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Review

Bibliometric Review of Magnetorheological Materials

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Abstract: The findings and technological developments related to intelligent materials are increasingly attracting the attention of scientists. One such field is that of magnetorheological (MR) materials. Scientific studies on MR materials have been carried out to determine the performance and characteristics of, for example, MR dampers, MR elastomers, and MR foams. To the best of the authors' knowledge, there has been no statistical discussion in the form of bibliometric analyses of developments in the field of MR materials in the last ten years. This is fascinating, considering that bibliometric studies have considerable impacts and contributions, such as studies on the growth of research patterns, avoiding the repetition of research topics, and analyzing future research. This also supports the future sustainability of the topic of MR materials, helping to bridge the gap that has probably existed since the introduction of MR materials. The relationship between the authors' scientific research, domestic and global collaborations, and the evolution of themes over the last few years is also shown in this analysis. Thus, this study aimed to fill the gap in such materials by conducting a bibliometric analysis of 1830 articles related to MR materials published over the last 10 years. The results indicated that the field of MR materials has exhibited good growth. The introduction of MR fluid materials to new types of MR materials is still in the early stages of research, such as in applications with MR foam. Further analysis showed that there is a connection and dominance of scientific publications related to MR technology. Furthermore, based on bibliometric analysis, dominant theme changes in the area of MR elastomers, particularly related to carbonyl iron particles and MR polishing, is seldom mentioned, as is also the case for MR gels, MR foam, and MR grease. However, the discussion of new MR materials is a good opportunity to promote developments in the field of MR materials.

Keywords: magnetorheological materials; magnetorheological; MR materials; MR fluids; MR elastomers; bibliometric

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1. Introduction

Material technology is increasingly showing progress and benefits for various applications. In addition, the research and applications of magnetorheological materials are advancing. Material technology has significant influences on human civilization [1–3]. One type of material that is still under development and research is magnetorheological material. Magnetorheological materials are advanced composites that change their properties due to external magnetic field stimuli. These materials have been developed and researched in various industrial fields. The magnetorheological properties of these materials are considered very good in terms of their response speed and accuracy [4]; these materials are widely used as sensors, actuators, and controllers of a system [5–7]. MR materials have different time

responses depending on the type; one type of MR fluid, MRF-132DG (Lord Corp., North Carolina USA), has a response time in the range of 0.4–1 ms [8]. As for MR elastomers, in one study, the response time achieved by MRE was under ten milliseconds [9]. Furthermore, in the case of MR grease, the response time achieved was in the range of 2–6 s [10]. Recently, intelligent materials have become increasingly popular and have attracted significant attention for various engineering applications. In addition to magnetorheological materials, electro-rheological materials, shape-memory materials, piezoelectrics, and electroactive materials have been the focus of research and development. The speed of change in the properties of MR materials due to external stimuli is a significant value that dominates the development of all types of intelligent materials [11–14]. MR materials usually consist of micron-sized [15] (usually 3–5 μm) iron or iron particles dispersed in various carrier media, such as liquids, foams, elastomers [2,16], greases, polymer gels, and plastomers. The field of magnetic materials has also reached the stage where nano-materials, such as ferrofluid, are being developed [17–20]. MR materials that have been introduced thus far include magnetorheological fluids (MRFs) [21,22], magnetorheological elastomers (MREs) [23], magnetorheological grease (MRG) [24], magnetorheological plastomers (MRPs) [25], magnetorheological foam (MR foam) [2], and magnetorheological polymer gels (MRPGs) [26]. Some of these are new findings still in the early stages of research, such as MR foam, MRPG, and MRPs.

Since the introduction of MR materials by Rabinow in 1948 at the US National Bureau of Standards [21], the discovery and development of new MR materials, such as MR foam and MRPGs, has been carried out, in addition to various related studies in the field [27]. Based on records released by Scopus, there have been more than ten thousand publications as of 30 May 2022. This was determined by searching for the articles published with general keywords, such as "magnetorheological", "magnetoactive", and "magnetosensitive". With this search method, we found 13,596 relevant published articles. The large number of publications related to the research and development of MR materials (reaching 262 articles per year) shows the considerable amount of estimated research and development carried out on MR materials. This amount is, of course, only within the limits recorded on Scopus. The Scopus database was used in this study because it includes more high-quality articles than other databases. In addition, Scopus provides complete data needed for statistical analysis. The development of related field publications in the Scopus database is also very good; thus, it is hoped that the results of the processed data will be closer to the existing statistics. Other databases do not provide easy access and completeness of data, which is why Scopus was preferable.

In this case, the initial search was carried out in each specific field with limited records of published articles on Scopus, revealing that as many as 7400 papers have been published with the search term "magnetorheological fluids". Moreover, about 1600 articles have been published under the term "magnetorheological elastomers". Furthermore, approximately 110 papers have been published with the key term "magnetorheological grease". In addition, 108 articles were found relating to "magnetorheological foam". Finally, 36 articles were published pertaining to "magnetorheological plastomers". This is in line with the fact that MR fluids were the first inventions that were later developed in various applications, while MR foams, greases, and plastomers are new inventions still in the early stages of research.

This paper presents an introduction to simplifying the work in this field. With the search method based on keywords according to the field, various benefits can be found, such as the level of popularity of the development of MR materials, the rapid rate of progress in MR materials, and overall competitiveness. This study presents the importance of bibliometric analysis as a comprehensive review of bibliometric magnetorheological materials based on data published on Scopus. Bibliometric reviews relating to MR materials have never been presented before. Moreover, bibliometric reviews are beneficial, such as for analyses of improvements and refinements of knowledge, historical records of research development, and library science knowledge [28–30]. Such studies have significantly

contributed to education, research, and advanced technological development. Bibliometric analysis also makes it possible to determine trends or patterns of growth related to the topic being researched by scientists, and the shortcomings and repetitions found in the research of related fields [31].

Case studies that have been carried out related to MR materials have presented evidence for the development of smart materials technology. However, the studies mentioned above have not examined bibliometric variables. Quantitative variables of a particular research flow can be identified using bibliometric facilities [32]. This method determines necessary information about a particular research topic, including authors in the field, the number of publications, keywords that reveal interactions between variables (policies, assets, and governance), and national data [33]. It also enables the application of science mapping techniques [34]. We performed bibliometric analysis using several supporting tools, such as VOSviewer, RStudio, and Biblioshiny. Biblioshiny is a valid tool for use in bibliometric analysis. This web interface application can be used to create conceptual maps and trend topic figures. This study was limited by the fields related to magnetorheological materials; thus, in the identification process, the limits used were determined based on keywords, types of articles, and the number of citations to related articles [35–37]. Time constraints were also present, related to the novelty and progress of research on magnetorheological materials. In addition to these limitations, the data collection process for published articles was only carried out on the Scopus database. Therefore, the results of this study were motivated by the publication of articles on Scopus. The sampling process was performed based on extracting the title and the author, and has limitations that also arose due to the chosen database. Using the Scopus database, a sample of less than 2000 needed to be obtained to optimize the analysis process. This limit is greater than what we expected for this research.

To achieve the research objectives, several questions were answered by conducting a bibliometric analysis process, such as: What is the trend or pattern of growth in material technology research in the specific field of MR materials? What information can be found from the development of research in that field? What are the future directions and possible findings that can be obtained in this field, and what are the relationships between articles and authors of articles in that field? The objectives of this bibliometric analysis are quite interesting, including providing bibliometric information on the 200 most influential scientific studies of magnetorheological materials based on the Scopus database; bibliometric analysis using VOSviewer, RStudio, and Biblioshiny software; and determining the relationships and influences on the sample taken.

2. Materials and Methods

2.1. Related Studies

Other researchers have performed analyses using bibliometric methods in various disciplines, such as in the materials and energy fields. These analyses generally use bibliographic data available on online databases (Scopus, Web of Science, Google Scholar, etc.). Bibliometric analysis enables the scientific study and a complete view of the field of library studies. In addition, the accessibility of bibliographic data has increased the number of bibliometric reviews in various disciplines. Therefore, the analytical method is often applied to multiple studies. However, no published records show bibliometric analysis of the field of magnetorheological materials. Thus, this study is the first example of bibliometric analysis conducted for MR materials.

This material was first introduced in 1948, with a subsequent publication record of more than 10,000 related scientific studies; therefore, the method of this study was deemed to be very feasible. Furthermore, similar bibliometric analyses have been carried out in other research fields, as shown in Table 1. The research data collection in Table 1 was also part of a simple bibliometric analysis of different substances, but was carried out using a similar analytical method. Therefore, these studies can be used as a reference to perform the bibliometric analysis of magnetorheological materials.

Table 1. List of bibliometric analysis studies in the field of materials science—Scopus database.

Authors	Presented Study
Zhu, S et al. (2020) [38]	15 Years of Small: Research Trends in Nanosafety
Merigo, J. M et al. (2018) [39]	Fifty years of Information Sciences: A bibliometric overview
Cheng, Y et al. (2020) [40]	A bibliometric analysis for the research on laser processing based on Web of Science
Zhu, S et al. (2021) [41]	A Bibliometric Analysis of Advanced Healthcare Materials: Research Trends of Biomaterials in Healthcare Application
Zhang, M et al. (2016) [42]	A bibliometric analysis of biodiesel research during 1991–2015
Jiao, Y et al. (2021) [43]	A scientometric review of biochar preparation research from 2006 to 2019
Davarazar, M et al. (2021) [44]	Engineered nanomaterials for (waste) water treatment—A scientometric assessment and sustainability aspects
Maier, A. and Manea, D. L. (2022) [45]	Perspective of Using Magnesium Oxychloride Cement (MOC) and Wood as a Composite Building Material: A Bibliometric Literature Review

The data summarized in Table 1 were searched based on the keywords "bibliometric analysis of material sciences", and were limited to articles and review papers, as well as the subject areas of engineering and material science in the Scopus database. These references are just a few examples of the 138 articles that appear on the Scopus database.

2.2. Data Preparation

In bibliometric analyses, library data are critical. Data providers' accuracy, completeness, and accessibility are some of the main factors for data processing (the sample used). In this case, the processing was performed using VOSviewer, RStudio, and Biblioshiny software. These applications require special data formats, such as files with CSV and BibTeX extensions, to be analyzed, such that outputs in the form of linkages between authors, linkages of articles, etc., can be obtained. Scopus provides these formats, being a library database of published scientific research, which significantly simplifies the bibliometric analysis process. However, there is an optimal limit for samples taken from the Scopus database [46]. The optimal number of CSV and BibTeX file samples that can be taken from the Scopus database is limited to only 2000 samples. This dataset allows users to access all elements of authorship, such as citation information, bibliographic information, abstracts and keywords, financing details, and other information (references used, trade names, manufacturers, accession numbers, and chemicals). Samples downloaded in CSV and BibTeX format can then be processed in VOSviewer and Biblioshiny. In comparison, RStudio is a terminal and console application that is used to create libraries and open the Biblioshiny platform. It allows users to access a desired collection of scientific work.

VOSviewer is a software tool for creating maps based on network data and visualizing and exploring these maps. One of the functions of this program is to create maps based on network data. Creating maps based on existing networks is generally possible, as is building a network in advance. For example, VOSviewer can be used to build a network of scientific publications, scientific journals, researchers, research organizations, countries, keywords, or terms. Items in this network can be linked by co-authorship, co-occurrence, citation, bibliographic coupling, or co-citation links. To build the network, bibliographic database files (i.e., Web of Science, Scopus, Dimensions, Lens, and PubMed files) and reference manager files (i.e., RIS, EndNote, and RefWorks files) can be provided as inputs to VOSviewer. Alternatively, VOSviewer can download data via APIs (i.e., Crossref API, OpenAlex API, Europe PMC API, etc.) [47–49].

RStudio is an integrated development environment (IDE) for "R". It includes a console, a syntax highlighting editor that supports direct code execution, and tools for planning, history, debugging, and workspace management. In this console, Biblioshiny can be accessed, which is then used to process library study data. Using Biblioshiny or VOSviewer requires databases with specific file extensions such as CSV and BibTeX. Figure 1 depicts a general flow of bibliometric analysis study methodology adapted from Aria and Cuccurullo (2017) and Firdaus et al. (2019) [35,50].

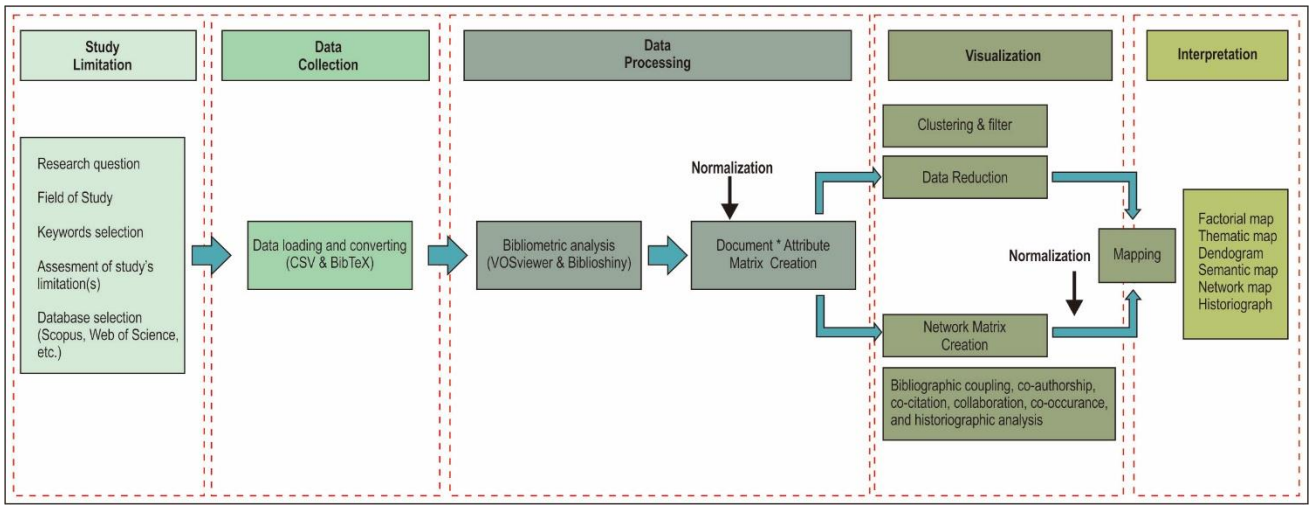

Figure 1. Bibliometric analysis methodology flow. * means the documents can be processed as the creation of the user.

The analysis of bibliometric results began by providing critical information related to the study, such as records of the number of published articles, authors, and collaborations. Furthermore, the investigation considered detailed information about the author, the relevance of the authors, citations, the authors' collaboration, and the study's country. Each of the categories mentioned above was thoroughly analyzed using the article type, annual scientific production, source growth, number of articles per author, author dominance, keywords used by authors, factorial map of articles with the highest contribution, article production in a country, country collaboration maps, state collaboration networks, and thematic, semantic, and historiographic maps [51].

Descriptive analysis was one of the approaches used in this research. This technique aims to describe the direction of research developments in magnetorheological materials. Meanwhile, bibliometrics was used to map the history of research that has been conducted in this field. Two approaches were combined to determine how advanced the research of magnetorheological materials is, and the acknowledged shortcomings in the field. Thus, there are opportunities for other research topics in the field of magnetorheological materials. This can be exemplified with one example output of the bibliometric analysis, namely, the development of keyword usage over the last 20 years. The collection of information related to articles published from 2013 to 2022 is described in Table 2. However, there were many associated papers published in the Scopus database in this period, i.e., 1830 articles. This was already included in the limitations, in addition to the keywords, year of publication, and type of article. The articles obtained are the results of searches and limitations given to the Scopus database. The keywords used in this analysis were those for magnetorheological materials and associated synonyms obtained through Scopus: (TITLE-ABS-KEY (magnetorheological AND materials) OR TITLE-ABS-KEY (magnetoactive) OR TITLE-ABS-KEY (magnetosensitive)) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013)) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (DOCTYPE, "ar")).

Table 2. Main information about publication data in the field of magnetorheological materials.

Description	Results
Main information about data	
Timespan	2013:2022
Sources (journals, books, etc.)	597
Articles	1830
Average years from publication	3.6
Average citations per articles	11.81
Average citations per year per article	2.391
References	56,706
Article types	
Article	1830
Article contents	
Keywords plus (ID)	9864
Author's keywords (DE)	4316
Authors	
Authors	4016
Author appearances	7813
Authors of single-authored articles	45
Authors of multi-authored articles	3971
Author collaborations	
Single-authored articles	51
Articles per author	0.456
Authors per article	2.19
Co-authors per article	4.27
Collaboration index	2.23

Research in the field of magnetorheological materials was introduced in 1948. However, the earliest publication year was taken as 2013. This year was considered sufficient for conclusions to be drawn from this research. In the period sampled, one author (Choi, H. J.) [52,53] published 53 articles present in the Scopus database.

Based on Table 2, the number of articles recorded from 2013 was from 597 sources, such as journals and books, with a total of 56,706 references used. Therefore, the average number of citations for each article recorded in that period was 11.81. Meanwhile, the average number of citations per year per article was 2391. The number of related publications for each year is shown in Figure 2.

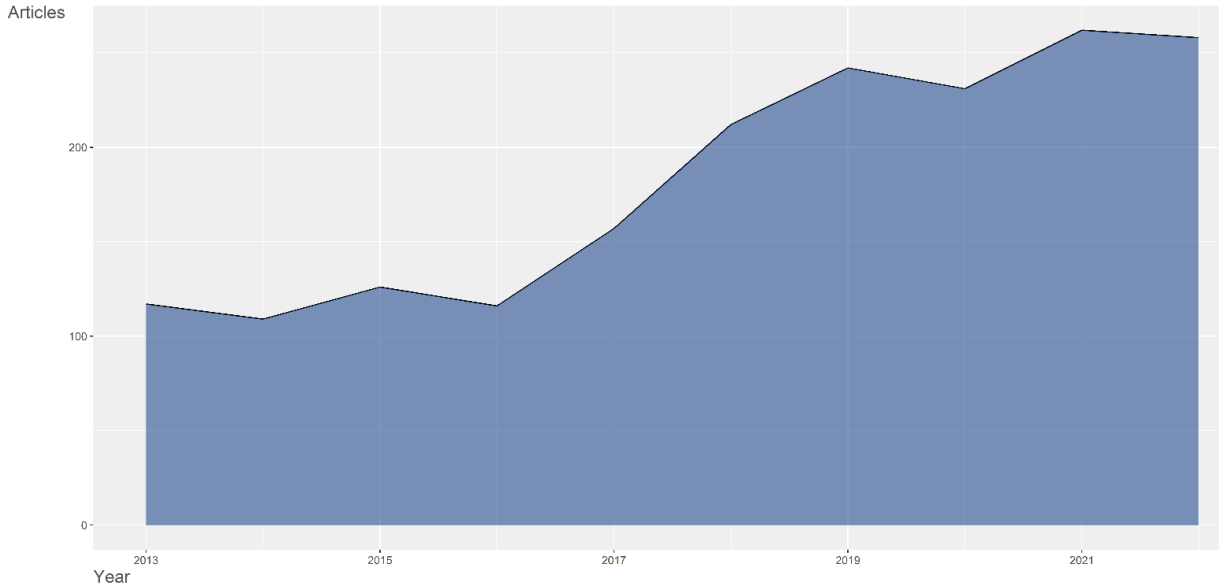

Figure 2. Annual scientific production.

The field of magnetorheological materials publications has shown significant improvement, based on Figure 2. For example, in 2019, there were 241 published articles. Even though in specific years, the number of papers decreased, the trend of the graph above exhibits a very significant increase; thus, there were 262 articles to be published in 2021. In addition, information related to the authors and their collaborations is presented in Table 2 above. From a total of 1830 articles, 4016 authors contributed to this field, with a collaboration index of 2.23. Fifty-one articles were reported as being from a single author.

2.3. Author Domination

An author's domination data were obtained by assessing the number of articles published and the citations received. The number of articles and citations can be seen based on the annual production and within a specified time [54]. The Biblioshiny tool was used in this bibliometric analysis to help determine an author's track record in the magnetorheological materials field from 2013 to 2022. Figure 3 shows the results of each author's bibliometric analysis related to this field. This is a record of the 35 authors with the highest number of article publications for the period 2013–2022. Choi, Hyoung Jin [55], from the Department of Polymer Science and Engineering, Inha University, Incheon 402–751, South Korea, has the highest number of articles. Based on Scopus data, Choi, Hyoung Jin published 828 articles on Scopus. These publications were dominated by the research topic "Nanofluidics; Rheometers; Electric Stimuli" in 52 articles, and "Magnetorheological Fluids; Liquids; Clutches" in 50 papers. This was in line with the results of the bibliometric analysis, in which Choi, Hyoung Jin's research focus was in the area of magnetorheological materials. The next most significant number of scientific studies was attributed to Choi, Seung Bok [56–58] from the Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam. Choi, Seung-Bok has a comprehensive publication record of 845 articles, with 54 articles on "Magnetorheological Damper; Semi-Active Control; Damping" and 52 in the research topics "Magnetorheological Fluids; Liquids; Clutches." The following highest contributor was Mazlan, Saiful Amri [59–61] from Universiti Teknologi Malaysia Kuala Lumpur, Kuala Lumpur, Malaysia. Mazlan, Saiful Amri mostly published research in the topics of "Elastomers; Insulators; Magnetic Field", with 52 articles, and "Magnetorheological Fluids; Liquids; Clutches", with 37 articles.

In addition to using Biblioshiny, VOSviewer was used to analyze author dominance. First, VOSviewer was used to determine the distribution of authorship in the form of a distribution map based on the number of published articles, author or article links, and citations carried out in the specified period [62]. Figure 4 shows the analysis results of the distribution map of the articles obtained using VOSviewer.

2.4. The Use of Keywords

The use of keywords is an essential factor in performing scientific studies. Keywords are usually chosen based on the topic of discussion in the researched scientific study. In addition, keywords are usually based on the most frequently used words. The selection of keywords is performed to make it easier for authors and other readers to find sources of scientific references that will suit their needs. In general, keywords for every scientific study with the same discussion theme will be the same as in this bibliometric analysis. The analysis was carried out based on the keywords used by the authors, and the most suitable words that appeared with the keywords we entered in the search engine. Appropriate keywords also affect how many scientific papers are read, referenced, or downloaded. Thus, an author's index can also be said to be influenced by the keywords [63].

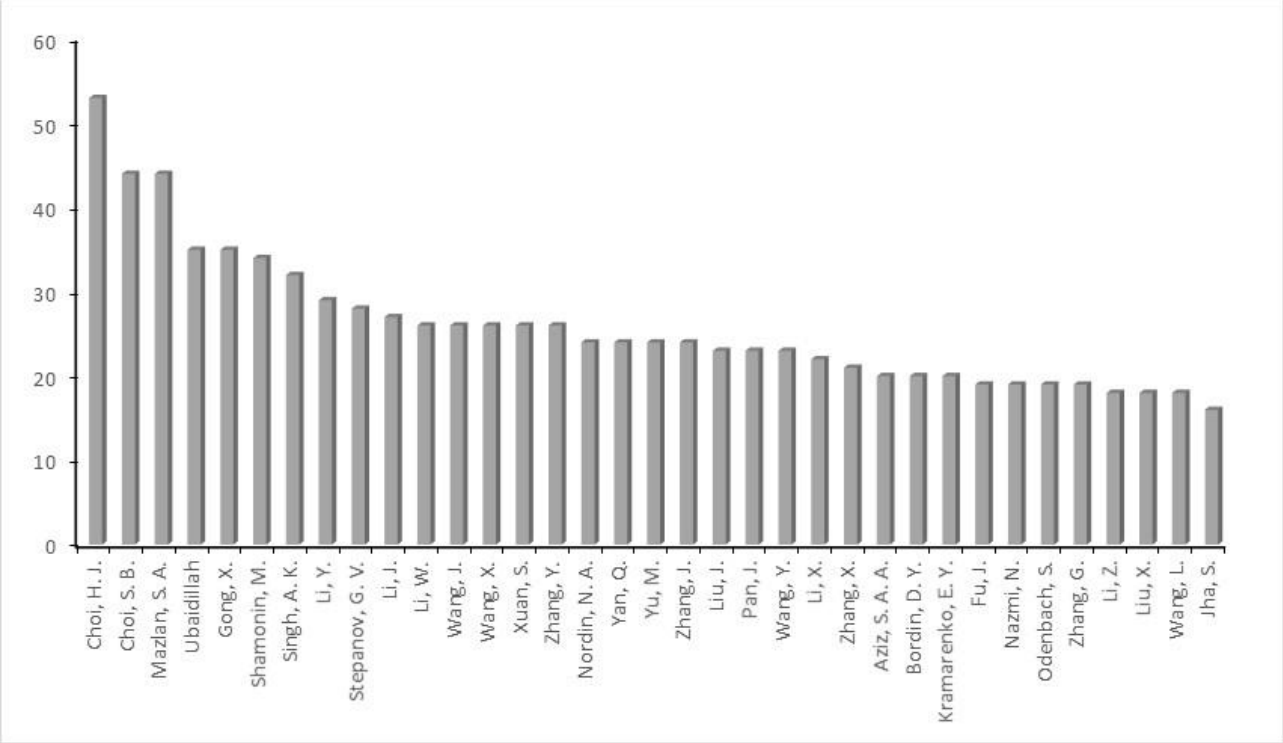

Figure 3. Most relevant authors in the magnetorheological materials field.

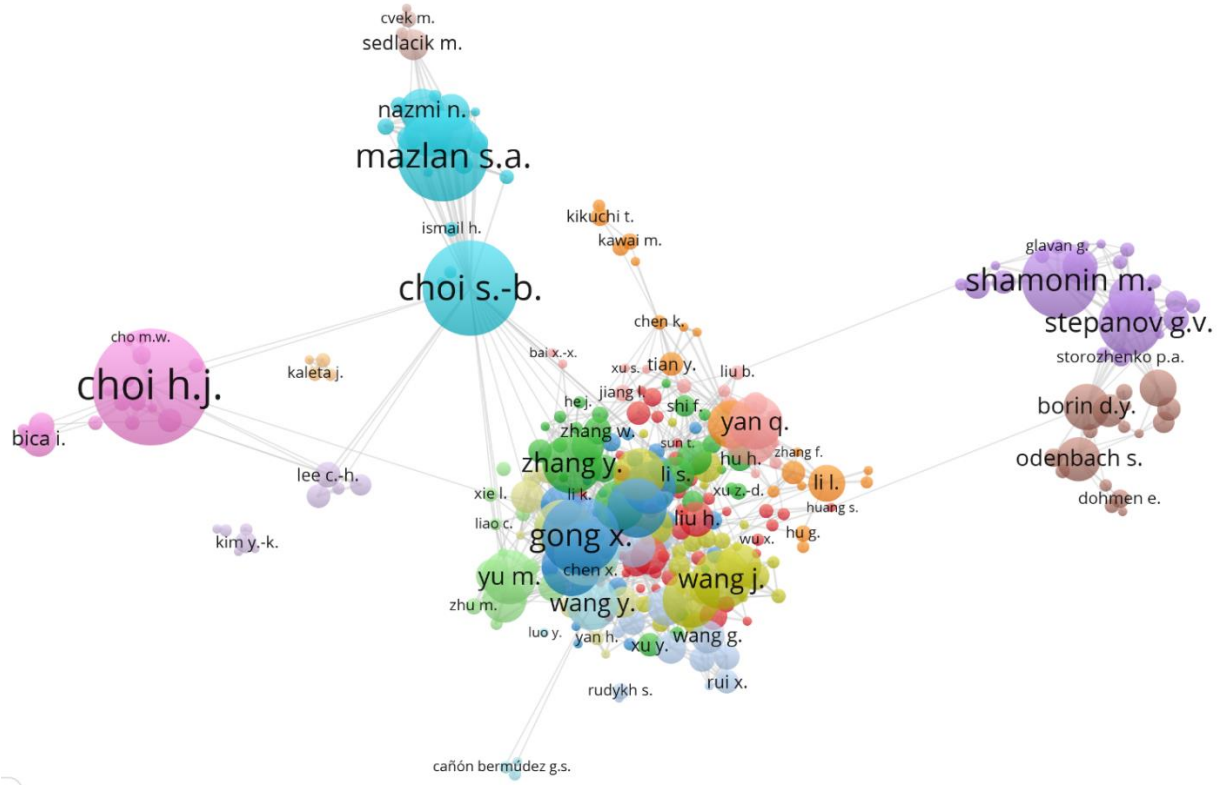

Figure 4. Results of the author's distribution map using VOSviewer.

In the field of MR materials, several keywords tend to be used frequently. These keywords are for the final analysis. In this field, the words "magnetorheological", "magnetoactive", and "magnetosensitive" appear the most frequently. This is evidenced by

the 13,493 articles found without any restrictions in the Scopus search. In the field of MR materials, the word "magnetorheological" appeared most often in the word cloud model analysis. Meanwhile, analysis of the word tree model showed that the use of keywords is more specific to its implementation. In this case, "magnetorheological elastomer" and "magnetorheological fluid" were the most dominant terms. In addition, the word "polishing" appeared quite a lot. This was expected because, in recent years, the discussion of MR polishing has become quite an interesting topic. However, MR fluids and elastomers have been topics of interest for a long time, and still dominate today.

2.5. Authors Impact and Collaboration

Scientific studies, whether in the article form or otherwise, of course, have values or impacts for others, such as through giving encouragement or motivation to perform similar novel research or continuing someone's work with the aim of development. In this case, several authors who have since become pioneers greatly influence the outcome in their fields for a continuation of research. The number of citations collated by the authors for one or several articles can be seen [64].

The collaboration section provides an overview of collaboration maps related both domestically and globally to the topic of MR materials. Collaboration analysis is essential, because by knowing the collaborations in this field, research actors in MR materials can determine which countries have worked together to conduct research or become competitors in developing research in a specific field. In addition, with this analysis, broad insights into research actors in this field could be used as a reference for future studies to be carried out [65].

3. Results and Discussion

Research on magnetorheological materials has progressed in the 75 years since it was first introduced in 1948. The data were obtained from the Scopus database. In this study, we reviewed bibliometric analysis methods for discussing magnetorheological materials. Based on the objectives, the bibliometric analysis in this paper represents a new contribution, considering that this method has never been reviewed in the field of MR materials. The records of over 200 published articles in the Scopus database have been processed with the help of VOSviewer and Biblioshiny software. In this case, descriptive analysis, author dominance, the use of keywords, records of collaborations both domestically and globally, and the author's influence on a field have been examined.

A descriptive bibliometric analysis performed between 2013 and 2022 shows that the number of publications fluctuates, with an increasing trend. The total number of articles recorded in that period is 1830 articles from 4016 authors. From the number of articles and authors, the ratio of articles to each author was about 0.456. Moreover, the ratio of authors to each paper was approximately 2.19. The Scopus database that was assessed showed that Choi, Hyoung Jin contributed 4.4% of the total publications in this field. This makes Choi, Hyoung Jin the most dominant author, as seen from the number of published articles on the Scopus records. However, there are interesting findings in the author's dominance rankings, namely, the Scopus database system, which may need to be more accurate in recording the author's name. This is because the author naming system in publishing articles follows a different format for each publisher. For example, one publisher may use the first name and last name format. At the same time, other publishers may use the first, middle, and last names. Thus, for exceptional cases, such as for someone who only has one name, the Scopus system cannot process this information. Thus, in Scopus records, some of the same people had two names, and the total published articles were divided. This happened to "Ubaidillah," who has one name; thus, it was found that the total number of articles published on Scopus system was either 19 or 16 articles for the same person. However, in other analyses of the Scopus system, the name "Ubaidillah" was attributed to 35 published articles. With this error, some people's dominance rank had dropped based

on whether the data were processed with Biblioshiny or VOSViewer. Here, the use of keywords was also studied based on the author's dominance [66–69].

The use of keywords was processed using the same software. The use of keywords used by each author was visualized in various forms, such as word clouds, treemaps, and word growth. These results showed that processing with different forms and different programs had similarities. Figures 5 and 6 show the results of the word clouds and treemaps. Word clouds were obtained through VOSViewer, whereas treemaps were obtained through Biblioshiny. The results that were calculated showed that the most widely used discussion approach is magnetorheological materials based on fluids, followed by elastomers. The discussion of other magnetorheological materials such as MR grease, MR foam, MR gels, and MR dust has yet to be fully elucidated. This study was an excellent opportunity to conduct research and development in this field and make an impactful contribution to the development of this sphere. The use of keywords is mainly applied in addition to MR fluids and elastomers, because MR materials with keyword limitations in the Scopus search tended more towards applications for both MR fluids and MR elastomers. The treemap shows several keywords that refer to the same purpose or meaning, such as "magnetorheological fluids", "magnetorheological fluids", "MRF", "MR fluids", and "magnetorheological elastomers".

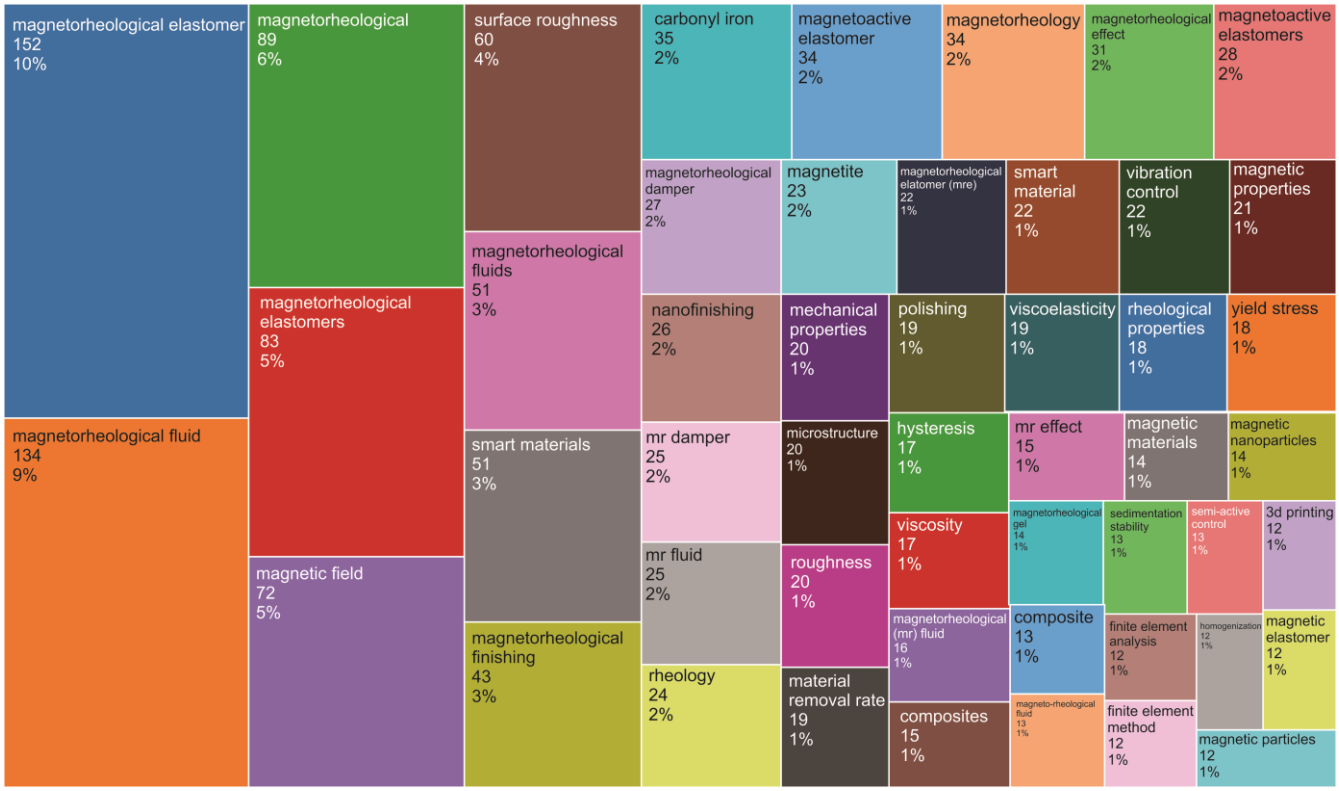

Figure 5. Treemap using author's keywords on magnetorheological materials publications.

The keywords "magnetorheological fluid" and "magnetorheological elastomer" exhibited growth over the period. Figure 7 shows the development of keywords used by the authors in the field of magnetorheological materials. The key term "magnetorheological fluid" exhibited the most significant growth and was the most dominant. These keywords are, of course, in line with the many applications that use magnetorheological fluid as the working material, such as MR dampers. The MR damper keyword appears on treemaps and word clouds with a proportion of 2%. This is sufficient to provide additional explanations that influence the dominant use of the keyword "magnetorheological fluid".

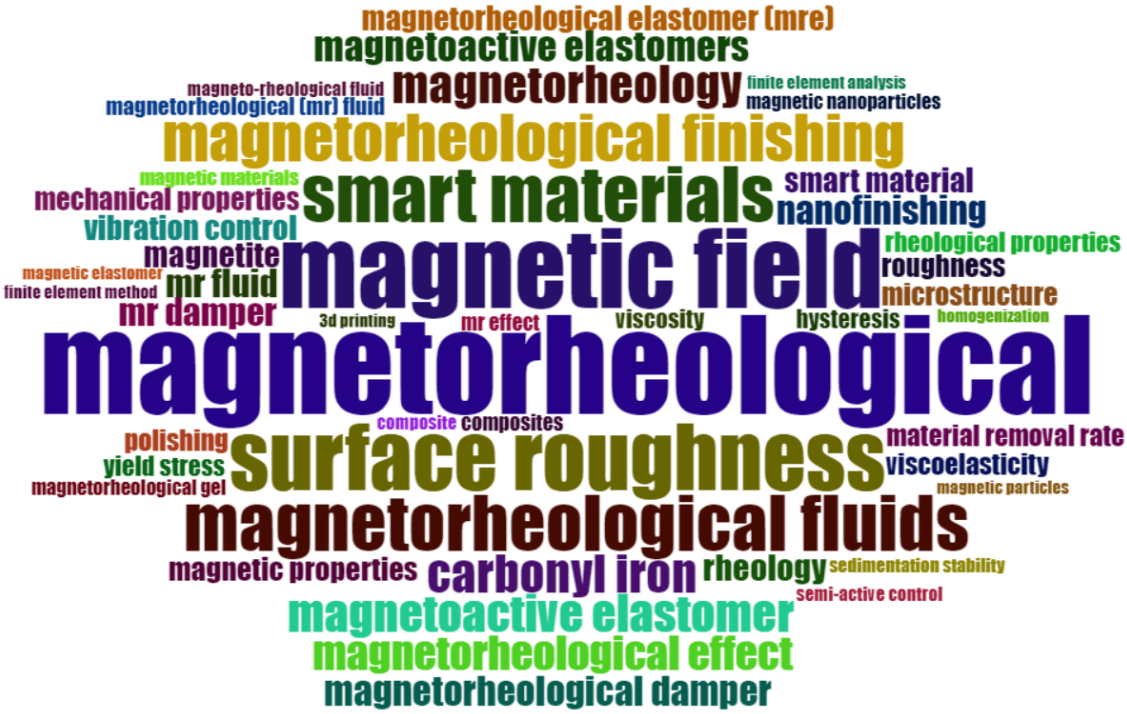

Figure 6. The results of the Scopus database analysis in the field of magnetorheological materials in the form of a word cloud.

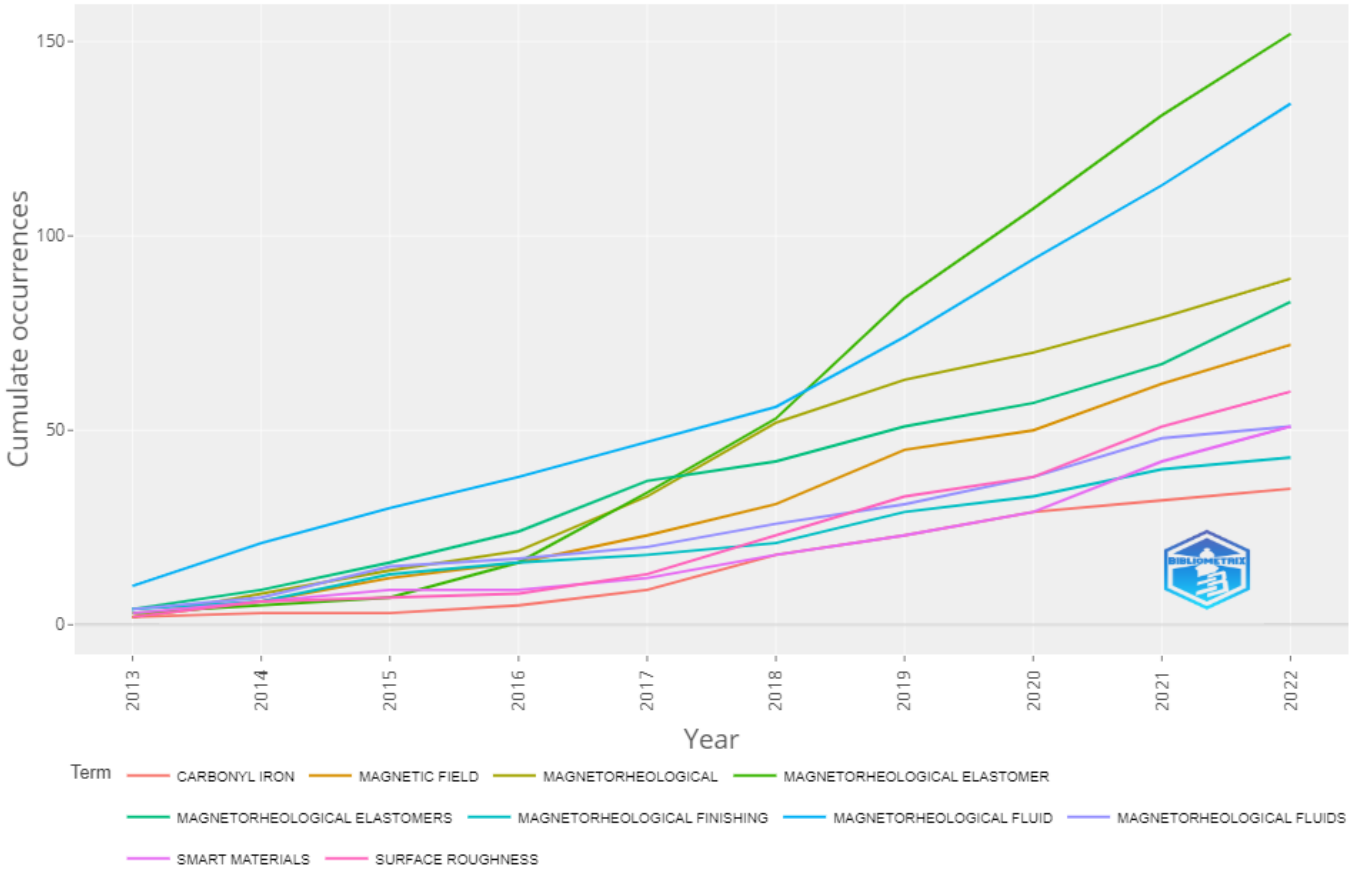

Figure 7. Growth of words used in magnetorheological materials research.

We next studied domestic and global collaboration events in the field of magnetorheological materials. The preliminary information obtained indicated that the collaboration index in the area of magnetorheological materials was 2.23. Based on the data processing results with Biblioshiny, 50 countries contributed to this field, dominated by China with a total of 463 articles. The articles were divided into 421 intra-country collaborations and 42 inter-country articles. The following most productive countries were India and Korea, as shown in Table 3 and Figure 8. Figure 8 shows a relatively significant difference between China and other countries. The difference between China and India in second position was 322 articles. India contributed one hundred and forty-one articles, with six collaborative inter-country articles and one hundred and thirty-five collaborative intra-country articles. The distribution of the collaboration map is also presented in Figure 9. The darker blue shows that the intensity of collaboration is increasing.

Table 3. The published articles and collaboration by country.

Position	Country	Articles	Intra-Country Collaboration	Inter-Country Collaboration	Total Citations	Average Article Citations
1	China	463	421	42	4023	8.69
2	India	141	135	6	1673	17.61
3	Korea	112	99	13	1661	14.83
4	Germany	95	75	20	1588	11.26
5	USA	87	75	12	1553	17.85
6	Iran	54	47	7	784	31.36
7	Poland	31	29	2	685	12.69
8	Japan	30	19	11	489	18.11
9	Spain	29	20	9	409	20.45
10	Czech Republic	27	14	13	333	15.86
11	Australia	25	8	17	296	9.87
12	Ukraine	25	16	9	267	11.61
13	United Kingdom	24	17	7	236	8.14
14	Canada	23	15	8	227	9.87
15	Malaysia	23	11	12	217	9.04
16	Indonesia	21	3	18	195	6.29
17	Italy	21	16	5	183	26.14
18	France	20	13	7	158	17.56
19	Belarus	11	9	2	150	18.75
20	Brazil	9	9	0	118	14.75

In addition, the terms of sources used as publications or references are detailed in Table 4. In this case, Smart Materials and Structures was the source that had the most influence on the field of MR materials. This was shown by the h-index records of *Smart Materials and Structures*, scoring 30. In total, there were 2956 journal citations from a total of 153 articles. This value is a record starting from 2013. The three next highest positions were filled by the Journal of Magnetism and Magnetic Materials, the Journal of Intelligent Material Systems and Structures, and Materials and Manufacturing Processes, with h-index values of 16, 15, and 13, respectively. The difference between the first and second position was fairly considerable, with difference of 14 in the h-index values. However, this was an expected occurrence from the number of citations and published articles. The difference in citations between the first and second positions was 2350 citations, and the difference in the number of published articles was 111.

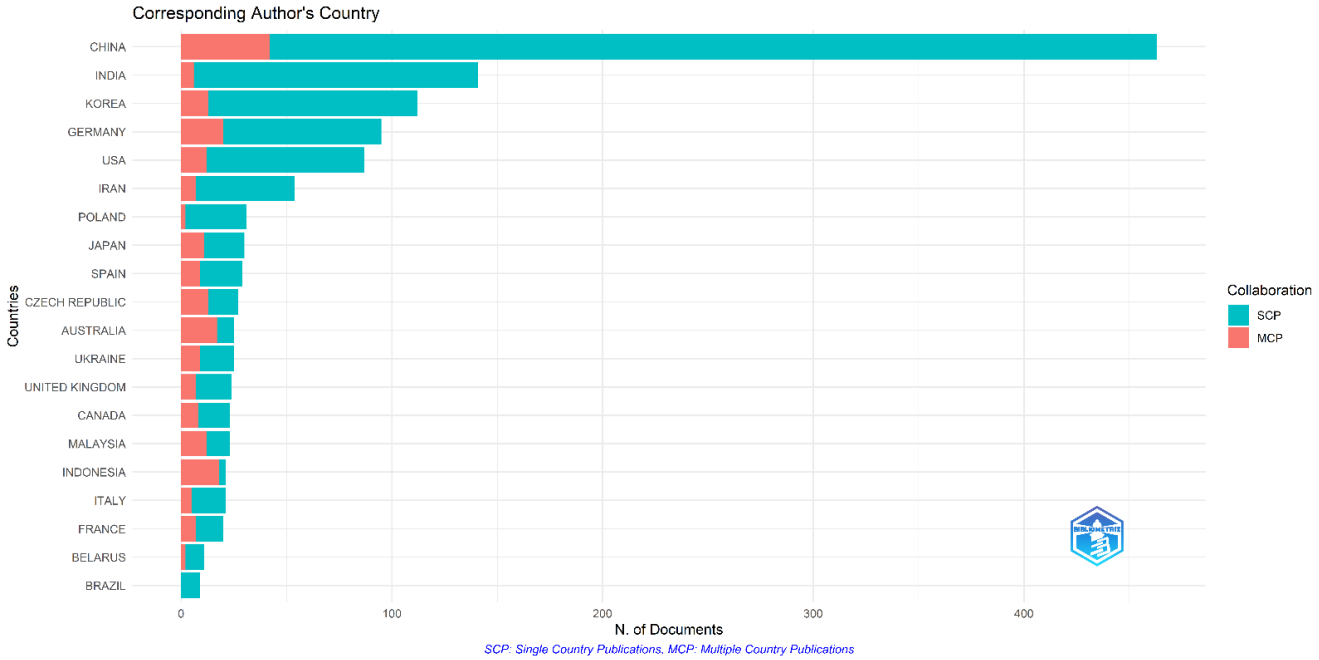

Figure 8. Corresponding author's country and intra-country collaboration (green); inter-country collaboration (orange).

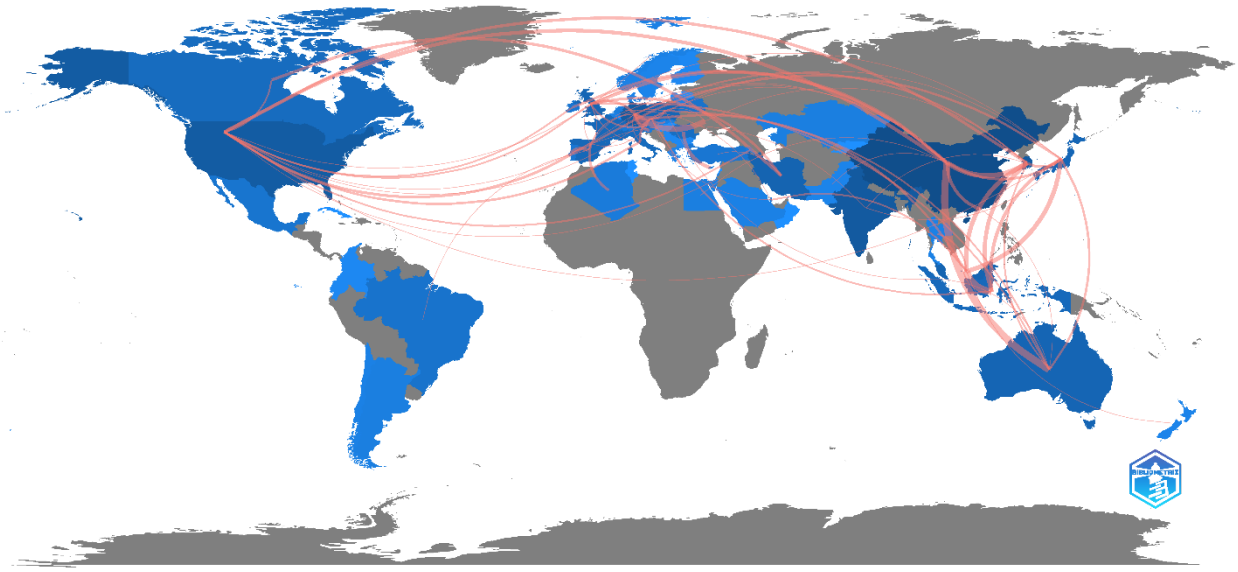

Figure 9. World map of collaboration.

Table 4. Source notes for journals in the field of magnetorheological materials.

Position	Journal	H-Index	Total Citation	Number of Publications	Initial Publication Year
1	Smart Materials and Structures	30	2956	153	2013
2	Journal of Magnetism and Magnetic Materials	16	606	42	2013
3	Journal of Intelligent Material Systems and Structures	15	647	54	2013

Table 4. *Cont.*

Position	Journal	H-Index	Total Citation	Number of Publications	Initial Publication Year
4	Materials and Manufacturing Processes	13	419	22	2013
5	International Journal of Advanced Manufacturing Technology	12	382	29	2013
6	Composite Structures	11	458	14	2014
7	Soft Matter	11	398	13	2013
8	Composites Part B: Engineering	9	326	9	2015
9	Journal of Industrial and Engineering Chemistry	9	202	10	2015
10	Journal of the Mechanics and Physics of Solids	9	510	9	2013
11	Materials	9	244	28	2015
12	ACS Applied Materials and Interfaces	8	277	14	2013
13	Colloid and Polymer Science	8	188	11	2013
14	Colloids and Surfaces A: Physicochemical and Engineering Aspects	8	195	15	2016
15	Mechanical Systems and Signal Processing	8	290	8	2018
16	Polymers	8	176	20	2017
17	Advances in Materials Science and Engineering	7	99	8	2013
18	Applied Optics	7	91	10	2014
19	Frontiers in Materials	7	113	16	2014
20	IEEE Transactions on Magnetics	7	160	25	2013

The greatest number of publications were attributed to Chinese studies, which exhibited a broad collaboration map based on the impact analysis of the authors; however, the highest ranked through the Scopus database was Li, Y. (2013), with 233 citations obtained. The second most impactful was the article by Zhao, R. (2019), with 172 citations. The most impactful articles by total citations are shown in Table 5.

Table 5. Most impactful articles by the number of citations.

Position	Title	Authors	Year	Total Citations	Citations per Year	Ref.
1	Development and characterization of a magnetorheological elastomer based adaptive seismic isolator	Li et al.	2013	233	23.3	[70]
2	Mechanics of hard-magnetic soft materials	Zhao et al.	2019	172	43	[71]
3	Experimental study and modeling of a novel magnetorheological elastomer isolator	Yang et al.	2013	137	13.7	[72]
4	Magnetic carbonyl iron/natural rubber composite elastomer and its magnetorheology	Jung et al.	2016	124	17.714	[73]
5	Experimental study of the magnetic field enhanced Payne effect in magnetorheological elastomers	Sorokin et al.	2014	123	13.667	[74]
6	Microstructure and rheology of magnetic hybrid materials	Odenbach	2016	119	17	[15]

Table 5. *Cont.*

Position	Title	Authors	Year	Total Citations	Citations per Year	Ref.
7	Stretchable and magnetosensitive strain sensor based on silver nanowire-polyurethane sponge enhanced magnetorheological elastomer	Hu et al.	2018	104	20.8	[75]
8	Computational homogenization in magneto-mechanics	Javili et al.	2013	103	10.3	[76]
9	Magnetoactive Acoustic Metamaterials	Yu et al.	2018	100	20	[77]
10	Vibration analysis of sandwich rectangular plates with magnetorheological elastomer damping treatment	Jia-Yi Yeh	2013	99	9.9	[78]
11	Field responsive mechanical metamaterials	Jackson et al.	2018	98	19.6	[79]
12	Magnetic and viscoelastic response of elastomers with hard magnetic filler	Kramarenko et al.	2015	95	11.875	[80]
13	Hysteresis of the viscoelastic properties and the normal force in magnetically and mechanically soft magnetoactive elastomers: Effects of filler composition, strain amplitude and magnetic field	Sorokin et al.	2015	94	11.75	[81]
14	A finite-strain constitutive model for magnetorheological elastomers: Magnetic torques and fiber rotations	Galipeau	2013	88	8.8	[82]
15	Soft magnetorheological polymer gels with controllable rheological properties	Xu et al.	2013	87	8.7	[83]
16	A novel high-torque magnetorheological brake with a water cooling method for heat dissipation	Wang et al.	2013	87	8.7	[84]
17	On the properties of magnetorheological elastomers in shear mode: Design, fabrication and characterization	Dargahi et al.	2019	85	21.25	[85]
18	Synthesis of Silicone Elastomers Containing Silyl-Based Polymer-Grafted Carbonyl Iron Particles: An Efficient Way To Improve Magnetorheological, Damping, and Sensing Performances	Cvek et al.	2017	85	14.167	[86]
19	Stability of anisotropic magnetorheological elastomers in finite deformations: A micromechanical approach	Rudykh et al.	2013	85	8.5	[87]
20	Evaluation of highly compliant magneto-active elastomers with colossal magnetorheological response	Stoll et al.	2013	81	9	[88]
21	Modeling of particle interactions in magnetorheological elastomers	Biller et al.	2014	79	8.778	[89]
22	Multifunctional polymer composite with excellent shear stiffening performance and magnetorheological effect	Wang et al.	2014	77	8.556	[90]
23	Dynamic behavior analysis of a magnetorheological elastomer sandwich plate	Aguib et al.	2014	75	8.333	[91]
24	Seismic performance and probabilistic collapse resistance assessment of steel moment resisting frames with fluid viscous dampers	Seo et al.	2014	74	8.222	[92]

Table 5. *Cont.*

Position	Title	Authors	Year	Total Citations	Citations per Year	Ref.
25	A new approach for modeling of magnetorheological elastomers	Norouzi et al.	2016	74	10.571	[93]
26	A novel hybrid magnetorheological elastomer developed by 3D printing	Bastola et al.	2017	71	11.833	[94]
27	Dynamic buckling of magnetorheological fluid integrated by visco-piezo-GPL reinforced plates	Fakhar et al.	2018	70	14	[95]
27	Magnetosensitive e-skins with directional perception for augmented reality	Bermudez et al.	2018	70	14	[96]
28	Enhancement of a magnetorheological PDMS elastomer with carbonyl iron particles	Perales-Martinez et al.	2017	69	11.5	[97]
29	Development of a multi-pole magnetorheological brake	Shiao et al.	2013	67	6.7	[98]
30	Magnetosensitive neurons mediate geomagnetic orientation in Caenorhabditis elegans	Vidal-Gadea et al.	2015	65	8.125	[99]
31	Design Considerations for Magnetorheological Brakes	Rossa et al.	2013	65	7.222	[100]
32	Resistor-capacitor (RC) operator-based hysteresis model for magnetorheological (MR) dampers	Bai et al.	2019	64	16	[101]
33	Effects of pressure and shear stress on material removal rate in ultra-fine polishing of optical glass with magnetic compound fluid slurry	Guo et al.	2014	64	7.111	[102]
34	Magnetically Addressable Shape-Memory and Stiffening in a Composite Elastomer	Testa et al.	2019	63	15.75	[103]
35	Shape Morphing of Hydrogels in Alternating Magnetic Field	Tang et al.	2019	63	15.75	[104]
36	A Liquid-Metal-Based Magnetoactive Slurry for Stimuli-Responsive Mechanically Adaptive Electrodes	Ren et al.	2018	63	12.6	[105]
37	Adaptive tuned vibration absorber based on magnetorheological elastomer-shape memory alloy composite	Kumbhar et al.	2018	63	12.6	[106]
38	Magnetic Actuation of Drops and Liquid Marbles Using a Deformable Paramagnetic Liquid Substrate	Vialetto et al.	2017	63	10.5	[107]
39	Magnetoreception—A sense without a receptor	Nordmann et al.	2017	63	10.5	[108]
40	Fabrication of polyaniline coated iron oxide hybrid particles and their dual stimuli-response under electric and magnetic fields	Sim et al.	2015	63	7.875	[109]

Scopus database processing was carried out, and eventually, the evolution of themes and topic trends in the field of magnetorheological materials was also obtained through the Biblioshiny analysis. The evolution of the themes was analyzed by dividing the period into two parts, namely, 2013–2017, and how the themes evolved in 2018–2022. The evolutions of the themes that arose in these periods did not show any significant changes. However, one theme was interesting because the changes were quite different from the others. In the first period, MR fluids and MR elastomers were the more oft-discussed magnetorheological

materials, but in the second period, a new theme emerged, namely, carbonyl iron, which is the primary material for both MR fluids and MR elastomers. This indicates promising research developments in the field of magnetorheological materials. Figure 10 depicts the evolution of the magnetorheological materials field themes.

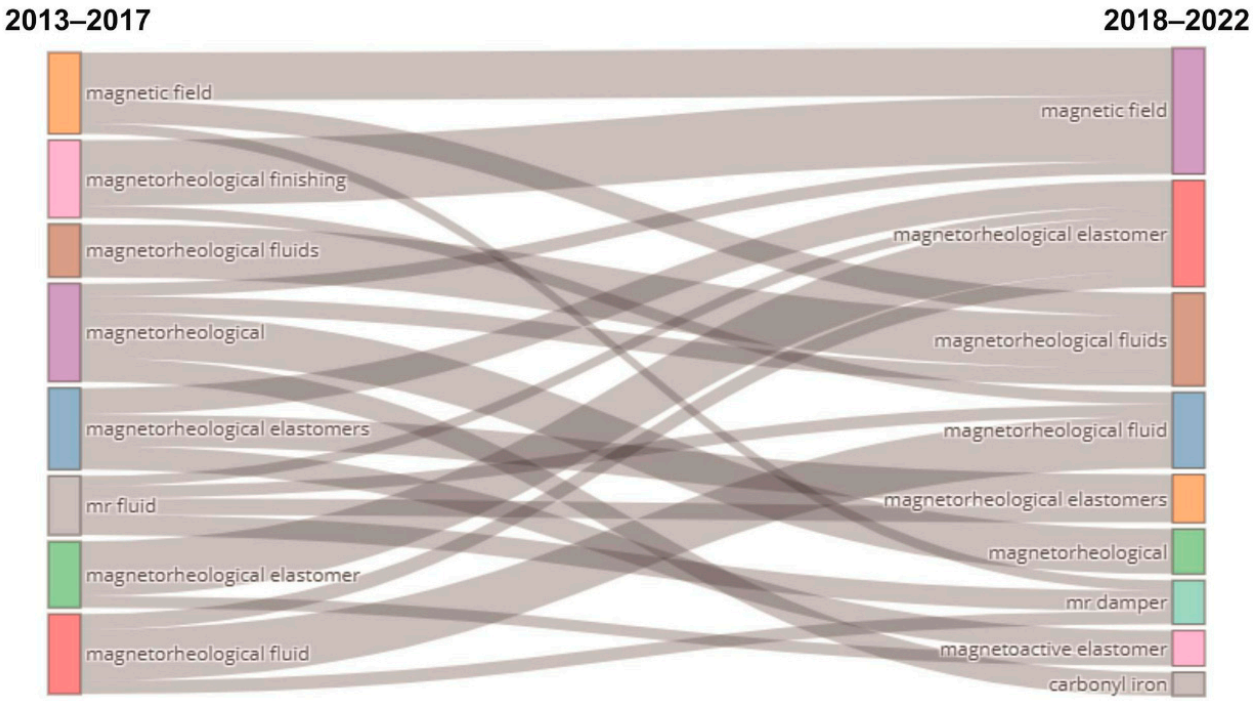

Figure 10. The evolution of the theme in two parts of the time span.

In addition to the theme evolution data, the trends of topics in this field were obtained from a predetermined period. Figure 11 shows the topic trends in the field of magnetorheological materials. Magnetorheological fluids became the most in-demand topic, with the highest frequency of published articles, in 2018. A shift in interest occurred in 2019, when the topic with the most interest was magnetorheological elastomers. In the latest year, since 2021, interest in magnetorheological materials shifted again to become more specific, such as analyses of the characteristics in fatigue loading, applications in polishing, and new models such as sandwich plates. However, the frequency of topic trends in that year was evenly distributed.

Concluding the discussions on magnetorheological materials, we present opportunities for future research. The results presented herein make it easier for readers to find the correct references for research development in that field. Furthermore, based on the results of the evolution of themes and changes in trends that occur, it is also possible to predict topics that have yet to be studied in detail. One example is that further research for new types of magnetorheological materials (MR foam, MR gels, and MR grease) is still not widespread, possibly including specific discussions that have never been explored. Research and development are frequently carried out on magnetorheological fluids and elastomers with various characteristics, models, and applications in the field of magnetorheological materials.

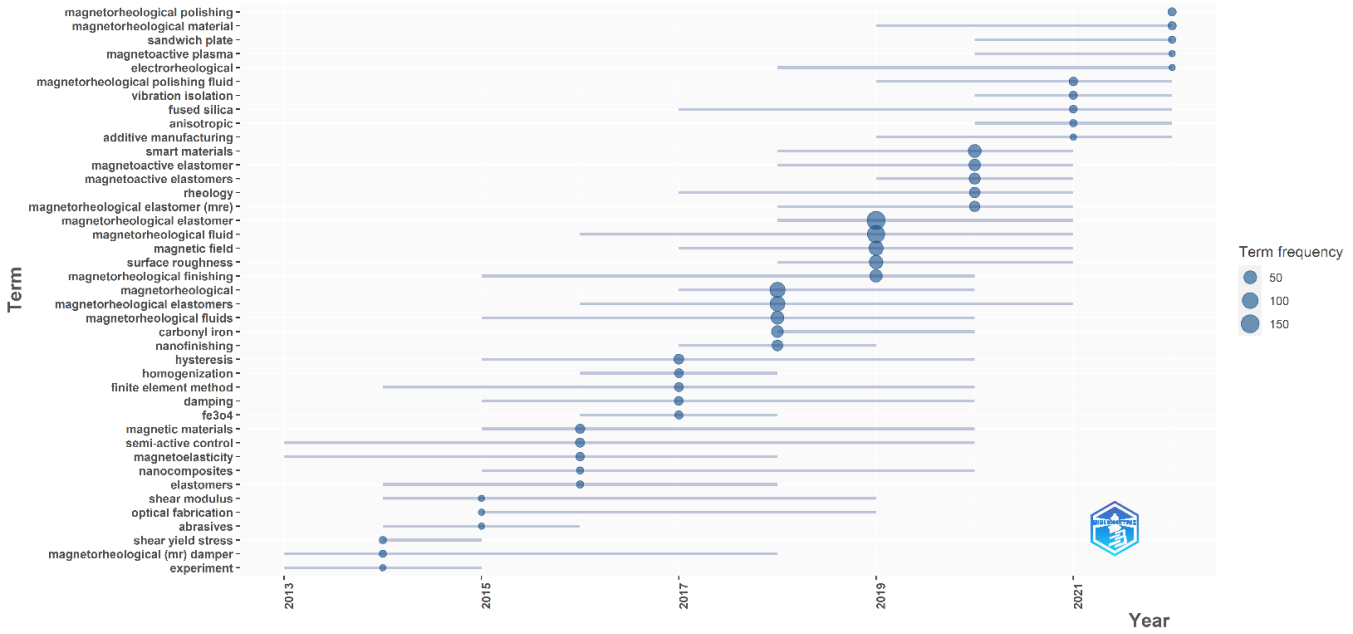

Figure 11. Topic trends in magnetorheological materials.

4. Conclusions

A complete review of magnetorheological materials with bibliometric analysis methods has been conducted. This study considered various types of analysis, such as descriptive, author dominance, the use of keywords used by the author, the author's impact on the field, and the collaboration of authors both locally and globally. The results show that the Scopus database can be processed accurately using the two applications (VOSViewer and Biblioshiny). In this case, accuracy means that no deviations occur according to the system in the database recorded on Scopus. However, some aspects could be improved, such as differences in publishers' formats for determining the author's name, especially for authors with single names. Based on the number of publications, the dominant author in the field of magnetorheological materials is Choi, Hyoung Jin of the Department of Polymer Science and Engineering, Inha University, Incheon 402–751, South Korea, with 53 articles published. However, the sheer number does not make Choi, H. J. the most impactful author in the period analyzed; Li, Y. has the highest impact, as confirmed from the total citations, with his article entitled, "Development and characterization of a magnetorheological elastomer based adaptive seismic isolator". This article was published in 2013, and has received 233 citations in the last 10 years.

Furthermore, assessment of collaboration in the field of magnetorheological materials showed that China contributes the greatest number of collaborations both locally and globally. Logically, China is also the country from which the most articles in this field are published. Finally, this review also presents a simple and brief estimate of the research and development opportunities that can be taken with other magnetorheological materials. The analysis results show that there is still much room for discussion in the field of magnetorheological materials for MR fluids and elastomers. In contrast, regarding certain other material fields, more specific research still needs to be carried out. For example, some reviews suggest that MR gels, MR grease, and MR foam are materials still in the early stages of research.

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