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Global trends in the research of biodegradable biomedical magnesium-based materials: a bibliometric analysis

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Background: In recent years, there has been a notable surge in the interest surrounding biodegradable materials, particularly in the context of biomedical applications. This has led to a significant rise in the number of research studies focusing on the utilization of biodegradable magnesium-based materials in the field of biomedicine. However, a dearth of comprehensive assessment exists regarding the body of research concerning biodegradable biomedical magnesium-based materials. In this study, a bibliometric approach was used to illustrate the current state of research and global trends pertaining to biodegradable magnesium-based materials for biomedical applications.

Methods: We conducted a search of the Web of Science core collection database for the past decade (2013–2022). VOSviewer software and the bibliometric online analysis platform were employed for bibliometric analysis and visualization.

Results: Correspondingly, 1267 documents were retrieved. We discovered that the number of papers in the field of degradable biomedical magnesium-based materials research has increased annually. In addition, China and the Chinese Academy of Sciences have published the largest number of papers in the field of biodegradable biomedical magnesium-based materials. Papers related to biodegradable magnesium-based materials for biomedical use were mainly published in *acta biomaterialia*, *materials science and engineering c-materials for biological applications* and *materials* journals. Keyword co-occurrence analysis showed that "corrosion"and "mechanical-properties" appear more frequently. The top 10 common keywords include corrosion, mechanical-properties, microstructure, biocompatibility, behavior, magnesium, magnesium alloys, degradation magnesium alloy, *in vitro*.

Conclusion: Research on biodegradable magnesium-based materials for biomedical use continues to increase steadily. China maintains a leading position in the world, and the Chinese Academy of Sciences represents a notable contribution to the research of biodegradable magnesium-based materials for biomedical use. Subsequently, "corrosion" and "mechanical-properties" were identified as the current research hotspots in the area of biodegradable biomedical magnesium-based materials.

KEYWORDS

biodegradable, magnesium, biomedical, bibliometric, visualization

1 Introduction

The presence of bone diseases and defects resulting from various diseases poses a significant risk to human health. Consequently, the exploration and study of bone repair materials have been a consistent focus throughout the course of human civilization. The assistance of internal fixation is frequently necessary for the successful recovery of fractures. Conventionally, stainless steel, cobalt, and titanium alloys have been the primary materials used for implants in such cases. These materials are known for their stability and durability within the human body, offering substantial support (Jin et al., 2020; Peng et al., 2021). Nevertheless, in the context of extended clinical utilization, these interventions have been deemed insufficient. The materials in question do not possess the same elastic modulus as human bone and are also non-degradable. In order to prevent infection and inflammation, surgical secondary removal becomes necessary during the process of bone tissue repair, thereby contributing to the patient's pain and financial burden (Adetunla et al., 2022). The utilization of biodegradable materials has emerged as a significant focus in the field of biomaterials research. Polymers and specific ceramic materials have gained prominence as commonly employed biodegradable materials in clinical applications (Antoniac et al., 2022). Medical polymers, such as poly lactic acid and calcium phosphate, have demonstrated favorable clinical outcomes in the management of maxillofacial fractures. Nevertheless, these materials exhibit certain limitations such as inadequate strength, low modulus of elasticity, incapability to function as an internal fracture fixation material at the bearing site, inability to exert pressure between fracture blocks, lack of visibility under X-ray, generation of local acidic byproducts, and induction of aseptic inflammation (Bernhardt et al., 2022). Additionally, it should be noted that biodegradable implants composed of polymers or ceramics exhibit reduced mechanical strength, resulting in limited clinical utility (Dutta et al., 2022). Hence, a thorough examination of biodegradable metallic biomaterials is crucial in order to mitigate these drawbacks. Consequently, the scientific community has shown a growing interest in biodegradable metals due to their remarkable properties (Chen X et al., 2022a; Chen Y et al., 2022b).

Among biodegradable metal materials, magnesium-based materials offer significant advantages. Magnesium's density and Young's modulus are closer to those of human bone, effectively reducing or even eliminating the stress masking effect. In addition, its excellent mechanical and processing formability makes it easy to prepare various types of medical devices with complex shapes; thus, as a temporary implant, it degrades as the bone tissue heals, eliminating the risk of secondary surgery (Hassan HW et al., 2022a). Moreover, the corrosion of magnesium-based implants *in vivo* results in the formation of harmless, soluble, non-toxic oxides excreted in urine; as a result, there is no cause for concern about degraded magnesium alloys posing a threat to human health (Hassan SF et al., 2022b). Furthermore, magnesium, an essential mineral element in the body, promotes osteoblast growth and adhesion, inhibits osteoclast activity, shortens the bone healing cycle, and regulates osteogenic cell signaling (Jian et al., 2022). However, magnesium-based materials suffer from unstable degradation rates. Thus, if their use is not better understood, the benefits may not be realized and may even result in adverse outcomes (Jing et al., 2022). To address these issues, scientists have conducted extensive research into the biomedical applications of biodegradable magnesium-based materials. However, the current literature on biodegradable magnesium-based materials for biomedical applications is fragmented and does not provide a clear picture of how patients can benefit from magnesium-based biodegradable materials for biomedical applications. Therefore, a comprehensive analysis and description of biodegradable magnesium-based materials is required.

Bibliometric analysis is a method of literature analysis that employs bibliometric principles to examine pertinent literature. It aims to assess and evaluate the quantity, quality, and trends of academic research (Li L et al., 2022a). Furthermore, bibliometric analysis is founded on the statistical analysis of existing literature data and is highly objective. Thus, by collecting and organizing literature data, researchers can accurately count and analyze a variety of indicators (Chen C et al., 2019; Li X et al., 2022b). Although there are many software programs for bibliometric and visual analysis, VOSviewer is one of the most frequently used to visually analyze the knowledge structure of different knowledge networks. VOSviewer is a free bibliometric analysis software used to construct and view bibliometric maps based on the co-citation and co-citation of literature, which can be used to map the science of various knowledge domains (Liu L et al., 2022b; Sugimoto et al., 2019). On the other hand, the bibliometric online analysis platform is relatively user-friendly and has its own distinct data structure. In this study, the combination of these software and platforms is used to present and analyze data more precisely. Although there has been a certain amount of research on biomedical degradable magnesium-based materials, there has not yet been any systematic visualization or analysis in this field. As a result, this study identifies current topics of interest and predicts future trends in the field of biomedical biodegradable magnesium-based materials by conducting a bibliometric and visual analysis of existing (2013–2022) research.

2 Methods

2.1 Data source and collection

The Web of Science database, developed by the Institute for Scientific Information (ISI), was used as the data source. Literature related to magnesium-based materials and biodegradable materials for biomedical applications published in the last decade (2013–2022) was selected. The literature search was performed on 12 March 2023. Document types were limited to articles and reviews, all retrieved records were saved in the "plain text" format with information including keywords, country/region of the paper, author, and institution of the paper, publication journal, references cited, frequency of citations, and keywords (Figure 1).

2.2 Data extraction and analysis

Two separate technicians independently conducted the literature review and compiled the data. Trends in annual

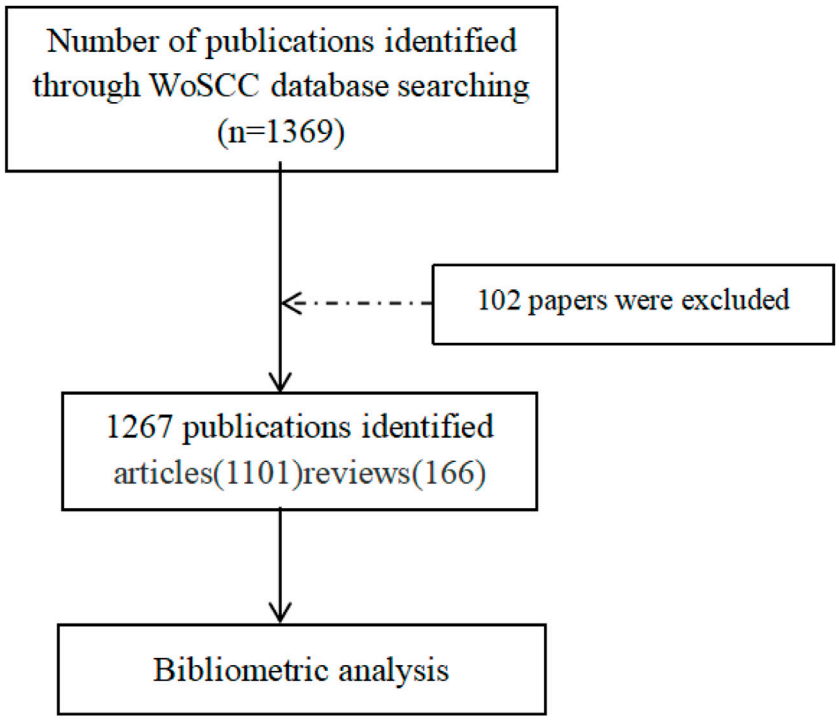

FIGURE 1
Flow diagram illustrating the process of literature identification.

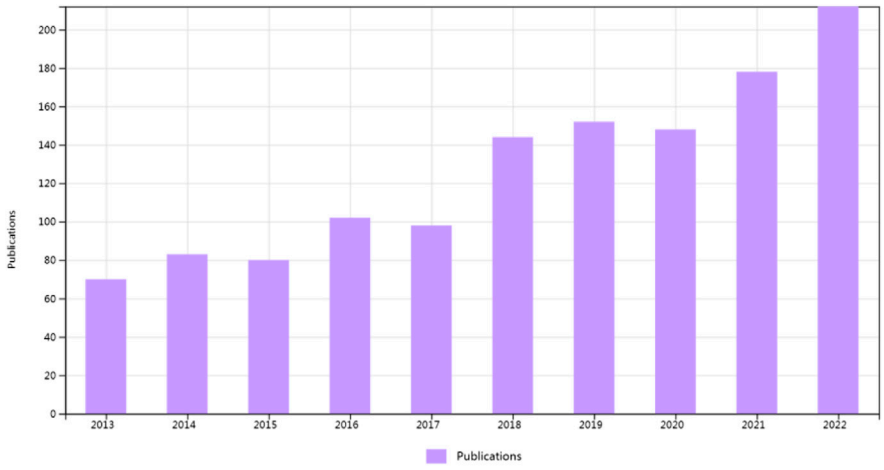

FIGURE 2
Number of annual research publications.

publication changes, country/regional distribution, source journals and references of the literature, keywords were extracted and analyzed from the screened literature, and institutions and authors who have made significant contributions to the field of biodegradable magnesium-based materials research for biomedical applications were identified. VOS viewer 1.6.17 (Netherlands) was utilized to conduct bibliometric statistical and visual analysis.

3 Results

3.1 Annual publications

A total of 1267 journal publications on biodegradable magnesium-based materials for biomedical use (total citation of 39843) were obtained from the WoSCC database covering the past decade (2013–2022), including 1101 articles and 166 reviews

TABLE 1 Top 10 countries contributing to research fields.

Rank	Country	Documents	Citations
1	China	501	17363
2	United States	210	9392
3	Germany	108	5512
4	India	103	2362
5	Australia	88	3776
6	Iran	85	2315
7	South Korea	66	2023
8	Italy	42	1253
9	Malaysia	41	1166
10	Romania	40	595

(Figure 1). As shown in Figure 2, since 2013, the number of publications in the field of biodegradable magnesium-based materials has increased annually.

3.2 National or regional contributions

A total of 58 nations/regions have published studies on biodegradable magnesium-based materials for biomedical applications. The countries/regions with the highest number of published articles are ranked in Table 1. With 501 papers, China is the nation with the most publications. This was followed by United States and Germany with 210 and 108 publications, respectively. In addition, with 17363, 9392, and 5512 citations of their respective research, China, the United States, and Germany were also the most influential nations. Figure 3 illustrates the annual trends in the number of publications in the ten most productive nations. Additionally, Figure 4 illustrates the regional and national distribution of papers.

A total of 1098 different institutions were found to be involved in publishing research on biodegradable magnesium-based materials for biomedical applications. Four of the top 10 most active institutions are located in China, while two are in United States (Table 2). At least five papers were published by 44 universities. Furthermore, a total of 72 papers were published by the Chinese Academy of Sciences (China), making it the most productive institution. Peking University and Shanghai Jiao Tong University were the next most prolific institutions. Accordingly, their studies have been cited 5224, 3311, and 1387 times, respectively. Figure 5 shows the distribution and cooperation of institutions.

3.3 Author analysis

A total of 3529 authors have contributed to the study of biodegradable magnesium-based materials for biomedical use. The core authors were visually analyzed (Figure 6), and Table 3 lists the 10 authors with the most publications. Accordingly, Zheng Yufeng, Liu Huinan, and Yang Ke were found to be the most productive authors, having published 42, 24, and 18 papers, respectively. Correspondingly, their research was cited 3054, 1225, and 818 times, respectively.

3.4 Journal analysis

A total of 273 journals published articles on the topic of biodegradable magnesium-based materials for biomedical use, of which 21 journals published more than five articles (Figure 7). Among them, *Acta Biomaterialia* was the most productive journal with 74 papers on the aforementioned topic. This was followed by *Materials Science and Engineering C-Materials for Biological Applications* and *Materials*, with 48 and 38 publications, respectively (Table 4). Furthermore, *Acta biomaterialia* was also the most cited journal.

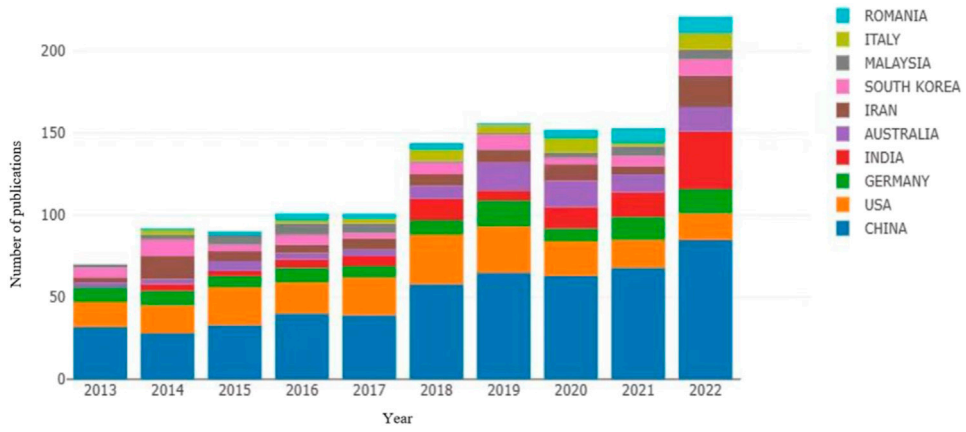

FIGURE 3
Annual trends in the number of publications in the top 10 countries.

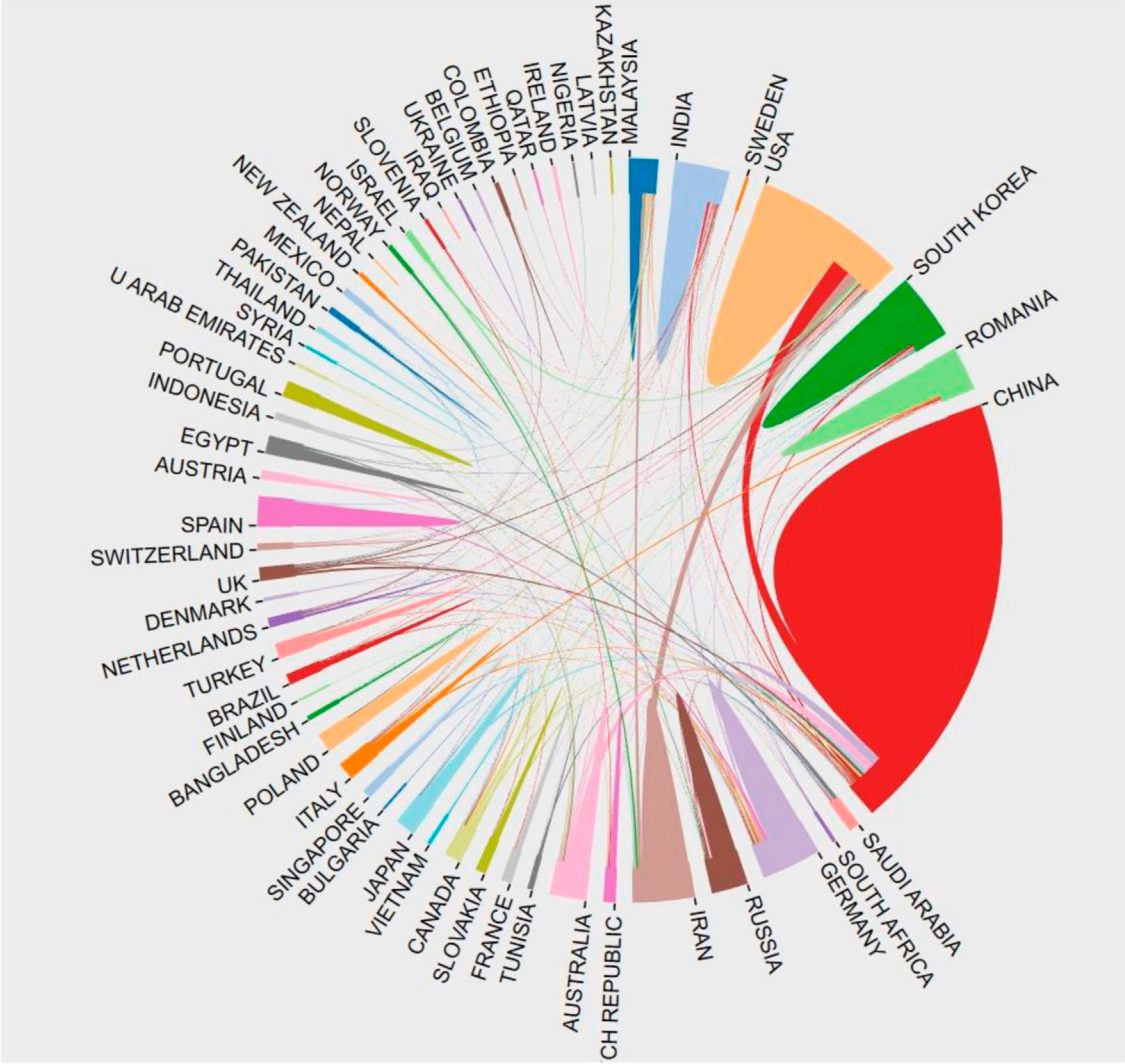

FIGURE 4
Publication and cooperation among countries.

TABLE 2 Top 10 most productive institutions.

Rank	Organization	Documents	Citations
1	Chinese Acad. Sci.	72	3311
2	Peking Univ.	64	5224
3	Shanghai Jiao Tong Univ.	40	1387
4	Rmit. Univ.	31	1258
5	Univ. Calif. Riverside	26	835
6	Univ. Teknol. Malaysia	26	823
7	Islamic Azad Univ.	25	552
8	Helmholtz Zentrum Geesthacht	24	701
9	Zhengzhou Univ.	24	760
10	Northeastern Univ.	22	838

3.5 Keyword analysis

The keyword analysis enables us to comprehend the trends in biomedical degradable magnesium-based material research (Figure 8). As indicatedby the results, corrosion, mechanical-properties, microstructure, biocompatibility, behavior, magnesium alloys, degradation, magnesium alloy, and *in-vitro*, were among the top 10 most frequently used keywords among 2048 keywords in 1267 papers (Table 5). In addition, the keyword "corrosion" was the most common keyword (470 co-occurrences), followed by "mechanical-properties" (321 co-occurrences).

4 Discussion

As a result of rapid advances in materials science, biodegradable materials have exhibited significant advantages in the biomedical

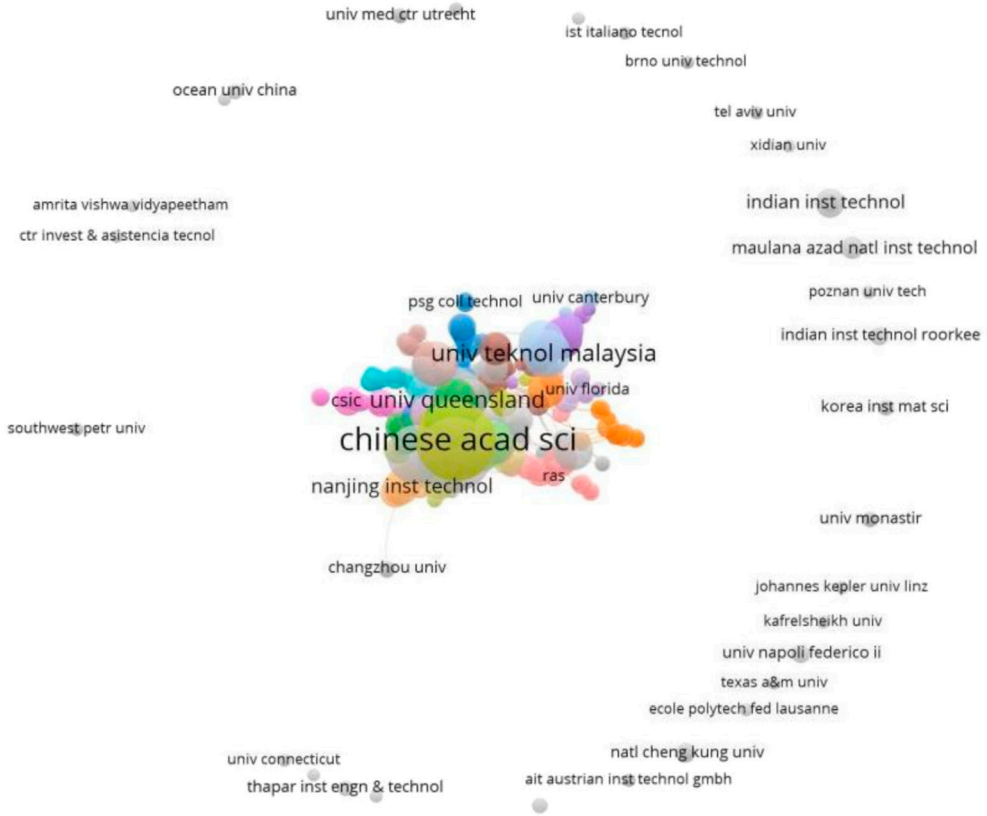

FIGURE 5
Institutional contributions to the research.

field (Sezer et al.,2020). In many surgical procedures requiring the use of implants to aid tissue growth, biodegradable materials have been used as temporary implants that degrade as the bone tissue heals, thereby avoiding the risks associated with secondary surgery and shortening the patient's course (Yang et al.,2020). This not only helps patients recover after surgery but also decreases the workload of surgeons and increases the efficiency and quality of care (Liu C et al.,2022a). However, traditional biodegradable polymers suffer from insufficient strength and low modulus of elasticity, limiting their application on a large scale (Mabrouk et al.,2022). In this regard, the use of biodegradable magnesium-based materials eliminates the issues of stress shielding effect, foreign body reaction, and lack of strength, and their clinical safety and efficacy offer significant advantages over conventional polymer materials (Martin et al.,2022). Correspondingly, the emergence of biodegradable magnesium-based materials for biomedical applications is likely to help patients access better healthcare services. Research on biodegradable magnesium-based materials for medical applications has been increasing in recent years. Accordingly, about 1267 research papers on biodegradable magnesium-based materials for medical applications were published between 2013 and the end of 2022. However, systematic analysis of these publications has been severely lacking. In this study, all the biomedical literature on biodegradable magnesium-based materials was analyzed from an informative and visual standpoint.

Currently, China leads in the total number of published papers. This indicates that China is a leader in research on biodegradable magnesium-based materials for biomedical use, which is attributable to China's revolution in materials science. China has a large land area and is one of the countries with the largest magnesium resources in the world, with ore, seawater, and brine from salt lakes constituting a significant portion of its magnesium reserves. Correspondingly, the development and utilization of magnesium resources in China began relatively early, and magnesium-based materials have been the subject of relatively more research(Monica et al.,2022). On the other hand, the United States medical industry has long been equipped with strong research and development capabilities, demonstrating world-leading technology in the field of materials science. As a result, biomedical degradable materials have been more maturely utilized in the United States medical market. In addition to the number of papers, the total number of citations and the average number of citations are important parameters for determining their academic value and reflecting the peer recognition of scientific results. In this regard, China ranks first in terms of total number of publications, as well as total citations and average citations per article, significantly higher than other nations. This indicates that China's publications are of relatively high quality and, consequently, are cited frequently. Although countries have started to work together on several active projects, most of the cooperative studies have been limited to a few nations. Thus, although research on biodegradable

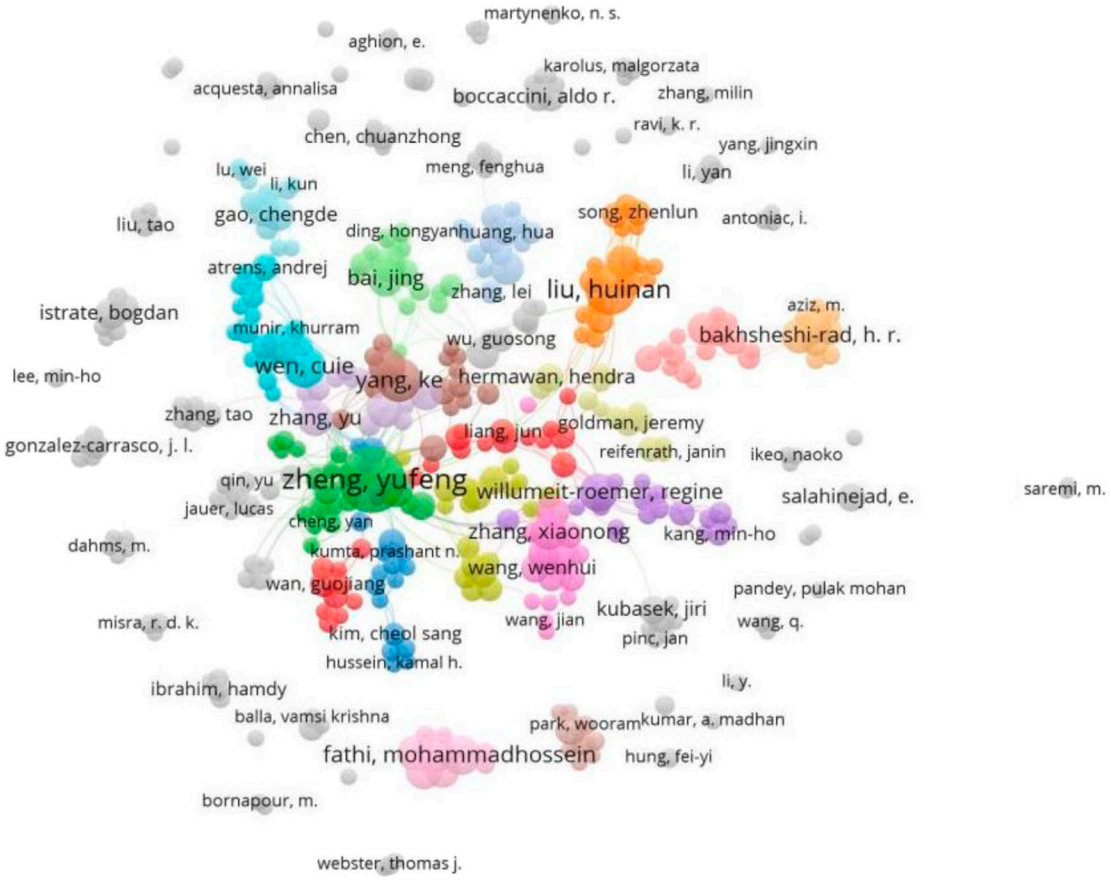

FIGURE 6
Cooperation network diagram of authors in the research.

TABLE 3 Top 10 most productive authors.

Rank	Author	Documents	Citations
1	Zheng, Yufeng	42	3054
2	Liu, Huinan	24	818
3	Yang, Ke	18	1225
4	Wen, Cuie	17	521
5	Fathi, Mohammadhossein	15	721
6	Li, Yuncang	14	488
7	Willumeit-Roemer, Regine	14	285
8	Razavi, Mehdi	13	637
9	Tan, Lili	13	751
10	Tayebi, Lobat	13	637

magnesium-based materials for biomedical applications has attracted worldwide interest, cooperation between nations must be strengthened.

The number and influence of research institutions in a particular field are indicative of the country's academic standing. China's leadership in the field of biodegradable magnesium-based materials is confirmed by the fact that four of the top ten biodegradable magnesium-based materials research institutions are located in China. Of these, the Chinese Academy of Sciences (China) comprised the institution with the most publications and citations contributing to research on biodegradable magnesium-based materials for biomedical purposes. Furthermore, Zheng from Peking University has published 42 manuscripts and is the most prolific author in the field, with the highest average number of citations per article published. For journal sources, the majority of journal types comprised those catering to articles in the field of material science. In this regard, the majority of articles on biodegradable magnesium-based materials for biomedical applications were published in *Acta biomaterialia*, *Materials science and engineering c*-materials for biological applications, and *Materials* journals, which are highly cited and devoted to advancing scientific knowledge. These highly cited journals have contributed to the global development of magnesium-based biodegradable materials for medical applications.

In bibliometric analyses, keyword co-occurrence analysis aids in the estimation of popular research topics. Biodegradable material systems have been shown to benefit surgical patients, and our keyword analysis revealed that the terms "corrosion" and "mechanical-properties" were the most frequently used. The rate of corrosion is a crucial factor in the successful application of biodegradable materials for biomedical applications (Ouyang et al.,2022). The complex service environment

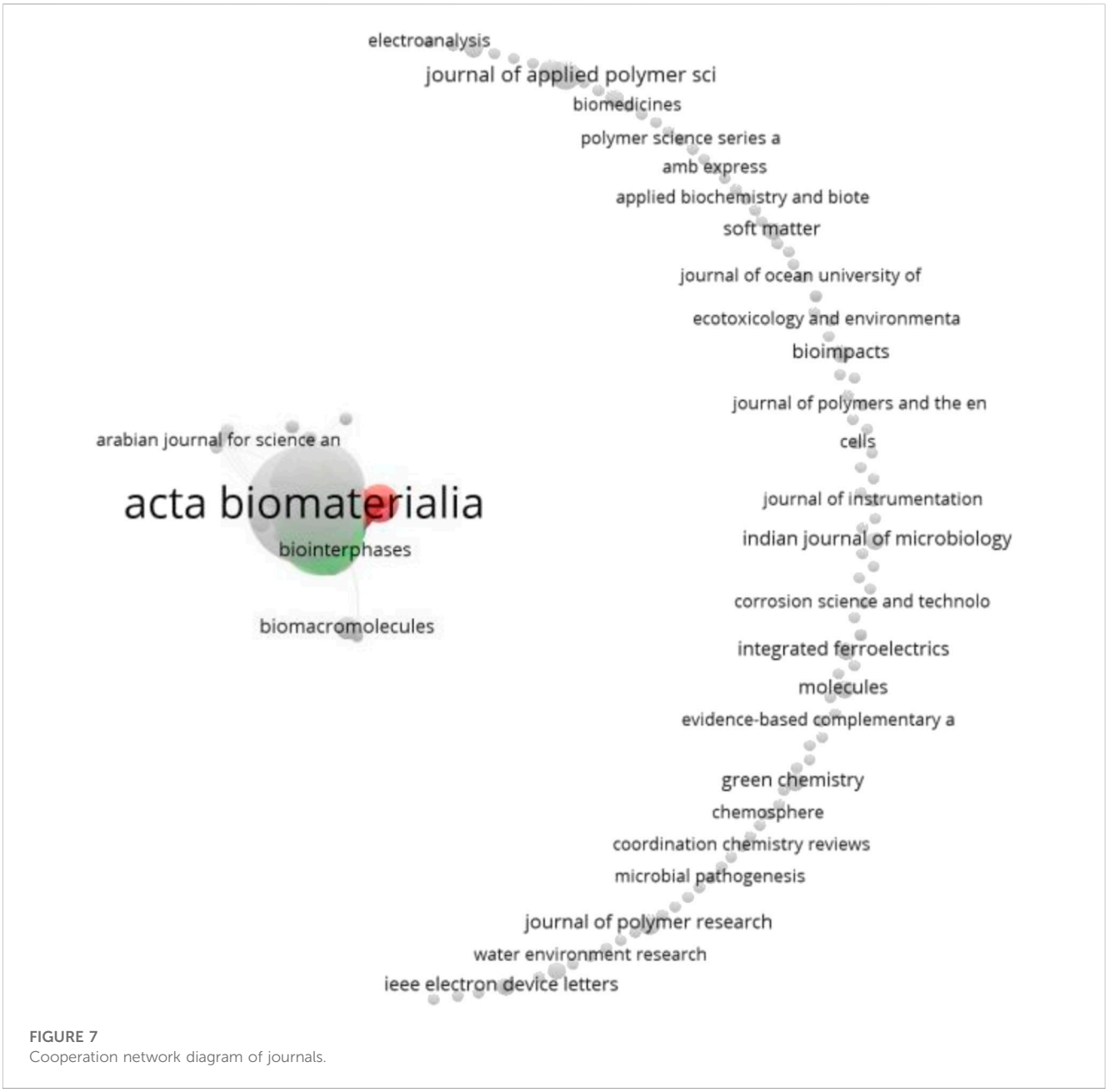

FIGURE 7
Cooperation network diagram of journals.

of biodegradable materials *in vivo* results in corrosion rates that significantly exceed those of conventional *in vitro* experiments. There are also different requirements for the degradation behavior of implants during the various stages of bone tissue repair (Rola et al.,2022). Bone defects are typically filled with biodegradable magnesium-based materials. During the early and middle stages of bone tissue repair, the implant must provide sufficient mechanical support to protect the fracture or bone defect site from secondary damage, and it must not corrode too quickly. In the final phase of bone tissue repair, in order to restore the original load-bearing function of the damaged bone tissue, the implant should degrade at a rate that is compatible with tissue healing. In addition to bone tissue repair, biodegradable magnesium-based materials can be used to create vascular scaffolds that degrade gradually after implantation in the patient's body, thereby reducing the likelihood of restenosis. Biodegradable magnesium-based materials can also be used to make implantable medical devices, such as screws, plates, and membranes. These devices can degrade gradually after implantation, reducing irritation and discomfort for the patient (Sahu et al.,2022). Magnesium matrix composites, because of their excellent dimensional stability and high mechanical properties, are not only widely used in the biomedical field but also have great potential for application in the fields of transportation, military equipment, electronics, etc., and are anticipated to replace traditional materials such as aluminum alloys (Shan X et al.,2022a).

While significant progress has been made in the application of magnesium-based materials in the field of biomedical degradability, there are still some challenges and limitations. Long-term experiments must be conducted to determine, for instance, if these added alloying elements are harmful to the human body and what effects they will have.

TABLE 4 Top 10 journals of the research.

Rank	Source	Documents	Citations	IF (2022)	JCR
1	Acta Biomaterialia	74	5554	9.7	Q1
2	Materials Science & Engineering C-Materials for Biological Applications	48	1950	7.9	Q1
3	Materials	38	726	3.4	Q2
4	Surface & Coatings Technology	37	1324	5.4	Q1
5	Journal of Magnesium and Alloys	35	1554	17.6	Q1
6	Journal of Alloys and Compounds	33	1166	6.2	Q1
7	Metals	29	557	2.9	Q2
8	Materials Science and Engineering C-Materials for Biological	25	869	7.9	Q1
9	Ceramics International	24	734	5.2	Q1
10	Journal of Materials Science & Technology	23	1561	10.9	Q1

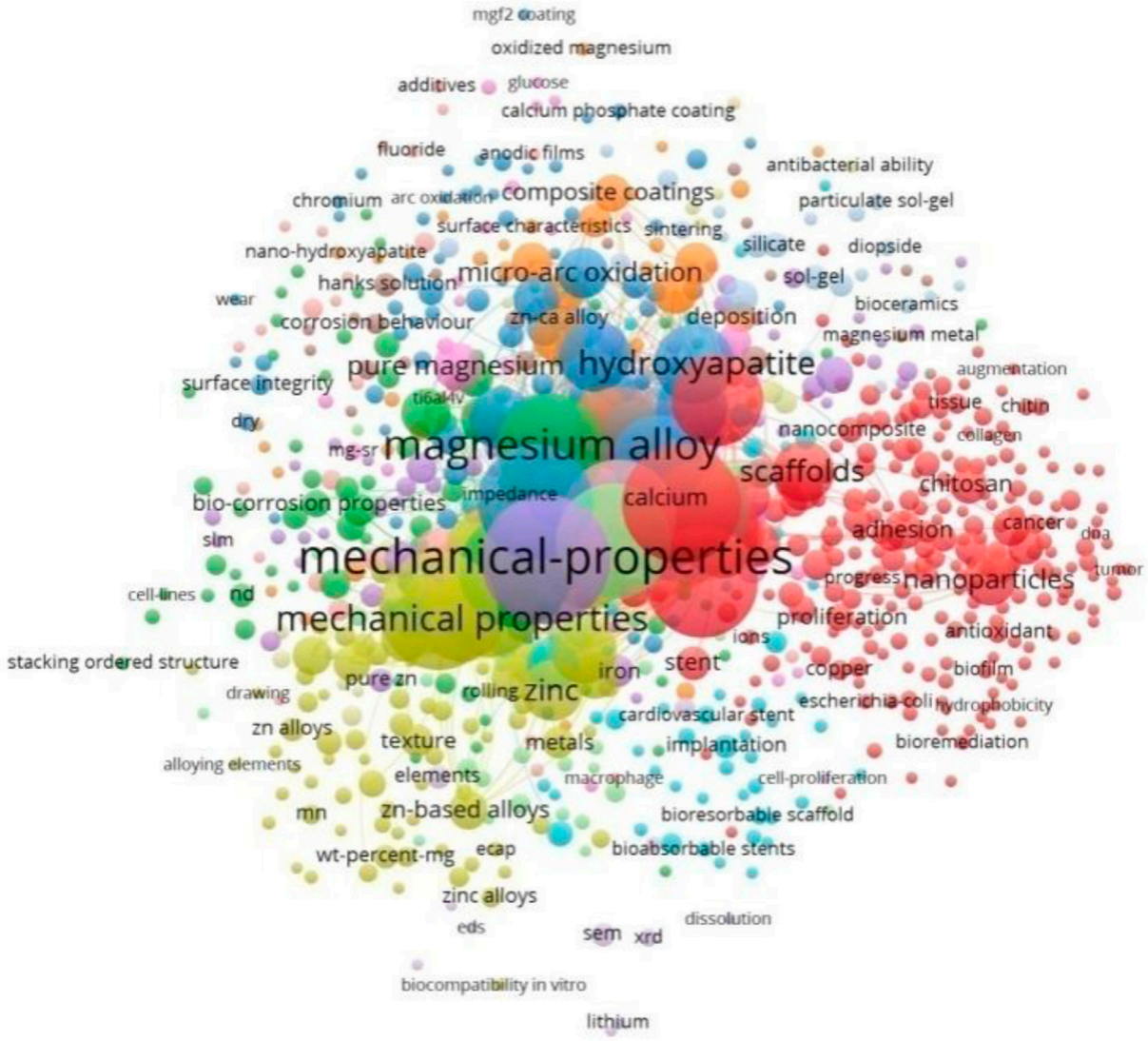

FIGURE 8
Keyword co-occurrence network diagram.

TABLE 5 Top 10 common keywords for the research.

Rank	Keyword	Occurrences	Strength
1	Corrosion	470	4594
2	Mechanical-properties	321	3171
3	Microstructure	275	2751
4	Biocompatibility	270	2703
5	Behavior	261	2546
6	Magnesium	255	2328
7	Magnesium alloys	247	2448
8	Degradation	242	2266
9	Magnesium alloy	228	2263
10	*In vitro*	196	1834

In addition, various aspects of the clinical application of magnesium matrix composites as artificial bone, such as material homogeneity and stability, require further research (Shan Z et al.,2022b; Li N et al.,2013). To develop biodegradable magnesium alloy medical materials to meet the needs of living organisms, a comprehensive examination of magnesium and its alloys inside and outside the organism's corrosion laws and mechanisms and the resulting impact on the organism are required(Somasundaram et al.,2022; Zhao et al.,2016; Atrens et al.,2015). Only systematic research on the properties and mechanisms of magnesium-based composites and their biomedical applications can better serve patients. In conclusion, the application of biomedical degradable material technology in the field of magnesium-based materials is promising and is anticipated to improve therapeutic effects and quality of life for patients.

However, the current study has a number of limitations. First, the WoSCC database was the source from which we obtained our data; thus, publications not collected in this database were excluded from the study. As the WOS database is the most authoritative citation-based database in the world today, the data contained in the WoSCC could satisfy the requirements of our current research questions. Secondly, because of the low frequency of citations, newly published works may be overlooked in our research. Consequently, the scientific trends in research on biodegradable magnesium-based materials may shift over time and as bibliometric data are updated.

5 Conclusion

Research on biodegradable magnesium-based materials for biomedical use continues to increase steadily. China maintains a leading position in the world, and the Chinese Academy of Sciences has made a significant contribution to the study of biodegradable magnesium-based materials for biomedical use. "Corrosion" and "mechanical-properties" are the current research hotspots in the field of biodegradable magnesium-based materials for biomedical applications. Greater national and inter-institutional collaboration is needed to help patients benefit from biodegradable materials for biomedical use.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YZ: Conceptualization, Data curation, Writing–original draft. YL: Conceptualization, Data curation, Writing–original draft. LW: Data curation, Resources, Writing–original draft. QY: Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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