Tsuchiya and Hirano (2007) and Bai et al. (2012a); which were related to the study of dissolution reactions in hydrothermal systems, and the study of scaling and corrosion problems in HDR geothermal systems, respectively. Key journals such as Petroleum Science and Engineering (1 PA; ~ 11%) and Transport in Porous Media (1 PA; ~ 11%) were used to publish the WRI-E studies in the CC7 cluster.

As shown in Fig. 8, the main clusters (represented by solid lines; e.g., the Geothermal Energy: CC-4) may enclosed some distant sub-clusters (represented by dashed lines). These distant sub-clusters may be also divided in two major sub-groups that show: (i) a major affinity with the main cluster topic (i.e., sub-cluster 4.B); and (ii) an affinity with two or more main clusters [e.g., the sub-cluster 4.A, which shows affinity with the main clusters: Geothermal energy (CC-4), Geochemistry (CC-5) and Geology (CC-2)].

Multiple Correspondence Analysis (MCA) To carry out the MCA for analyzing the dominant research topics, a conceptual structure map was created by applying an exploratory factor analysis method using the Keywords Plus included in the working database of 160 PA (Fig. 9). To reduce the data dimensionality of the Keywords Plus, the key factor analysis variables Dim 1 and Dim 2 were defined after formulating the Burt Matrix through a numerical procedure suggested by Cuccurullo et al. (2016). From this MCA model, it was found that close to the ~ 75% of the bibliometric information obtained from the 160 PA on the research subject was efficiently represented by these two key factor variables (Dim 1: ~ 52% and Dim 2: ~ 23%).

After plotting the results of these variables (Fig. 9), new bibliometric classification clusters on the WRI-E research subject were obtained. Strong connections among Keywords Plus (given by closer proximities) or weak connections (given by the wider separation distances) are clearly depicted. These classification clusters may be roughly grouped into five major thematic clusters, which may be used to represent the intellectual structure of the geothermal WRI-E research subject: (1) *Geochemistry*; (2) *Thermodynamics*; (3) *Enhanced Geothermal Systems*; (4) *Capture of carbon dioxide*; and (5) *Hydrothermal alteration*. According to the MCA conceptual map of the working database: n = 160 PA (Fig. 9), the strongest correlated clusters were given by the *Geochemistry* and *Thermodynamics* clusters (1 and 2), whereas the weakest correlation among Keywords Plus was evidenced by the *Hydrothermal Alteration* cluster (5). In the case of the *Geochemistry* cluster (1), it is characterized by nine major Keywords Plus, among which the experimental study, the dissolution and reaction kinetics, and the minerals pairs exhibited a stronger association in comparison with the other Keywords Plus (Fig. 9). On the other hand, the *Thermodynamics* cluster (2) is characterized by containing eight major Keywords Plus, where three stronger connections among Keywords Plus pairs are inferred: Kinetics – Dissolution Kinetics, pH – Temperature, and Aqueous solution – System. In contrast with these strong correlation clusters, the *Hydrothermal Alteration* cluster (5) was characterized by containing only four Keywords Plus which exhibited a weaker correlation among the Keywords Plus: Hydrothermal alteration, Seawater and Carbon sequestration, and Hydrothermal system.

To complete the analysis of the intellectual structure, a pattern of interrelationships among major research topics was created using hierarchical dendrograms (inferred from the MCA clustering). Table 7 show the schematic dendrograms and bibliometric data about the most cited articles reported on the research subject WRI-E. The dendrograms and Keywords Plus were used to validate the MCA conceptual structure map. From the Keywords Plus analysis per MCA cluster, the results obtained from the dendrogram are in good agreement with those classification results provided by the MCA structure map (Fig. 9). Regarding the term-level similarity [0, 2], it was found that similarity values close to zero provided stronger connections among Keywords Plus, whereas those values > 1 represented the weakest connections among them. According to these results, and as an example, for the *Geochemistry* cluster (1), stronger connections were observed for the Keywords Plus pairs: Experimental study – Dissolution, whereas for the *Thermodynamics* cluster (2), such strong connections were also evidenced for the Keyword Plus pair: pH – Temperature. In contrast, weak connections were observed for the *Hydrothermal Alteration* cluster. It is also important to show that the interrelations among MCA clusters, *Geochemistry* (1) and *Capture of carbon dioxide* (4) exhibited a good similarity. To highlight the PA with higher investigation impact per MCA cluster, the most cited PA were also included in Table 7, where the PA with the higher number of citations (312) correspond to the study published by Gislason and Oelkers (2003), whereas the article reported by Shibuya et al., (2013) has the lower number of cites (36).

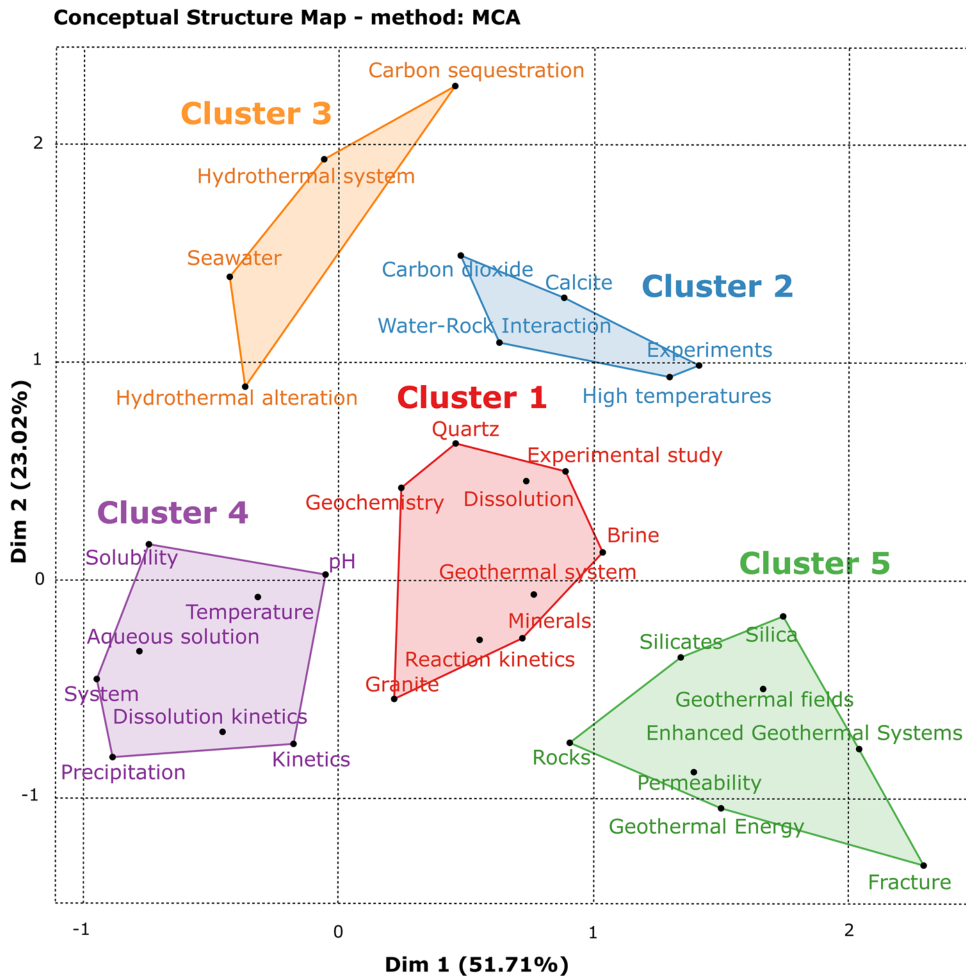


Fig. 9 Conceptual structure map performed through MCA of WRI-E applied to geothermal using keywords plus. The totality research in WRI-E is grouped in five clusters: cluster-1 (geochemistry general topics), cluster-2 (capture of carbon dioxide), cluster-3 (hydrothermal alteration themes), cluster-4 (thermodynamic aspects), cluster-5 (themes involved to Enhanced Geothermal Systems)

Conclusions

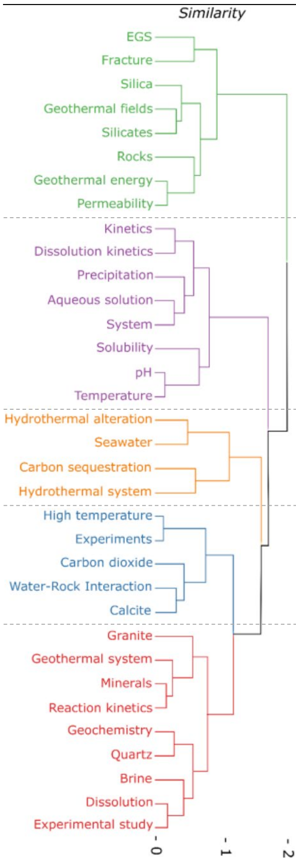
A methodological and comprehensive bibliometric analysis was applied to assess the worldwide research progress on geothermal WRI-E studies. This investigation was successfully carried out by using WoS and Scopus, bibliometric indicators and schematic maps for the time period 1963–2022.

According to Price's law phases, the productivity evolution and latest development of these research studies were typified by two main passage-time moments (before and after 2008), where 160 PA were compiled in the present bibliometric study. Before 2008, the productivity of these PA was characterized by the forerunners zone, whereas for the time period 2008—2022, the number of PA depicted a rapid and higher increase typified by an exponential growth zone. For this growth zone, the geothermal WRI-E research subject has gradually become a hot topic for Earth science researchers involved in geothermal prospection and exploitation studies. Within this context, researchers from USA, France, Japan, China, Germany, and Iceland are leading the publication of geothermal WRI-E articles in peer-review journals.

In the last 14 years, a close collaboration were mainly observed in some world academic institutions (e.g., USA–China and Iceland–France), whereas alliances between academia and industry were only carried out in Japan. Regarding the peer-review journals preferred by the authors to publish their WRI-E studies, Geochimica et Cosmochimica Acta led the production of PA, followed by Chemical Geology and Applied Geochemistry. These journals actually form the three main pillars of scientific production in the core zone of the Bradford law of scattering. With respect to the research groups that lead these WRI-E studies, the research groups from the universities of Iceland (Gíslason et al.), Toyama (Ueda et al.), Toulouse (Oelkers et al.), Jilin (Xu et al.) and Tohoku (Tsuchiya et al.) have been the most active teams working

Table 7 Dendrogram of the term-level similarity clustering and authors with more citations and contributions on the topic of WRI-E for geothermal applications (Time period 1963 – 2022)

Topic Dendrogram



Cluster	Author	The most cited documents per cluster	Contribution	Total Citations
3	Caulk et la. 2016	Experimental investigation of fracture aperture and permeability change within Enhanced Geothermal Systems	12.46	42
2	Gislason and Oelkers 2003	Mechanism, rates, and consequences of basaltic glass dissolution: II. An experimental study of the dissolution rates of basaltic glass as a function of pH and temperature	0.83	312
5	Shibuya 2013	Reactions between basalt and CO2 rich seawater at 250 and 350°C 500 bars implications for the CO2 sequestration into the modern oceanic crust and the composition of hydrothermal vent fluid in the CO2 rich early ocean	22.27	36
4	Gysi and Stefnsson 2012	Experiments and geochemical modeling of CO2 sequestration during hydrothermal basalt Alteration	9.14	57
1	Daval et al. 2009	Carbonation of Ca-bearing silicates, the case of wollastonite: Experimental investigations and kinetic modeling	2.19	158

on this knowledge field, which is supported by their PA and number of citations.

From the intellectual structure analysis of PA, some key insights and the development path of the WRI-E research subject were inferred. Three major clusters of KeyWords Plus® (Dissolution, Geothermal Fields and High Temperature) were identified as a first approach where the works on dissolution–precipitation of minerals appears as main research hotspot. Among these clusters, other relevant research topics such as geochemistry, thermodynamics, enhanced geothermal systems, carbon dioxide capture, and hydrothermal alteration were identified, where the WRI-E works has exhibited strong implications. By considering the impact on inter- and multi-disciplinary research areas involved in the geothermal WRI-E works, seven clusters were additionally identified among some specific research areas such as: Geochemistry & Geophysics, Geology, Energy & Fuels; Geothermal energy, Geochemistry, Mineralogy, and Engineering.

All these research areas were identified as the main bibliometric hotspots with a strong potential to be used for the future design of new WRI experiments to address some crucial problems still present in the geothermal prospection and exploitation. Among these problems stand out the study of: (i) hydrothermal, superhot and enhanced geothermal systems and their geological structures; (ii) hydrogeological and geo-mechanical processes; (iii) the chemical fractionation of major and trace elements; (iv) the hydrothermal alteration; (v) the correct calibration of solute and gas geothermometers; (vi) the mineral scaling control; (v) the pipe and well corrosion; (vi) the CO_2 capture and storage; (vii) the transport of geothermal fluids inside power plant installations; (viii) the evaluation of environmental issues; among others.

The present BA is expected to benefit all the scientist, technicians and scholars interested in the research topic of the WRI-E for planning or designing a wide variety of future geothermal applications. We are very confident that the major findings and research gaps inferred from this BA may provide useful ideas to those researchers interested in solving some of the current scientific and technological problems present in the worldwide harnessing of the geothermal energy.

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Author contributions D. Yáñez-Dávila: Bibliometric model conceptualization, Work methodology, Data collection, Bibliometric analysis, Result Interpretation, and Writing. E. Santoyo: Leader of the GRG group, Bibliometric model conceptualization, Bibliometric analysis, Interpretation of results, and Writing - Review & Editing. G. Santos-Raga: WoS and Scopus Searching Process, Data collection and merging, and Visualisation mapping

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Authors confirm that all relevant data of the present research are included in the article and the supplementary file. Other related data may be available upon request from the corresponding author: Professor Dr. E. Santoyo (esg@ier.unam.mx).

Declarations

Competing interests The authors declare no competing interests.

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