Heliyon 10 (2024) e24943

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Mapping the research landscape of bauxite by-products (red mud): An evolutionary perspective from 1995 to 2022

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ARTICLE INFO

Keywords:
Red mud
Bauxite residue
Bibliometric analysis
Valorisation
circular economy
Critical materials

ABSTRACT

The global population growth has significantly impacted energy and raw material consumption, unmatched since the Industrial Revolution. Among metals, aluminium ranks second only to steel, with annual production exceeding 69 million tonnes. Due to its high demand, bauxite, the primary ore from which aluminium is extracted, is now classified as a critical material in the EU and the US, given the potential risk of supply shortages for essential applications. Geographical and production challenges surround bauxite, presenting geo-economic and environmental challenges. A critical concern in aluminium production is managing by-products, notably red mud, a bauxite residue, generating over 175 million tonnes annually worldwide. Comprehensive bibliometric research is imperative due to the high amount of bibliographical resources related to this topic, encompassing circular economy, re-valorisation, sustainability, and disposal. This study employs bibliometric methods to assess red mud valorisation, offering insights into research topics, influential authors, and key journals, shedding light on the past, present, and future of red mud research. Such bibliometric analysis not only highlights the current state of the field but also serves as a valuable tool for decision-making, enabling researchers and policymakers to identify trends, gaps, and areas for further exploration, fostering informed and sustainable advancements in the by-products of the aluminium industry.

1. Introduction

Aluminium is one of the most highly produced metals in the world, with an annual production that exceeded 69 million metric tonnes as of December 2022, compared to the previous year's 67.5 million metric tonnes, second only to steel. Although it is the third most abundant element in the earth's crust after oxygen and silicon, aluminium does not occur naturally in its metallic form [1]. Bauxite is among the primary ores that are rich in aluminium, with alumina, or aluminium oxide (Al_2O_3), content ranging from 30 wt% to 60 wt%. The Bayer process, patented by Karl Joseph Bayer in 1888, is the predominant method used to refine bauxite ore into alumina, which is then reduced electrolytically to produce aluminium metal using the Hall-Heroult process. The first refinery utilizing

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https://doi.org/10.1016/j.heliyon.2024.e24943
Received 23 October 2023; Received in revised form 16 January 2024; Accepted 17 January 2024
Available online 19 January 2024
2405-8440/

the Bayer process was established in the 1800s, and presently, there are approximately 100 operating alumina refineries worldwide [2].

As depicted in Fig. 1, the annual production of alumina (Fig. 1a) and primary aluminium (Fig. 1b) in metric tonnes per year in 2022 is illustrated. Bauxite is extracted from various countries such as Australia, Brazil, China, Ghana, Greece, Guinea, Hungary, India, Indonesia, and Jamaica, among others, with the main producing nations being Australia, Brazil, China, and Guinea. China, with an

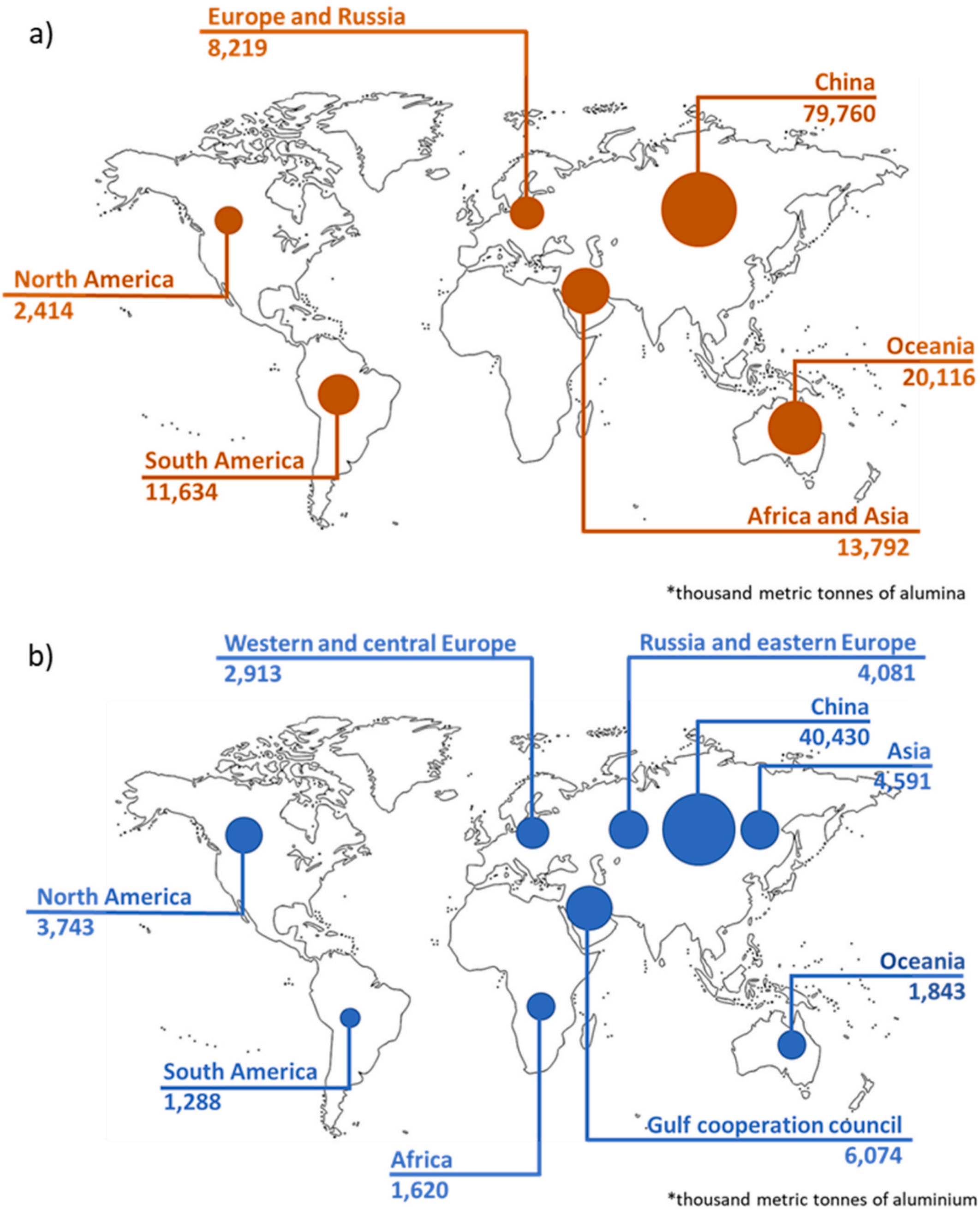

Fig. 1. a) Regional Alumina production in 2022, b) Regional primary aluminium production in 2022. Africa (Cameroon, Egypt, Ghana, Mozambique, Nigeria, South Africa). North America (Canada, United States of America), South America (Argentina, Brazil, Mexico, Venezuela), Asia (Azerbaijan, Bahrain, India, Indonesia, Iran, Japan, Kazakhstan, Malaysia, North Korea, Oman, Qatar, South Korea, Tadzhikistan, Taiwan, Turkey) Western & central Europe (Austria, France, Germany, Greece, Iceland, Italy, Netherlands, Norway, Spain, Sweden, Switzerland, United Kingdom), Russia and Eastern Europe (Bosnia and Herzegovina, Croatia, Hungary, Montenegro, Poland, Romania, Russian Federation, Serbia and Montenegro, Slovakia, Slovenia, Ukraine), Oceania (Australia, New Zealand), Gulf Cooperation council (Bahrain, Oman, Qatar, Saudi Arabia, United Araba Emirates), China [3].

annual production of over 79,760 thousand metric tonnes in 2022, is the largest global producer of alumina, followed by Australia with a production of 20,116 thousand metric tonnes per year in 2022.

Over the past 25 years, primary aluminium production has surged by 25 % in 2022 and is projected to increase by approximately 81 % by 2050 compared to 2018 levels [4], prompting the European Commission on Fundamental Raw Materials to include bauxite ore in the EU's critical material list for the first time in 2022 [5]. This designation reflects the potential supply risk of bauxite, alumina, and aluminium for essential applications.

The aluminium industry faces significant challenges related to material criticality and achieving global climate goals, such as carbon dioxide neutrality and zero-waste objectives. Addressing these challenges requires substantial efforts from technological and scientific perspectives, particularly in managing the substantial residue generated during aluminium production. Potential solutions involve more efficient recycling, exploring new aluminium sources, extracting aluminium from bauxite residue, and one of the most important, minimizing red mud generation during the alumina production process through process optimization, improved alumina extraction efficiency, and the adoption of cleaner technologies. Ongoing projects, such as the ABTOMAT (www.abtomat.ue) project funded by the European Union, aim to find bauxite alternatives, considering regional characteristics in EU and EFTA countries, and design high-value symbiotic multi-product production systems aligned with circular economy principles, zero-waste practices, and cost-effectiveness, as outlined in the Strategic Implementation Plan of the European Innovation Partnership on Raw Materials and the ERA-MIN Research Agenda.

The Bayer process generates waste known as red mud, a residue from alumina extraction in bauxite processing. Its composition varies based on bauxite ore, containing elements like Al_2O_3 (6–24 wt%), Fe_2O_3 (7–50 wt%), SiO_2 (3–24 wt%), TiO_2 (2.5–18 wt%), CaO (1.8–46 wt%), Na_2O (1.6–13 wt%), and other minor elements (4.6–33 wt%) [6,7]. On average, 1.23 tonnes of red mud are produced per tonne of alumina, ranging from 0.55 to 2.21 based on specific bauxite and production processes. Annually, approximately 175 million tonnes of red mud are generated, with an expected accumulation of 4 billion tonnes by 2022. The International Aluminium Institute [8] proposes using 15 % bauxite residue by 2025 to promote circular economy practices, aiming for sustainable growth through optimized resource use. However, only 2–3% of annual red mud production is currently effectively valorised in other technological applications [9].

Red mud is typically stored in Bauxite Residue Storage Facilities (BRSF), requiring extensive land for storage until final closure and rehabilitation. The main challenges involve ensuring its safe containment to transform into a secure and environmentally stable landform capable of supporting vegetation and other land-based activities [10]. Environmental risks arise due to the high alkalinity (pH) of red mud, with potential issues of soil permeation and contamination of underground water sources, posing risks such as heavy metal leaching, radioactivity, high sodium content, alkalinity, moisture levels, and transportation expenses [11].

The reuse of red mud is constrained by its high alkalinity, leading to alkali aggregates' production and corrosion of steel parts during application [12]. Challenges include high alkalinity, sodium content, electrical conductivity, and a smaller particle size distribution (<100 μm in 80 % of particles), limiting potential reuse [13,14]. Various industrial processes have been developed to address red mud alkalinity, involving press filters during production, calcium oxide addition in the Bayer process for dealkanisation, and amelioration techniques like gypsum treatment (mainly after the Ajka accident [15,16]), neutralization with seawater, pressure leaching with carbon dioxide or water, and acid leaching [17–19].

Nowadays, there are several approaches employed for the repurposing of residue, including (i) utilization as a bulk material for various applications such as landfill cover, soil and mine waste amendments, road base, and cement supplementation; (ii) extraction of valuable compounds such as iron, scandium, titanium and rare-earths; (iii) formulation of building materials, such as bricks, tiles, geopolymers, wood substitutes, pigments, and others; and (iv) creation of specific properties or application, such as aggregates, proppants, water treatment, reagents, and catalysts [3]. Moreover, red mud can be regarded as a secondary raw material for recovering valuable substances. This can be achieved through three main routes: (a) re-vegetation, (b) residue revalorization (changing the value of the residue to transform it into a by-product), and (c) extraction of valuable metals. The extraction of valuable metals, notably rare earth elements like scandium, enhances the significance of red mud as a valuable by-product. Given the substantial content of these valuable metals, red mud assumes critical importance for the future [20,21].

Table 1 presents red mud typical concentration ranges of the main rare earths and critical metals [5,22]. Therefore, the red mud residue can become an essential resource for obtaining critical metals, which, in some cases, have a higher concentration than conventional ore grades, thus contributing to the circular economy while guaranteeing supply.

Table 1
Rare-earths and critical materials typical average concentration in red mud [23,24].

Element	Concentration (ppm)	Element	Concentration (ppm)
La[a]`	149 ± 40	**Er**[a]`	17.2 ± 3.1
Ce[a]`	12.7 ± 52.9	**Yb**[a]`	15.6 ± 1.9
Pr[a]`	25.8 ± 7.5	**Y**[a]`	91.2 ± 15.7
Nd[a]`	115 ± 27	**Lu**[a]`	2.4 ± 0.32
Sm[a]`	28.9 ± 5.2	**Sc**[a]`	127.9 ± 14.7
Eu[a]`	5 ± 0.9	**Al**[a]`	$6\cdot10^4$-$23\cdot10^4$
Gd[a]`	23.3 ± 3.2	**Si**[a]	$3\cdot10^4$-$24\cdot10^3$
Dy[a]`	12.8 ± 1.9	**Ti**`	$25\cdot10^3$-$18\cdot10^4$
Ho[a]`	4.3 ± 1		

[a] Critical material EU list, ` Critical material on US list.

The increasing interest in red mud has led to a significant number of publications and researchers working in the field in recent years, due to concerns about the high volume of residues. As a result, more applications and areas of study are being explored, leading to a high level of specialization and a high amount of literature [6,12,20,25–30]. Although there are various specialized reviews of the state of the art of red mud available in the literature, these reviews mainly analyse specific aspects, such as applications. Therefore, there is a lack of information regarding the scope, social and economic impact, forthcoming trends, and, most notably, due to the high volume of literature, a general mapping of knowledge in this research field. These parameters are crucial to understanding the impact of red mud research on the scientific community and analysing its historical development, current state, and future directions.

Bibliometric studies, are a powerful tool to examine crucial facets across diverse research domains, enabling effective knowledge management and information monitoring. This analytical methodology involves the statistical analysis of written publications within specific research fields, using diverse metrics to gauge the impact of scientific output and establish its relevance [31]. These studies have proven instrumental in evaluating scientific impact, given the exponential growth in scholarly publications, reaching nearly 3 million annually, with a doubling rate of every 15 years [32]. The utility of bibliometrics extends across various research areas, providing valuable insights in fields such as management, econometrics, data envelopment, health economics, marketing, statistics, production management, renewable energies, thermal energy storage technologies, concentrating solar power, and more [33–35]. In navigating the vast landscape of scientific output, bibliometric analyses play a pivotal role, aiding researchers, policymakers, and stakeholders in identifying trends, assessing impact, and identifying areas for further exploration. Such studies not only facilitate an understanding of the current state of research but also inform strategic decision-making, fostering advancements in multiple disciplines.

Bibliometric studies help contextualize research fields, identify relevant or specialized researchers, and quantitatively analyse the global relevance of the research field. Involving a quantitative analysis of publications, these studies utilize mathematical and statistical methods to assess the impact and evolution of scientific research through various indicators.

The main objective of this study is to present a comprehensive overview of the field of red mud research using bibliometric methods. This analysis will encompass various aspects, including regional trends, author collaborations, and primary applications. Consequently, this study does not introduce new experimental findings on the subject but rather constructs a knowledge map based on the existing literature. Moreover, the study will aid researchers in identifying knowledge gaps and forming future research connections to advance the study of red mud. Thus, this bibliometric analysis holds critical importance in assessing the evolution and influence of research in the realm of aluminium industry waste, offering a robust foundation for informed decision-making and the identification of key areas of focus.

2. Materials and methods

Fig. 2 illustrates the multi-stage steps employed in this study, which were previously well established and defined in a prior study [35].

Following are described all the stages.

(1) The search field under study is red mud, the by-product from the aluminium industry obtained during the Bayer process, and the bibliometric analysis was based on this definition.
(2) Once the search field is correctly delimited, and restrictions are defined, a keyword map was built to prepare a search string used to acquire the database. For this, it is necessary to establish the main phrases, exclusion phrases and complement phrases that define the red mud research field. To achieve this, it is necessary to establish the main phrases, exclusion phrases, and complement phrases that define the red mud research field. The main phrase represents the term that must be present for a positive match. However, it may also include one or more complement phrases to ensure the accuracy of the search. Exclusion phrases will discard any paper in which one or more of these terms are found. In this case, the selected main phrases were "*red mud*," "*bauxite tailing*", "*bauxite residue*", "*red sludge*", and "*alumina refinery residue*" without complement phrases. In contrast, "*red mudstone*" was selected as the exclusion phase. As a result of the keyword map, the following logical search string was defined:

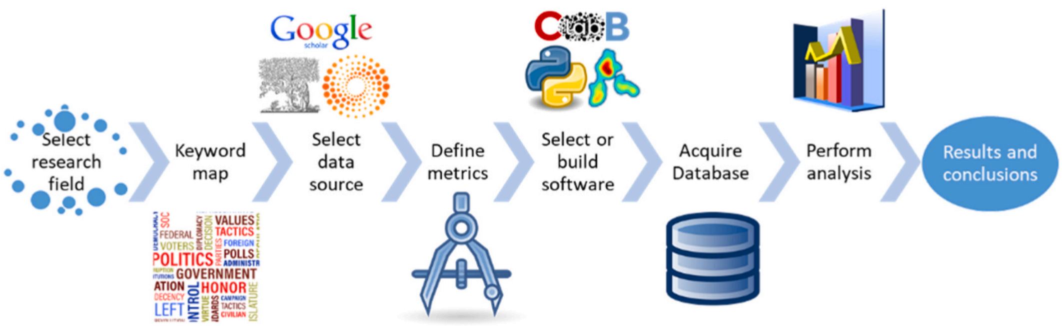

Fig. 2. Methodology stages for performing a bibliometric study [35].

"(TS= ((" red mud ") NOT (" red mudstone* ") OR (" bauxite tailing* ") NOT (" red mudstone* ") OR (" bauxite residue ") NOT (" red mudstone* ") OR (" red sludge* ") NOT (" red mudstone* ") OR (" alumina refinery residue* ") NOT (" red mudstone* ")))"

(3) The data sources for this bibliometric study included scientific journals, conference proceedings, books, and book chapters. These sources (*i.e.*, metadata) are usually used in scientific studies searching but also can be useful for performing bibliometric analyses. This data is available in many platforms such as Web of Science, Scopus, Google Scholar, among others. For this study Web of Science Core Collection (WOS) was selected as the main source since it has detailed metadata (which is adequate for the desired metrics) and includes more than 64 million high-quality publications. The available data in the metadata was: title, abstract, author's keywords, authors, year, and the number of citations, affiliations, and journals.

(4) (5) The next step consisted of selecting the metrics to be extracted from the database. Table 2 provides a complete list of the metrics reported in the current study, the software tools used, and whether the metric was used. For obtaining these metrics, Python programming, and CLab complexity network in Python and JavaScript were used [36]. Also, Origin from OriginLabs®, V.O.S. Viewer from Centre for Science and Technology Studies (CWTS) in Leiden University, and Microsoft® Excel were used for data visualization.

(6) During data acquisition from WOS Core Collection data source, 4757 papers were selected (data available at the end of December 2022). The search was limited to papers, reviews, book chapters, and books. Additionally, the search string was narrowed down by subject. These include searching by title, abstract, author, keywords and Keywords Plus®. This last is defined by WOS and is not under the authors' control.

3. Results

3.1. Worldwide red mud research: trends in publications and citations

The obtained documents through the search string defined in the methodology section were 4,757, which comprised 3741 papers, 296 reviews, 678 proceedings papers, 5 books, and 37 book chapters. Please note that patents were not included in this count. These documents originated from 80 countries around the world where more than 10,000 researchers have been implicated. These papers were published in 1108 scientific journals. Despite the high amount of journals, 71 are the most relevant to this topic, covering 50 % of all the publications, and only 10 main journals cover 20 % of all the publications. The average citation per paper is 25.1, indicating high scientific-technological interest.

The first publication in the database where the red mud is named for the first time was in 1966, entitled "*Phase transformation in complex processing of red mud*" by Dobos, G et al. [37] in the Acta Chimica Academiae Scientiarum hungaricae. Highlight that previous research has been conducted on this topic before the publication of this database. However, much of this research is not included in the database due to the inclusion of patents. After the mid 90's that the number of publications per year started to increase. The first publication to reach more than 100 cites was *"Selective separation and determination of scandium from yttrium and lanthanides in red mud by a combined ion exchange/solvent extraction method"* by Ochsenkuhn-Petropulu, M. et al. [38] in 1995.

Fig. 3 depicts the global landscape of red mud research. Specifically, Fig. 3a graphically illustrates the accumulative count of the number of publications spanning from 1995 to 2022 and the corresponding cumulative citations per year (indicated by the grey dashed line). Notably, a peak of 53 publications annually was reached in 2005. Furthermore, there has been a rapid increase in the annual publication rate in recent years, resulting in a cumulative total of 618 publications and over 116,626 accumulated citations by the end of 2022. Fig. 3b (as of February 2023) displays the distribution of accumulated publications across the world map, limited to countries that have produced over 70 publications. A total of 12 nations has met this threshold. Another pertinent consideration when contemplating the body of published word is that primary aluminium manufacturers, they wield considerable impetus in discovering applications and have frequently conducted substantial research, often in conjunction with other corporate entities. Nevertheless, due

Table 2
The metrics used during the study.

Metric	Software
Total publication's evolution	Python, Origin
Total citations per year	Python, Origin
Total publications per country	Python, Origin, Ms Excel
Country and E.U. evolution	Python, Origin
E.U. country's evolution	Python, Origin
Country and E.U. increment per year	Python
Country and E.U. co-citation interaction	Python, V.O.S. viewer
Journals with h-index and performance ratio	Python
Top authors evolution	Python, Origin
Top authors with h-index	Python
Author communities	Python, CLab
Author co-citation evolution	V.O.S. Viewer
Research areas evolution	Python, Origin
Bibliometric coupling of documents	V.O.S.

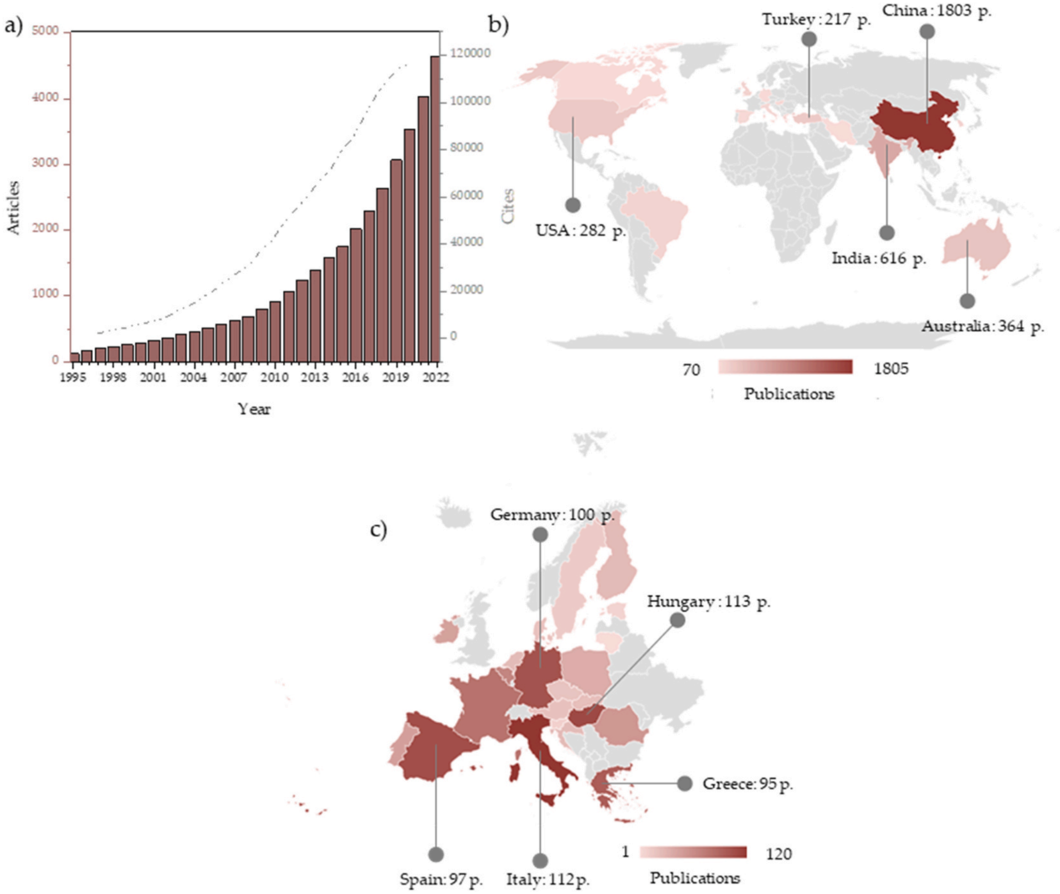

Fig. 3. Red mud research evolution: a) an accumulative number of papers (dark red bars) and cites (grey dotted line) from 1995 to 2022. b) Intensity world map of the countries with the highest total number of publications from 1995 to 2022 (from light to dark red). c) Intensity world map of the countries of the European Union (U.E.) with the highest total number of publications from 1995 to 2022 (from light to dark red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

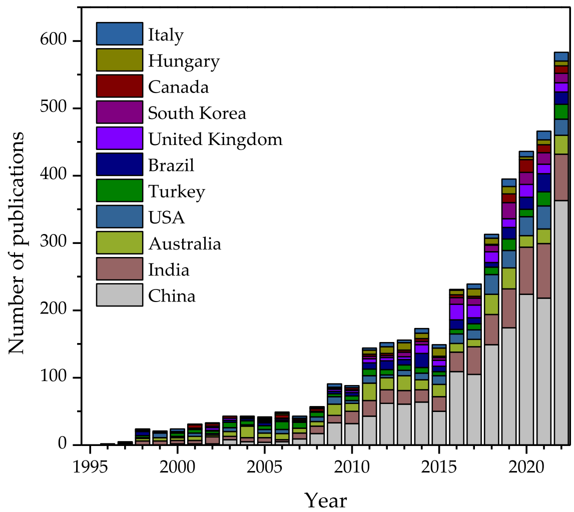

Fig. 4. Evolution of the number of publications of the top-10 countries from 1995 to 2022.

to proprietary interests, they exhibit no inclination to disseminate any of this research, thereby preserving the confidentiality of their finding or published in patents. Therefore, is noticeable that the analysed data majorly correspond to academic research.

The 5 main countries with the highest number of publications are: China (1803 p.), India (616 p.), Australia (364 p.), U.S.A. (282 p.) And, finally, Turkey (217 p.). This can be correlated with the fact that the USA, Australia, and Turkey do not practically reuse red mud. To better understand the country's relevance, in Fig. 3c were analysed European Union separately: Hungary (113 p.) followed by Italy (112 p.), Germany (100 p.) and Spain (97 p.) are leading the red mud research.

In more detail, Fig. 4 shows the evolution per year of the number of publications of the 10 main countries in the period 1995–2022. In general terms, all the countries grow their research on red mud. In the early stage of the investigation, the EU led this topic until 2010, when China started to lead the research in terms of the number of publications. When analysing the main countries, an analogy can be observed with some of the main alumina producer's countries and, consequently, where the largest by-product amounts of red mud are generated, as seen in the introduction section (China, Australia, Turkey, India, Canada, and Greece). Conversely, countries like Hungary, the large number of papers is mainly related to the accident in Ajka in 2010 [15]. Nowadays, the most cited paper is the one authored by Imran, A. entitled "*Low-cost adsorbents for the removal of organic pollutants from wastewater*" [39]. This highlights the high potential for revitalization and supports the circular economy concept of red mud as an adsorbent material in wastewater treatment. As it will later explore, this topic becomes one of the main applications of red mud.

3.1.1. Countries interaction: network for authors collaboration

Fig. 5 represents the network connections between the 20 main author's countries worldwide with more than 10 publications in common. The size of the circles is relative to the number of publications of each country, and the lines and their strength indicate the intensity of collaboration. This analysis is crucial to strengthen the collaboration network and finding potential collaborators. The interactions between the author's countries (represented by the thickness of the lines) result in three main academic hubs of scientific production in red mud. The first hub (in green) is led by China, the second hub (in blue) is led by India, and the third hub (in red) is from Turkey. Interestingly, the high interconnection between the countries on the rear hub, mainly the countries of Europe, and its main link with hub 1 is through Italy, Turkey, and England. Conversely, the countries that are part of the second hub (blue group) show lower international collaborations. The most relevant parameters of these hubs are detailed in Table 3. The 14 main countries described in this table represent 92 % of the overall publications. Moreover, the total of publications of China and India together represents 52 % of all the publications and the EU 20 %. If the performance ratio (determined as the quotient between the number of cites/number of documents), cluster 3 shows the best performance of 34 cites as an average per paper. Otherwise, cluster 1 shows the highest number of publications in Q1 quartile journal, about 40 %.

Apart from the country's interaction, other relevant metric is to analyse the main research institutions/universities leading the research. The 10 most relevant institutions, under contour conditions of a minimum of 5 interactions, are: (1) Chinese Academy of Sciences (227 documents, 6107 cites and 234 link strength), (2) Central South University, China (227 papers, 4792 cites and 133 link strength), (3) The University of Queensland, Australia (85 documents, 2804 cites and 65 link strength), (4) Harper Adams University,

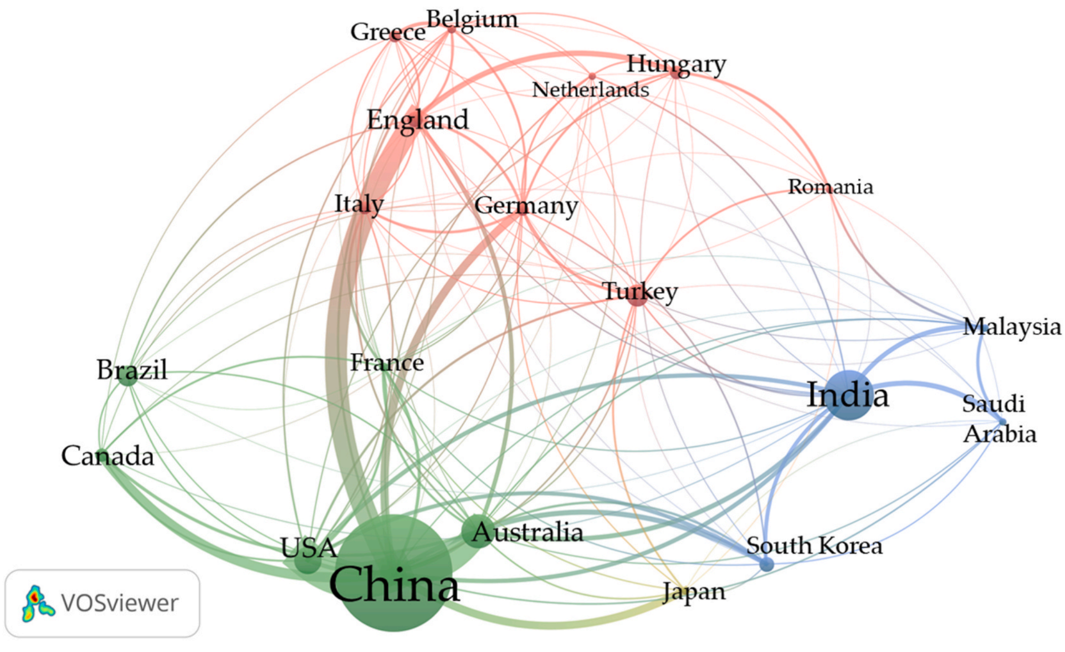

Fig. 5. Co-authorship of Top 20 affiliations (countries/regions) of the main authors publishing in the red mud field, and the three main interaction clusters (1) red, (2) blue and (3) green. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Co-authorship cluster of the top 20 countries: main countries, N°P: Number of publications, N°C: number of cites, PR: performance ratio, number of papers in interquartile Q1 and Year of the first publication.

Cluster	Main Countries	N°P	N°C	PR	Q1	Year first P
1	China, U.S.A., Canada, Australia, Brazil	2767	66,264	24.0	40 %	1973 (U.S.A.)
2	India, South Korea, Saudi Arabia, Malaysia	844	23,305	27.6	29 %	1974 (India)
3	Turkey, Germany, England, Italy, Hungary	722	24,525	34.0	36 %	1972 (Hungary)

United Kingdom (41 documents, 1575 cites and 58 link strength), (5) Budapest University of Technology and Economics, Hungary (35 documents, 1176 cites and 54 link strength), (6) GuangXi University, China (72 documents, 764 cites and 54 link strength), (7) Northeastern University, Boston (114 papers, 1026 cites and 50 link strength), (8) Tongji University, China (34 documents, 952 cites and 48 link strength, (9) China University of Geosciences (53 documents, 1068 cites and 45 link strength) and (10) University of Pannonia, Hungary (33 documents, 627 cites and 45 link strength). Despite this, if the impact is analysed by the number of cites appears in the top ten institutions like the Indian institute of technology (40 documents, 3281 cites and 16 link strength), the Katholieke university Leuven, Belgium (20 documents, 2491 cites and 40 link strength) or the Curtin university of technology, Australia (20 cites, 2466 cites and 8 link strength), with high citation but low interconnection with other institutions.

3.1.2. Most impactful authors in red mud research

The accumulated number of publications, H-index in this topic, number of cites, performance ratio and the year of the first and last publication about the red mud of the most relevant authors are listed in Table 4.

Notice that this analysis does not remark the authorship order, only if they are in the author list. The impact of the authors cannot be measured only by one way, if not that is a combination between different indicators. For this reason, Table 4 is divided in two parts, the first range the authors by the number of publications and the second by the number of cites. It is relevant that there are not an author's matches between the two categories. In the sense of authors' impact related to its number of cites and therefore, the impact that produces its publications is V.K. Gupta, the most impactful author with 1980 cites (February 2023) with only 6 publications. Moreover, together with the authors K. Binnemans, A. Tor, I. Ali and C. Klauber does not publish in the last years in the red mud research field.

3.1.3. Keyword: an indicator of research trends and evolve

The analysis of the main keywords and their evolution over time is a powerful metric for providing a historical perspective on any topic, current trends, and most importantly, future perspectives of research. This paper presents a co-occurrence analysis of the 50 main keywords used in red mud research from 1965 to 2022, as shown in Fig. 6a. As expected, the term "*red mud*" is the most used keyword in the bibliography. However, other mining terms such as "*bauxite residue*" are also widely used and have a high link strength between them. There is interesting to highlight that in general trends in Europe, North America, China, and India, the historical term predominantly used has been "*red mud*". Nonetheless, in the 1990s, Australia embraced the term " *bauxite residue*," and this designation has steadily gained acceptance, now being the prevailing term. Furthermore, co-occurrence of other relevant keywords like "*Bauxite*", "*Alumina*" or "*Bayer process*" were also identified. Four clusters of co-occurring keywords were identified in the analysis, each

Table 4
Most impactful authors related to the number of papers and the number of cites: Author name, N°P: number of publications, H_index is red mud topic, PR: performance ratio, year FP.: Year of the first publication and Year LP.: Year of the latest publication.

Name	N°P	H-index	Cites	PR	Yeah FP.	Year LP.
Xue, Shengguo	43	23	1603	37.3	2016	2022
Zhu, Feng	39	17	1216	31.2	2016	2022
Hartley, William	38	23	1493	39.3	2016	2022
Liu, Xiaoming	37	18	1281	34.6	2009	2022
Zhang, Ting-an	34	10	325	9.6	2013	2022
Zhang, Jiakuan	32	22	1957	61.2	2008	2022
Zhang, Yihe	29	10	345	11.9	2011	2022
Liu, Yan	27	11	300	11.1	2009	2022
Zhang, Na	25	13	979	39.2	2009	2022
Castaldi, Paola	24	16	1124	46.8	2006	2022
Gupta, VK	6	6	1980	330.0	2001	2004
Yang, Jiakuan	32	22	1957	61.2	2008	2022
Wang, Shaobin	13	11	1693	130.2	2007	2022
Binnemans, Koen	22	18	1659	75.4	2015	2020
Tor, Ali	16	11	1454	90.9	2006	2020
Van given, Tom	14	12	1421	101.5	2015	2021
Pontikes, Yiannis	23	14	1388	60.3	2015	2022
Ali, Imran	6	6	1316	219.3	2006	2020
Zhang, Guoping	12	10	1303	105.6	2010	2021
Klauber, C.	4	4	1245	311.3	2011	2011

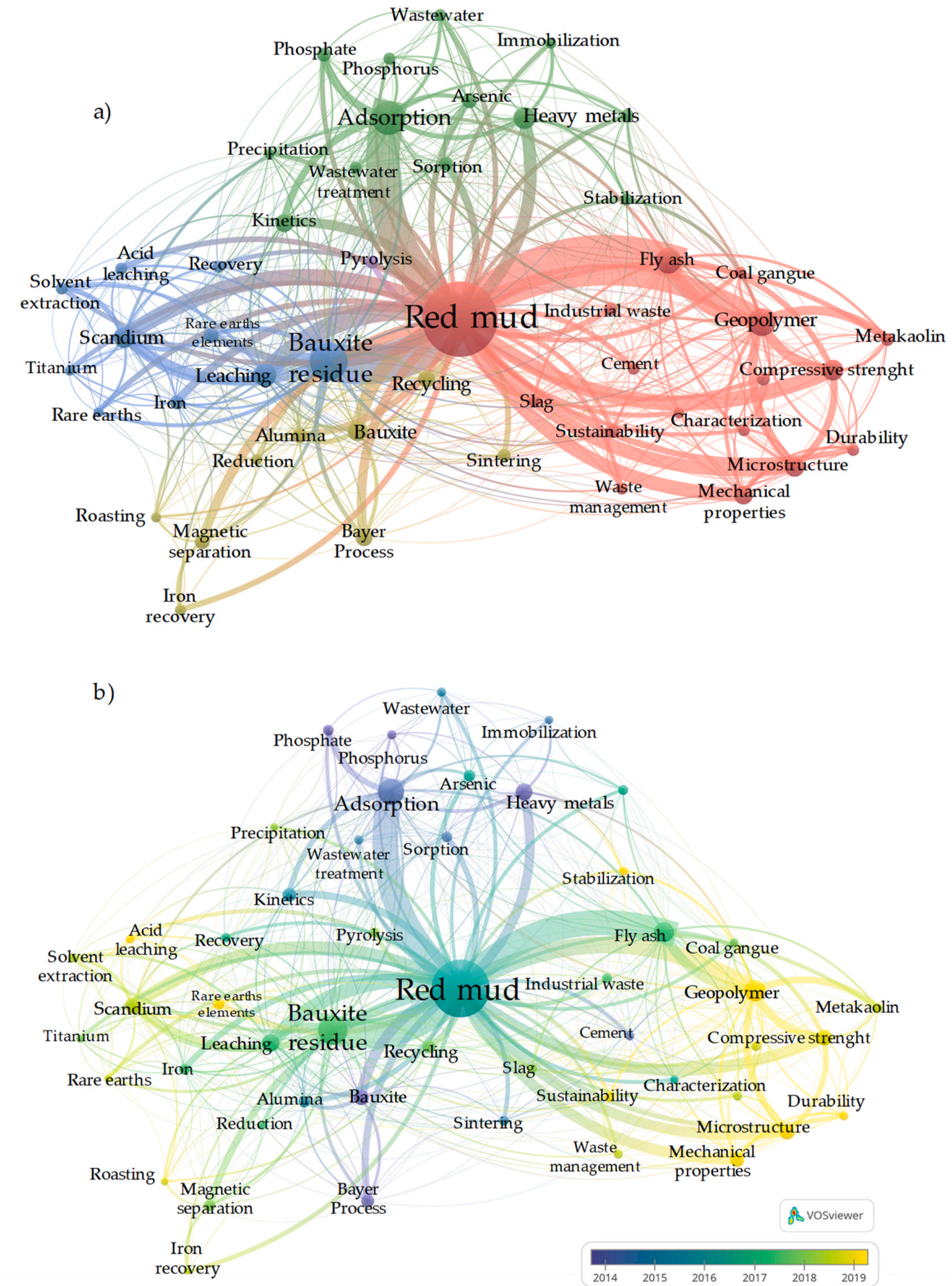

Fig. 6. Co-occurrence of the 50 main keywords; a) Main keyword groups about red mud research, b) keywords evolution in the period between 2014 and 2019, from blue to red. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

representing a specific thematic domain and group of keywords used together by authors. Thus, the analysis provides a map with a general overview of the main research topics on red mud.

Currently, red mud utilization is estimated to be over 3 million tonnes per year, and the largest applications are in construction materials, specifically in cement production in several countries such as India, Greece, and China. This is evidenced by the red cluster in Fig. 6a, where keywords like "*cement*", "*geopolymer*", "*Fly-ash*" or "*metakaolin*" form a strong domain. Red mud has the potential to improve the reactivity of fly-ash, which is a residue produced in coal-fired power plants, to synthesize geopolymers. This process can reduce the consumption of alkali activators, implying the reduction of the consumption of mineral reserves such as limestone and the emissions of greenhouse gases [40]. Residue mixtures with clay, shale, sand, and fly ash have also been widely evaluated for brick production. The iron and aluminium compounds contained in the red mud provide valuable additions in the production of Portland cement at a low cost [41,42]. Otherwise, fly-ash has a strong connection with "*adsorption*" keywords, being two potential residues as an absorbent for the treatment of contaminated water [43,44]. Already, their use of cement was proposed in the 1930s and has been commercially implemented intermittently since.

Iron recovery is the second main studied topic of red mud, mostly in China. This is evidenced by keywords like "*magnetic separation*" and "*iron recovery*" in the yellow cluster or "*iron*" in the blue cluster. Residue's high iron content (up to 60 %) has inspired numerous studies into methods for iron recovery [45], mainly by solid-state reduction-magnetic separation and smelting [46,47]. The blue cluster shows that the mineral components of the residue present a clear value recovery opportunity. Iron, titanium, or silicon is the highest proportion by weight, but the highest value is in the extraction of trace amounts of high-value rare earths or precious metals. The growing demand for rare earths for many technological applications has increased interest in their recovery from residue. Furthermore, the terms "*acid leaching*" and "*solvent extraction*" appears in this blue cluster, as rare earths extraction is typically done by acid-leaching, followed by solvent extraction [48]. Despite work on rare earth extraction was done in the 1980s and patented in the early 1990s, remains an interesting area which is no closer to being implemented.

Red mud ability to absorb and retain metals has been widely studied, particularly from mine or mineral processing wastewater, as evidenced by the keywords forming the green cluster. Many studies show the effectiveness of red mud in removing phosphorus from water [49]. Additionally, there are many co-occurrences of the keyword "*heavy-metals*" in this cluster, with a high number of studies showing red mud's potential for removing heavy metals from metals-contaminated wastewater [50,51].

The analysis on the evolution of red mud research keywords between 2014 and 2019, as depicted in Fig. 6b. This analysis is relevant to gain insights into the direction of future research in this field. This term signifies one of the earliest applications of red mud, yet significant utilization in terms of tonnages remains limited. Over the years, there is a noticeable shift towards keywords related to leaching and recovery, which is not surprising given the significant quantity of valuable metals, including critical metals, present in red mud and their geo-economic implications. In more recent years, terms such as geopolymer, cement and rare-earth elements highlights their growing importance and potential as the most relevant applications in the near future. Being actually the usage in Portland cements the largest usage. Therefore, geopolymers, rare earths recovery, scandium, and adsorption are enticing areas for researchers; however, nowadays they require significant investment to compete with alternative routes and processes.

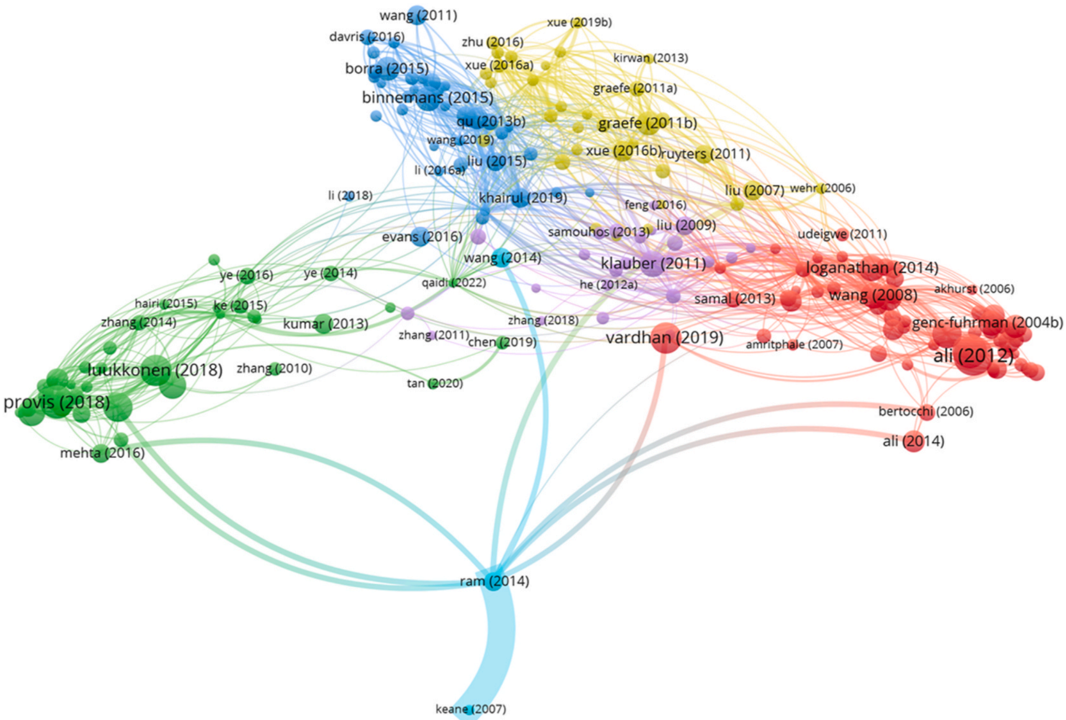

Fig. 7. Bibliographic coupling of the top 200 documents.

Table 5
30 most cited papers in the red mud research topic, from 1966 to 2022.

Authors	Title	Journal	Cites	Year	Country Affiliation	Type	Ref.
I. Ali	Low cost adsorbents for the removal of organic pollutants from wastewater	Journal of environmental management	824	2012	India	Review	[39]
A. Bhatnagar	Fluoride removal from water by adsorption-A review	Chemical Engineering journal	784	2011	Portugal	Review	[59]
S. Wang	Removal of dyes from aqueous solution using fly ash and red mud	Water Research	713	2005	Australia	Paper	[44]
V. K. Gupta	Process development for the removal of lead and chromium from aqueous solutions using red mud - an aluminium industry waste	Water Research	638	2001	India	Paper	[60]
S.H Lin	Adsorption of phenol and its derivatives from water using synthetic resins and low-cost natural adsorbents: A review	Journal of environmental management	621	2009	Taiwan	Review	[43]
J. L. Proves	Alkali-activated materials	Cement and concrete research	608	2018	United Kingdom	Paper	[53]
K. Pirkanniemi	Heterogeneous water phase catalysis as an environmental application: a review	Chemosphere	586	2002	Finland	Review	[61]
T.A. Kurniawan	Comparisons of low-cost adsorbents for treating wastewaters laden with heavy metals	Science of the total environment	554	2006	China	Review	[50]
A. Mittal	Adsorption of hazardous dye crystal violet from wastewater by waste materials	Journal of colloid and interface science	554	2010	India	Paper	[62]
T. Luukkonen	One-part alkali-activated materials: A review	Cement and concrete research	532	2018	Finland	Review	[52]
K.H. Vardhan	A review on heavy metal pollution, toxicity and remedial measures: Current trends and future perspectives	Journal of molecular liquids	512	2019	India	Review	[26]
V. K. Gupta	Adsorption studies on the removal of hexavalent chromium from aqueous solution using a low cost fertilizer industry waste material	Journal of colloid and interface science	495	2010	India	Paper	[63]
L. Zeng	Adsorptive removal of phosphate from aqueous solutions using iron oxide tailings	Water Research	485	2004	Canada	Paper	[64]
X. Y. Zhuang	Fly ash-based geopolymer: clean production, properties and applications	Journal of cleaner production	449	2016	China	Review	[40]
M. Ahmaruzzaman	Industrial wastes as low-cost potential adsorbents for the treatment of wastewater laden with heavy metals	Advances in colloid and interface science	444	2011	India	Paper	[65]
G. Power,	Bauxite residue issues: I. Current management, disposal and storage practices	Hydrometallurgy	441	2011	Australia	Paper	[10]
L. Zhang	Production of bricks from waste materials–- A review	Construction and building materials	401	2013	U.S.A.	Review	[41]
J. He	Synthesis and characterization of red mud and rice husk ash-based geopolymer composites	Cement & concrete composites	399	2013	U.S.A.	Paper	[66]
S. B. Wang	Novel applications of red mud as coagulant, adsorbent and catalyst for environmentally benign processes	Chemosphere	377	2008	Australia	Review	[67]
D. Kossoff	Mine tailings dams: Characteristics, failure, environmental impacts, and remediation	Applied geochemistry	367	2014	United Kingdom	Review	[11]
C. Klauber	Bauxite residue issues: II. Options for residue utilization	Hydrometallurgy	364	2011	Australia	Paper	[56]
A. Papua	Solid waste generation in India and their recycling potential in building materials	Building and environment	362	2004	India	Paper	[68]
P. Loganathan	Removal and Recovery of Phosphate From Water Using Sorption	Critical reviews in environmental science and technology	361	2014	Australia	Review	[54]
V. K. Gupta	Removal of rhodamine B, fast green, and methylene blue from wastewater using red mud, an aluminum industry waste	Industrial & engineering chemistry research	357	2004	India	Paper	[69]
W. Huang	Phosphate removal from wastewater using red mud	Journal of hazardous materials	351	2008	Australia	Paper	[49]
K. Binnemans	Towards zero-waste valorisation of rare-earth-containing industrial process residues: a critical review	Journal of Cleaner Production	349	2003	Belgium	Review	[6]
A. R. Hind	The surface chemistry of Bayer process solids: a review	Colloids and surfaces a-physicochemical and engineering aspects	348	2008	Australia	Paper	[70]
H. G. Fuhrman	Adsorption of arsenic from water using activated neutralized red mud	Environmental science & technology	330	2004	Australia	Paper	[71]
V. K. Gupta	Aluminum(III) selective potentiometric sensor based on Morin in poly (vinyl chloride) matrix	Talanta	324	2007	India	Paper	[72]
C.W. Grey	Field evaluation of in situ remediation of a heavy metal contaminated soil using lime and red-mud	Environmental pollution	323	2006	United Kingdom	Paper	[73]

3.1.4. The most impactful publications

After analysing the main research topics through the keywords in Fig. 6, the natural question that may arise is, which are the most relevant publications? Therefore, this section is focused on the analysis of the most impactful and relevant publications. Firstly, the most impactful publications are analysed according to the number of citations. Secondly, the analysis focuses on bibliographic coupling to determine the most relevant publications.

3.1.4.1. Bibliographic coupling. Bibliographic coupling through co-citations allows the establishment of similarity between publications, according to the references in common. Accordingly, it allows us to identify the most relevant publication on a specific topic identifying the main thinkers. Due to the sheer volume of publications, often in the course of research, one cannot be fully aware of all the advancements made by researchers from around the world. Consequently, it is not uncommon to come across similar publications. This is why this metric is of particular interest. Fig. 7 shows the bibliographic coupling of documents related to red mud, which reveals the most impactful publications. Six main clusters have identified: yellow group (1), red group (2), blue group (3), green group (4), violet group (5), and (6) cyan group. The green (4) cluster is led by the publication *"One-part alkali-activated materials: A review"* by Luukkonen, T. et al. (2018) [52], focused on a review of activated materials as potential alternatives to ordinary portal and, where red mud is one of the most promising alternatives as a by-product. According to their intensity, these publications have a great impact on this sub-topic research: alternative materials for building applications. Other two impactful publications in the green group are the performed by Provis, J. *"Alkali-activated materials"* (2018) [53], with the highest clustering coupling.

Otherwise, the three publications performed by Binnemans, K. et al. (2015) *"Towards zero-waste valorisation of rare-earth-containing industrial process residues: a critical review"* [6], Liu, YJ. et al. (2015) *"Hidden values in bauxite residue (red mud): Recovery of metals"* [30], and Khairul, M.A. et al. (2019) *"The composition, recycling and utilization of Bayer red mud"* [54] are the most relevant of the blue (3) cluster. The publications of this cluster are vocalizing mainly on the revalorization and recovery of valuable metals of red mud. The red cluster (2) has more bibliographic coupling according to the number of publications than the other ones. This cluster is led by Vardhan, K.H. et al. (2019) *"A review on heavy metal pollution, toxicity and remedial measures: Current trends and future perspectives"* [26], and *"Low cost adsorbents for the removal of organic pollutants from wastewater"* by Ali, I. et al. [39] (2012) and finally the study performed by Loganathan, P. Ell et at. (2014) [54]. Denote that the publication by Vardhan, K.H. has the lowest centrality related to their group. This is not surprising due to being a review paper and the scope of the topic. In this cluster are more publications related to red mud disposal and management, notwithstanding the main topic of this cluster is about one of the most potential applications of red mud as an adsorbent material.

The yellow cluster (4) is the most interconnected group and is led by the publications *"Bauxite residue issues: I. Current management, disposal and storage practices"* by Graefe, M. et al. (2011) [10] and *"A review of the characterization and revegetation of bauxite residues (Red mud)"* by Xue, S. et al. (2016) [55]. This cluster is focused mainly on the final management and disposal of red mud. The violet cluster (5) has the lowest centrality and therefore the lowest bibliographic coupling, has the most relevant paper been the performed by Powe, G. et al. (2011) [56]*"Bauxite residue issues: II. Options for residue utilization"*. Finally, there is the cyan group. This group shows the lowest bibliographic coupling and very high decentralization with other cluster groups. Mainly, the publications relate to less studied applications like the publication by Ram, L.C. et al. [57] (2014) *"Fly ash for soil amelioration: A review on the influence of ash blending with inorganic and organic amendments"*, or the performed by Keane, M.A. et al. (2007) *"Catalytic Transformation of Waste Polymers to Fuel Oil"* [58]. This last publication is one of the examples with which special care must be taken. This publication has been incorporated into the database because it incorporates the keyword plus "red mud" added by web of science, but the paper itself does not comply with the criteria. Therefore, sometimes the automatically generated keyword plus must be careful since they are generated based on each paper reference.

3.1.4.2. The most impactful publications. The 30 most relevant publications are listed in Table 5, with information about the main author, the title of the publication, the journal where it is published, the number of citations, year of publication, the country affiliation of the main author, type of publication and the reference. The time-lapse between the most cited papers-reviews is 2001–2019, where 2223 documents are papers and 19 review papers. It is interesting to highlight two papers published in 2019, *"A review on heavy metal pollution, toxicity and remedial measures: Current trends and future perspectives"* [26] with 512 cites reached in less than 2 years, denoting a high scientific interest.

It is remarkable that there is a publication that is a collection of 4 vol that address different aspects of bauxite residues, as more recommendable sources: *"Bauxite residue issues: I. Current management, disposal and storage practices"* [10], *"Bauxite residue issues: II. Options for residue utilization"* [56], *"Bauxite residue issues: III. Alkalinity and associated chemistry"* [74] and *"Bauxite residue issues: IV. Old obstacles and new pathways for* in situ *residue bioremediation"* [7].

Table 6
Top 10 of the journals that publish red mud research: Journal name, number of papers (N°P), red mud h-index (H index), number of citations (N°C), performance ratio (PR), Impact factor 2021 (IF2021) and quartile score (QS).

Journal	N°P	H Index	N°C	PR	IF2021	QS
Construction and building materials	177	44	5662	32.0	6.141	Q1
Journal of cleaner production	159	43	6167	38.8	9.297	Q1
Journal of hazardous materials	150	58	9565	63.8	10.588	Q1
Environmental science and pollution research	86	25	1743	20.3	4.223	Q2
Hydrometallurgy	81	30	3717	45.9	4.156	Q1
Materials	67	10	415	6.2	3.478	Q2
Chemical engineering journal	58	33	3735	64.4	16.774	Q1
Science of the total environment	56	24	2103	37.6	7.963	Q1
Materials today - Proceedings	53	10	290	5.5	1.460	Q3
Minerals engineering	52	22	1781	34.3	4.765	Q1

*N°P: Number of publications, C: Number of citations, PR: Performance ratio (C/N°P), IF: Impact factor (web of science), Q.S.: Quartile Score (S.J.R.)

3.1.5. Most impactful sources for red mud research

Knowing the main journals where research on red mud is published is of great help for researchers or people interested in the subject. In this section, the most relevant journal based on the number of publications were analysed. Table 6 lists the top 10 journals, their number of publications (N°P), the H-index related to this topic, the number of citations, the performance ratio, the impact factor, and the quartile score based on SJR (Scimago Journal & Country Rank). The journal *Construction and Building Materials* from Elsevier published the highest number of papers related to red mud, a total of 177 publications at the end of 2022, becoming one of the most relevant journals on this topic. Otherwise, the most cited journal is the *Journal of Hazardous Materials* with 9565 cites, ranked in the third position, and reflected in their highest performance ratio together with the *Chemical Engineering Journal* of 63.8 and 64.4, respectively. It is remarkable the high impact factors of the journals, in special of the *Journal of Hazardous Materials* (10.588) and *Chemical Engineering Journal* (16.774), denoting the high interest and quality research that are doing researchers in this topic. In addition, of the top 10 journals, 7 are for quartile 1. In more detail, the overall 58 % of all the publications are published on Q1 journals, 18 % in Q2, 7 % in Q3 and the 16 % in other quartiles.

4. Conclusions

The investigation of red mud has attracted significant global attention, primarily led by countries such as China, India, and Australia—major players in the global aluminium production area. The literature on red mud research has undergone substantial growth since 1966, evidenced by environmental concerns, amassing over 4757 publications to date. Notably, China, India, Australia, the USA, and Turkey are at the forefront of research efforts, a fact unsurprising given the longstanding history of these nations as substantial contributors to the metal industry. Extensive bibliography covers various aspects of red mud, including its applications, management, mining processes, disposal, and the extraction of valuable metals.

A temporal analysis of primary keywords in red mud research hints at an impending focus on geopolymers. Additionally, there is a notable interest in extracting valuable and critical metals from red mud. However, the current state of extractive and separation processes for these metals remains relatively low on the Technology Readiness Levels (TRLs), necessitating further efforts to develop efficient separation routes. The study also illuminates the main journals, authors, and publications, providing a valuable resource for high-quality information and international collaboration among institutions and researchers. This bibliometric perspective on red mud research provides an overview of red mud research available on major scientific platforms and a search tool for relevant information.

In conclusion, the analysis of red mud literature unveils a robust global interest, with key contributions from 80 countries and over 10,000 researchers, resulting in more than 1100 publications across scientific journals. Finally, this comprehensive bibliometric analysis not only highlights the current state of the field but also serves as a valuable decision-making tool for researchers and policymakers, identifying trends, gaps, and avenues for future exploration. This foster sustainable advancements in the by-products of the aluminium industry.

Funding

This research was partially funded by the Gobierno de Navarra (contract 0011-3998-2021-000006) corresponding to the ERA-MIN project JTC-2021_131 “Utilization of aluminium bearing raw materials for the production of aluminium metal, other metals and compounds” (ABTOMAT).

Researchers from University of Barcelona belongs to DIOPMA group. DIOPMA is a certified agent TECNIO in the category of technology development of the Government of Catalonia. The authors would like to thank the Catalan Government for the quality accreditation given to their research groups DIOPMA (2021 SGR 00708).

Data availability statement

The data has not been deposited in a publicly accessible repository but will be made available upon reasonable request.

CRediT authorship contribution statement

Adela Svobodova-Sedlackova: Writing – review & editing, Writing – original draft, Visualization, Resources, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alejandro Calderón:** Writing – review & editing, Software, Methodology, Data curation. **A. Inés Fernandez:** Writing – review & editing, Visualization, Methodology, Data curation. **Josep Maria Chimenos:** Writing – review & editing, Visualization, Supervision, Data curation. **Carlos Berlanga:** Writing – review & editing, Visualization, Supervision. **Onuralp Yücel:** Writing – review & editing, Visualization, Supervision. **Camila Barreneche:** Writing – review & editing, Visualization, Supervision, Funding acquisition. **Rafael Rodriguez:** Writing – review & editing, Visualization, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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