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The top 100 most cited articles on magnesium alloy orthopedic implants: A bibliometric and visualized analysis

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Abstract. Magnesium (Mg) alloys are considered as promising bone implant materials due to their natural degradability, good biocompatibility, and good mechanical properties. Therefore, magnesium alloys have received considerable attention in the field of orthopedic implants due to their superior comprehensive properties. In this study, we analyzed the basic information of the top 100 most frequently cited articles on mg alloy orthopedic implants that met the inclusion criteria in the WoS Core Collection database, and the VosViewer software was used for web visualization and keyword analysis. Through bibliometric and visual analysis, this article systematically introduces the research status of magnesium alloy orthopedic implants, discusses the advantages of magnesium and its alloys as orthopedic implants, and explores four strategies to improve corrosion performance, including purification, alloying treatment, surface coating and Mg-based metal matrix composites (MMC). In addition, this paper revealed the future research focus in this field.

Keywords: Magnesium Alloy, Orthopedic, Implant, Bibliometric Analysis, Citations.

1. Introduction

Biomedical metal materials are closely related to human life activities and health needs and have a long history of application as orthopedic implants [1, 2]. Metallic orthopedic implants have been widely used to replace and regenerate damaged hard tissues due to their superior mechanical strength and toughness compared to polymers or polymer-ceramic composites [3, 4]. Metals have long dominated orthopedic surgery, contributing significantly to the majority of orthopedic de-vices, including both temporary ones like bone plates, pins, and screws and permanent ones like complete joint re-placements. Modern biomedical applications require the use of biomedical alloys, which account for nearly 80% of all materials used in bioimplants [5]. As orthopedic implants, medical alloy materials serve in the complex environment of body fluids, so the material properties of implants are very strict. Due to their high specific strength and adequate Young's modulus, natural degradability, good biocompatibility, and osteopromoting qualities, magnesium and its alloys are regarded as a breakthrough biomaterial [6, 7]. At present, Mg-based alloy orthopedic implants can be divided into two categories: (1) Bone fixation devices mainly include bone screws, bone needles, bone plates, etc., which perform a stabilizing effect in the healing of bones; (2) Magnesium and related alloys are also considered viable scaffold materials for bone tissue engineering transplants of autologous osteoblasts, bone marrow stromal cells, or chondrocytes [8, 9].

In addition, the plasticity, stiffness and surface treatment of magnesium alloy are also satisfactory, and the process and sterilization are easy to control [10, 11]. Conventional nondegradable biometals need to be surgically removed a second time, which frequently causes the patient more agony and financial hardship. However, magnesium and its alloys have attractive breakdown characteristics and can totally disintegrate in vivo [12]. The majority of common surgical alloys (such those made of cobalt, chromium, and nickel) include corrosion byproducts that could potentially injure human tissues [13, 14]. Degradation products of Mg-based alloy implants are mainly magnesium ions, which have no obvious toxicity to human tissues [15]. Additionally, Mg transporter 1 (MagT1) and transient receptor potential cation channel subfamily member 7 (TRPM7), which facilitate the release of calcitonin gene-related peptide (CGRP), mediate the release of magnesium ions [16]. When cyclic AMP binds to the response element-binding protein of the released CGRP, osterix substantially rises and new bone formation in the periosteal region is stimulated [17].

Millions of individuals suffer from bone defects brought on by natural illnesses and unintentional traumas, and as the population ages, life expectancy increases, and the urban environment deteriorates, bone defect therapy has become a significant therapeutic endeavor [18]. For age-related bone illnesses, such as osteoporotic fractures, there is an increasing need for cutting-edge clinical orthopedic implants [19]. Meanwhile, patients' expectations for medical prognosis continue to increase, which promotes the continuous development of medical technology and medical consumables. According to a survey by Allied Market Research, the market for orthopedic implants worldwide reached $47.261 billion in 2016 and is projected to reach $74.796 billion by 2023 [20]. On the whole, Mg and its alloys are one of the important development directions of orthopedic implant materials in the future, which is worthy of further research and clinical application and has great market potential.

An increasingly used statistical method known as bibliometrics may track the general direction of research in a certain topic [21]. One of the primary bibliometrics methods is citation analysis, and the quantity of citations to a given work is typically seen as a measure of its impact and worth [22]. Significant new discoveries and trends in a scientific subject can be found in highly cited works [23]. To our current understanding, magnesium alloy orthopedic implants have not been the subject of a thorough biblio-metric analysis. The top 100 highly cited publications on magnesium alloy orthopedic implants that were indexed by the Web of Science (WoS) were analyzed bibliometrically and visually by our team. We wish to provide researchers with research hotspots and to discuss the existing status and new initiatives in magnesium alloy orthopedic implants. These instructions, which are structured in the manner of a submission, outline the ideal Microsoft Word layout for your work. utilize the following page setup measures if you don't want to utilize the provided Word template.

2. Materials and methods

As shown in Figure 1, using the specific search function with the restrictions of "English" and "Articles or Review Articles" as the document type, we were able to obtain pertinent articles from the WoS Core Collection databases on November 20, 2022.The articles were found using the terms TS=(Magnesium or Mg) AND TS=(alloy) AND (TS=(orthopedic) OR TS=(Orthopaedic) OR TS=(bone)) AND TS=(implant). After sorting the search results by the quantity of citations, the top 100 papers were analyzed. The full texts or abstracts were evaluated independently by two reviewers (T.B. and J. W.) to determine the top 100 referenced articles on magnesium alloy orthopedic implants. When the two reviewers couldn't agree, a third reviewer (Y.C.) jumped in and helped forge a consensus.

Bibliometric analysis can swiftly comprehend the fundamental knowledge and research trends in a certain topic in addition to exploring the characteristics, structure, and evolution of academic literature. A bibliometric analysis often includes the evaluation of citations, journals, authors, nations, institutions, and keywords [24]. The journal impact factors (IF) were obtained from the “Journal Citation Reports (JCR)©(2021)”[25]. Moreover, Microsoft Excel and VosViewer were used for data mining, mapping, and visualization of the network analyses [26].

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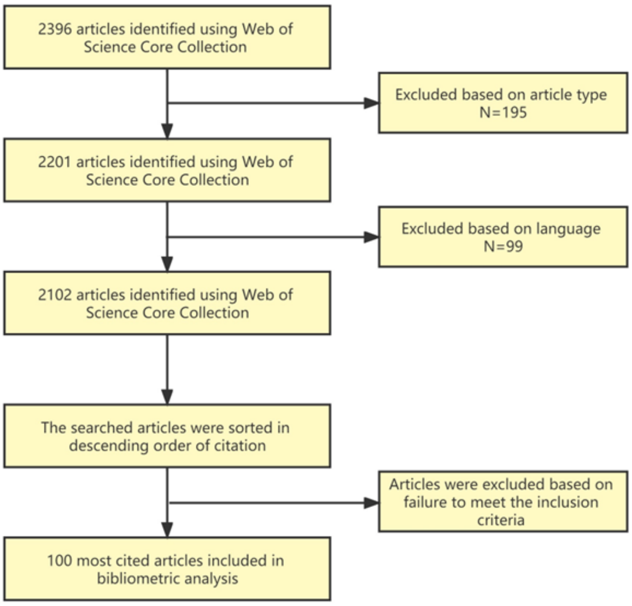

Figure 1. Flowchart of the methodology for identifying the top 100 cited articles.

3. Results and Discussion

Using the aforementioned method, a total of 2396 documents were obtained from the WoS Core Collection database. After narrowing our search to only original research articles and reviews in English, we eventually found 2102 publications. The top 100 articles with the most citations based on the inclusion criteria were our last focus. The top 100 most cited articles on magnesium alloy orthopedic implant research are presented in Table A1.

3.1. Temporal and spatial analysis

The publication year was from 2005 to 2020, and 2013 and 2016 were the most productive, with 12 papers published respectively. The number of published articles in 2013 and 2016 ranked second, with 11 articles each. Figure 2 displays the publishing time patterns in terms of citations and publications. Prior research has shown that it often takes 10 to 20 years for well-known works to achieve their maximum recognition and peak in terms of the number of citations [27, 28]. The findings indicate a general upward trend in research on orthopedic implants made of magnesium alloy.

A total of 26 countries published the 100 most cited articles. Figure 3 shows the geographic distribution of the top 100 literature. The results showed that China started the research on magnesium alloy orthopedic implants early and was in a leading position in this field, with the largest number of publications (n=44). The second place was Germany and USA, with 21 publications each. This was followed by Australia (n=8), Iran (n=4) and South Korea (n=4). Canada, India, Italy and New Zealand published three papers each. The output of China, Germany and USA far ex-ceeded that of other countries during the whole study period. The cooperation between these countries is relatively frequent (Figure 4). Among them, the USA has the most active partnerships, with close cooperation with China, Germany, Japan, Italy, Israel and Canada. China also has close cooperation with the USA, Germany, Australia and Japan. In general, the countries with the highest number of publications are generally rich in magnesium resources or advanced metallurgical technology.

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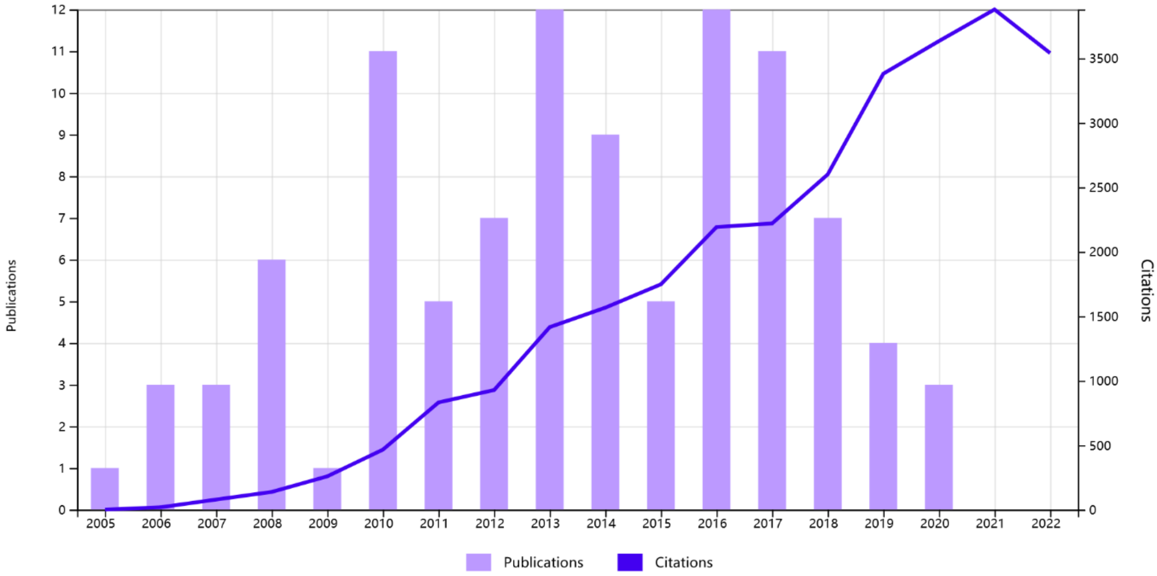

Figure 2. Total publications and citations on magnesium alloy orthopedic implants.

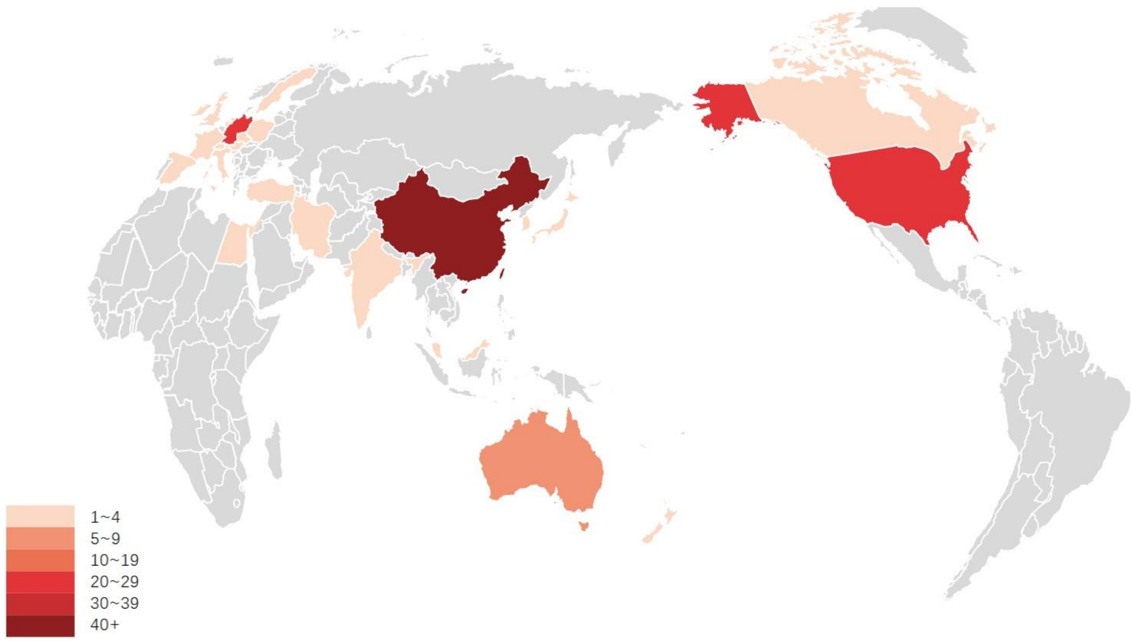

Figure 3. Geographical distributions of publications.

Figure 4. The collaboration network of the most productive countries.

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3.2. Analysis of journal, institution and author

42 journals published the 100 selected papers, with only one publication appearing in roughly two-thirds of them. Table 1 lists 14 journals that have published more than 2 articles on magnesium alloy orthopedic implants, accounting for 72% of the total number of publications. *Acta Biomaterialial* (IF=10.633) had the largest number of publications, with a total of 24 articles. The second was *Biomaterials* with the highest impact factor (IF=15.304) and a total of 9 articles. *Journal of Biomedical Materials Research Part A* (IF=4.854) and *Journal of Biomedical Materials Research Part B Applied Biomaterials* (IF=3.405) each published 5 articles. Among the most influential journals, most were produced in the USA (n=5), followed by the Netherlands (n=4) and China (n=3).

A total of 162 institutions participated in 100 articles. Table 2 reports the top 10 institutions that have published more than 5 articles, of which the institution with the most published articles was the Chinese Academy of Sciences(n=18), which was cited over 3,230 times. In the second place, Hannover Medical School from Germany published 14 articles, which were cited 1,868 times. Peking University from China ranked third with a total of 13 publications and 1,291 citations. Next in line were Leibniz University Hannover (Germany) (n=9), Shanghai Jiao Tong University (China) (n=8) and Helmholtz Association (Germany) (n=7). In the top 10 institutions, six were in China, four were in Germany. A cooperative network composed of the following institutions was created by the leading organizations: Chinese Academy of Sciences, Peking University, Shanghai Jiao Tong University, City University of Hong Kong, Fudan University, Monash University and so on. Figure 5 shows the close cooperation among these institutions. Cooperation between institutions from China is very active, and cooperation with institutions from other countries has also been carried out.

Magnesium alloy orthopedic implants were the subject of research by 444 writers, however only 77% of them had more than one article published. The top 12 authors, each of whom produced at least 4 publications, are listed in Table 3. Witte F and Zheng YF are the most prolific authors with 13 articles each. Yang K from Peking University ranked third with 9 articles. Witte F has published 6 articles as the first author, also ranking first in these highly productive authors. The networks of author partnerships on magnesium alloy orthopedic implant research were evaluated using Vosviewer software in order to examine the interaction and coordination of high-yield authors with other authors (Figure 6).

Based on the above analysis, it can be found that the research and development of magnesium alloy orthopedic implants require extensive cooperation of different countries, institutions and authors at home and abroad.

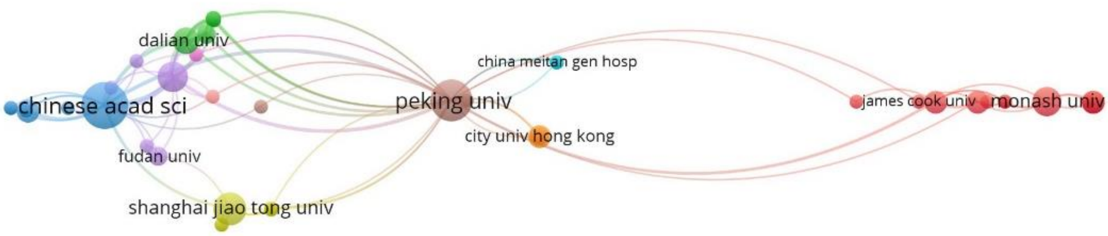

Figure 5. The collaboration network of the most productive institutions.

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Table 1. The most productive journals that have published more than 2 articles on magnesium alloy orthopedic implants.

Ranking	Journal	Country	IF[a]	TP[b]	TC[c]
1	Acta Biomaterialia	USA	10.633	24	6589
2	Biomaterials	Netherlands	15.304	9	9930
3	Journal Of Biomedical Materials Research Part A	USA	4.854	5	1090
4	Journal Of Biomedical Materials Research Part B Applied Biomaterials	USA	3.405	5	600
5	Applied Surface Science	Netherlands	7.392	4	366
6	Journal Of Materials Science Technology	China	10.32	4	932
7	Materials Science Engineering C Materials for Biological Applications	Netherlands	8.457	4	793
8	Acs Applied Materials Interfaces	USA	10.383	3	333
9	Journal Of Materials Science Materials in Medicine	Netherlands	4.727	3	433
10	Surface Coatings Technology	Switzerland	4.865	3	375
11	Cirp Annals Manufacturing Technology	USA	4.482	2	214
12	Journal Of Magnesium and Alloys	China	11.862	2	309
13	Materials Design	England	9.417	2	259
14	Regenerative Biomaterials	China	5.763	2	174

Note: [a]IF is the impact factor; [b]TP is the number of total publications; [c]TC is the number of total citations.

Table 2. The most productive institutions that published more than 5 articles on magnesium alloy orthopedic implants.

No.	Institute (country)	TP[a]	TC[b]
1	Chinese Academy of Sciences (China)	18	4285
2	Hannover Medical School (Germany)	14	7812
3	Peking University (China)	12	3764
4	Leibniz University Hannover (Germany)	9	5489
5	Shanghai Jiao Tong University (China)	7	953
6	Helmholtz Association (Germany)	7	3683
7	Chinese University of Hong Kong (China)	6	1824
8	Shenzhen Institute of Advanced Technology Cas (China)	6	508
9	Monash University (Australia)	5	2032
10	University of Veterinary Medicine Hannover Foundation (Germany)	5	2532
11	Zhengzhou University (China)	5	653

Note: [a]TP is the number of total publications; [b]TC is the number of total citations.

Table 3. The authors who have published more than 5 articles on magnesium alloy orthopedic implants research.

Authors	Institution	Position on author list	TP[a]	TC[b]
Witte F	Chinese Academy of Sciences	First author-6 correspond author-4 second-2, third-1 last-5	13	8361
Zheng YF	Hannover Medical School	First author-0 correspond author-8 second-1, third-0 last-11	12	3764
Yang K	Peking University	First author-0 correspond author-3 second-0, third-1 last-9	9	1780
Qin L	Institute Of Metal Research Cas	First author-0 correspond author-3 second-2, third-0 last-6	6	1824
Windhagen H	Leibniz University Hannover	First author-1 correspond author-0 second-1 third-0 last-5	6	3818
Guan SK	Shanghai Jiao Tong University	First author-0 correspond author-5 second-4, third-0 last-1	5	653
Hort N	Helmholtz Association	First author-1 correspond author-0 second-2, third-0 last-4	5	2484
Wang LG	Chinese University of Hong Kong	First author-0 correspond author-0 second-0, third-1 last-4	5	653

Note: [a]TP is the number of total publications; [b]TC is the number of total citations.

3.3. Citation analysis

Citation times is one of the important indexes to measure the influence of publications. Citations may be influ-enced by a variety of elements, including the accessibility and age of IF journals [29]. Due to cumulative effects, older articles are likely to receive more citations. A total of 28,981 times were cited in the top 100 articles on orthopedic implants made of magnesium alloy. The most cited article was *Magnesium and its alloys as orthopedic biomaterials: A review*, which was cited 3,234 times. Staiger MP was the first author of the article, which was published in *Biomaterials* in 2006. This review examines the characteristics, biological effectiveness, difficulties, and potential applications of magnesium-based biomaterials [4].

According to earlier research, average citation rates (ACY) are a better indicator of an article's impact and ability to affect future trends [30]. We show the top ten articles with the highest ACY in Table 4. As the article with the highest number of citations, *Magnesium and its alloys as orthopedic biomaterials:*

A review was also the article with the highest ACY, which was 190.24 times. *Metallic implant biomaterials* ranked second, which was published by Chen QZ et al. in *Materials Science & Engineering R-Reports* in 2015. This review discusses critical issues with clinical applications of metallic implant biomaterials, including movement-induced wear of joint replacements, fatigue failure of structural components from repeated loading, and systemic toxicity of released metal ions from corrosion [31]. *Topological design and additive manufacturing of porous metals for bone scaffolds and orthopedic implants: A review* ranked third and was published by Wang XJ et al. in *Biomaterials* in 2016. This article examines the most recent topological design and manufacturing techniques for various kinds of porous metals [32]. The original works are less frequently cited as concepts from earlier, prominent pieces are incorporated into common understanding. More time must pass before studies with more recent publication dates can amass enough citations to support their significance. Articles with high citation counts but low ACY are probably the product of historical accumulation [30]. From the ACY top ten articles, we can find that the research on magnesium alloy orthopedic implants mainly focuses on degradability, biocompatibility, surface modification and clinical application.

Table 4. The top ten articles with the highest ACY on magnesium alloy orthopedic implants research.

Ranking	Title	First author	Journal	ACY[a]	TC[b]
1	Magnesium and its alloys as orthopedic biomaterials: A review	Staiger, MP	Biomaterials	190.24	3234
2	Metallic implant biomaterials	Chen, Qizhi	Materials Science & Engineering R-Reports	103.94	1223
3	Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: A review	Wang, Xiaojian	Biomaterials	86.2	1022
4	In vivo corrosion of four magnesium alloys and the associated bone response	Witte, F	Biomaterials	152.88	1871
5	The history of biodegradable magnesium implants: A review	Witte, Frank	Acta Biomaterialia	93	1209
6	Degradable biomaterials based on magnesium corrosion	Witte, Frank	Current Opinion in Solid State & Materials Science	79.6	1293
7	Current status on clinical applications of magnesium-based orthopaedic implants: A review from clinical translational perspective	Zhao, Dewei	Biomaterials	64.59	507
8	Recent advances on the development of magnesium alloys for biodegradable implants	Chen, Yongjun	Acta Biomaterialia	146	737
9	The development of binary Mg-Ca alloys for use as biodegradable materials within bone	Li, Zijian	Biomaterials	81.89	1194
10	Biodegradable magnesium alloys for orthopaedic applications: A review on corrosion, biocompatibility and surface modifications	Agarwal, Sankalp	Materials Science & Engineering C-Materials for Biological Applications	34.13	489

Note: [a]ACY, average citations per year; [b]TC is the number of total citations.

3.4. Keyword analysis and research hotspots

3.4.1. Keyword analysis. A total of 243 keywords from 100 research are sorted and combined according to the gerund's abbreviation, singular form, and plural form. The co-occurrence network based on high-frequency terms (more than 2) is shown in Figure 7. Keywords co-occurrence analysis found that the words “corrosion”, “biocompatibility”, “biodegradable”, “degradation”, “mechanical properties”, “coating”, “corrosion resistance”,” antibacterial activity”,” orthopedic applications” and “surface modification” had the highest frequency of co-occurrence in the research of magnesium alloy orthopedic implants. In addition, the keywords “porous structures”, “nanoparticles” and “bone scaffold” were also worthy of attention in the highly cited articles. Through the analysis of high-cited articles and keywords, our study objectively reflects the research hotspots of magnesium alloy orthopedic implants.

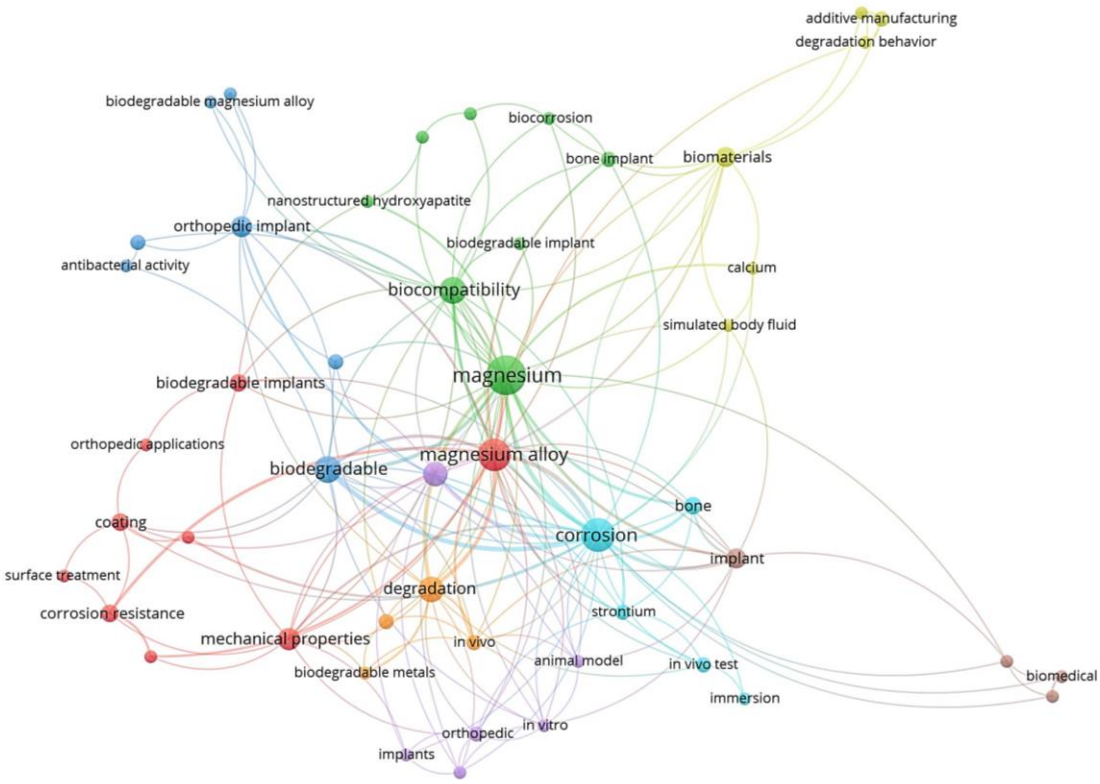

Figure 7. The co-occurrence network of magnesium alloy orthopedic implants keywords.

3.4.2. Clinical application status of magnesium alloy orthopedic implants. An increasing number of surgeons are reevaluating the clinical application potential of biodegradable metals as a result of the rapid advancement in metallurgy in recent years, which has made it possible for engineers and scientists to create magnesium or magnesium alloys with improved mechanical qualities and increased corrosion resistance [6]. In general, there are two types of magnesium alloy orthopedic implants: scaffolds for bone tissue engineering and bone fixation devices [33].

The basic components of a bone fixation device, which is used to mend broken bones, are a bone screw, bone pin, bone plate, etc. Since the first clinical test employing Mg materials as orthopedic implants, more than a century has passed [34]. In Magnesium alloys were originally used as bone nails and bone plates for the fixing of injured bone in 1900, according to Payr et al. [4]. Mg-Al-Mn alloy screws, nuts, and plates were used in 20 fracture treatments carried out by Mcbridge et al. in 1938 [33]. Plates and screws constructed of Mg-Cd alloy were used to treat 34 cases of pseudoarthrosis successfully in 1948, according to Troitskii et al. [34]. Surgeons in Korea recently used Mg-Ca-Zn screws to fix two

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radial fractures, while Germany was the first country to report using MgYReZr alloy screws to treat hallux valgus [35].

Magnesium and related alloys may be suitable materials for tissue engineering bone scaffolds due to its good complete mechanical characteristics, biodegradability, and osteogenesis [36]. Autologous osteoblasts, bone marrow stromal cells, or chondrocytes are placed onto biocompatible synthetic scaffolds for bone tissue engineering before eventually degrading and being absorbed by the body [8, 37]. Recently, a bone defect repair scaffold with anti-infective potential was created, and it has also been extensively proposed that porous magnesium containing biological growth factors or cells might serve as an ideal scaffold for bone tissue creation [38, 39]. A magnesium scaffold was created by Čapek et al. using powder metallurgy and pore-forming chemicals [40]. Mechanical testing revealed that the scaffolds' flexural strength, which ranged from 12 to 38 percent porosity, was comparable to that of human bone. Using the template replication technique, Jia et al. successfully obtained Mg scaffolds and assessed their degrading behavior [41]. There has recently been some work that discusses the laser additive fabrication of magnesium bone scaffolds [42, 43].

3.4.3. Advantages of magnesium alloy orthopedic implants. Magnesium and its alloys have a density of about 1.74 g/cm3, which is comparable to the density of human compact bone (1.75 g/cm3), and their Young's modulus (about 45 GPa) is comparable to that of human bone (15-30 GPa), which can offers good mechanical compatibility and reduces stress shielding during load transfer at the bone-implant interface [44, 45]. Magnesium has a higher modulus than permanent metals, but a lower mechanical strength than biodegradable polymers. The toughness of magnesium is higher than that of bioceramics. In order to prevent mechanical failure imposed on implants and to address potential stress-shielding effects, these point to magnesium and its alloys as being ideal for development as fixators for low load-bearing sites in orthopedics.

Mg and its alloys have favorable biocompatibility as biomaterials. The degradation products of magnesium alloy orthopedic implants are mainly Mg ions, which have no obvious toxicity to human tissues [7]. Mg and its alloys can totally decay in vivo, displaying attractive degradation characteristics and distinctive osteopromotive effects [46]. In order to fully accomplish their therapeutic goal as a temporary alternative, researchers are hoping that magnesium alloy orthopedic implants will gradually disintegrate over time as the bone tissue is healed in addition to initially providing stable mechanical support. Without the need for a second operation to remove this temporarily implanted device, the implants can gradually disintegrate and be absorbed by the body or eliminated from the body, which significantly lowers the expense of surgery and the agony associated with the second operation. Magnesium transporter 1 (MagT1) and transient receptor potential cation channel sub-family member 7 (TRPM7), which can facilitate the release of calcitonin gene-related peptide (CGRP), mediate the release of magnesium ions following the implantation of magnesium alloy implants in vivo [17]. Cyclic AMP can attach to its response element-binding protein in reaction to the released CGRP. Osterix is consequently markedly increased, promoting the production of new bone in the periosteal area.

3.4.4. Techniques to improve corrosion resistance. Despite the many advantages of Mg-based alloys, their main limitation as biomedical materials is the high corrosion rate [47]. We found that there are four typical methods to improve corrosion resistance, including purification, alloying treatment, surface coating and magnesium-based composite (MMC):

• *Purification.* Researchers have suggested using purification techniques to increase the corrosion resistance of magnesium alloys because electrochemical kinetics shows that lowering impurities and the second phase in the Mg matrix can effectively reduce the incidence of galvanic corrosion [48].

•*Alloying treatment.* To enhance the mechanical characteristics and corrosion resistance of magnesium, alloying is a necessary step [49, 50]. A workable strategy is to utilize alloying elements to either generate a second phase that is more favorable or minimize the volume and size of the second phase in the magnesium matrix. This will lessen the galvanic corrosion that the second phase causes. Utilizing alloying components to increase the inertness or structural integrity of the oxides or hydroxides on the surface of the magnesium matrix would be another viable strategy, creating a more protective surface film to halt corrosion expansion [51].

•*Surface coating.* Surface modification of the Mg matrix, as opposed to alloying, can effectively isolate or limit the surface area of interaction between the matrix and body fluids, which may assist retain the mechanical integrity of the Mg-based im-plant until the fracture is fully healed [52, 53].

•*Magnesium based composite (MMC).* Another possible method to control the pace of deterioration is to produce magnesium-based MMC with reinforcing particles [54-56]. Currently, several biologically active biological cancers, including HAp, TCP, and bioglass, are used as enhancing particles of magnesium-based MMC [57-59]. As a low-dimensional nano-material, Graphene oxide (GO) has also been reported to be used as the reinforcement phase of magnesium-based materials [60]. In some research, mesoporous silica (MS) has also been used as reinforcing particles in magnesium-based MMC [61].

4. Conclusions

Mg and Mg alloys have good biocompatibility, degradability and biosafety. In addition, Mg is abundant in re-sources, low in price, suitable for large-scale industrial production, and can be degraded by corrosion in the physio-logical electrolyte environment, which shows its great potential application prospects in the field of orthopedics, and its application effect in orthopedics is remarkable. Although biodegradable magnesium alloys have a lot of potential for orthopedic applications, the primary issue is their high rate of corrosion, which makes the surrounding tissues bioincompatible. There are many animal experiments and basic researches on magnesium alloy implants, and re-searchers are focusing on improving the corrosion resistance of magnesium alloy orthopedic implants and exploring more advanced manufacturing techniques.

Despite numerous reports using magnesium and its alloys as bone-conducting, biodegradable orthopedic im-plants, considerable research is still needed to properly evaluate the potential of magnesium alloys. In order to achieve the wide clinical application of magnesium alloy orthopedic implants, there are still some challenges to be faced, and we look forward to the future research direction in this field. The durability of magnesium alloy orthopedic implants is the primary issue of patient safety. To reliably maintain damaged tissues during service, the mechanical characteristics of magnesium alloys must be improved. Although local sight alkalinity generated by Mg breakdown can limit bacterial adhesion, it is commonly acknowledged that bacterial infection usually occurs in orthopedic treatment, which results in bone healing failure. Therefore, it is crucial to design magnesium implants with anti-bacterial qualities for bone healing. Additionally, the development of orthopedic implants made of magnesium alloy with sustained release mechanisms appears promising. The demand for customized bone implants will rise in the future, so it's important to pay attention to the additive fabrication of magnesium bone implants. Magnesium items produced by laser additive manufacturing can have tiny and consistent microstructures, which should result in enhanced mechanical and corrosion properties. Another pressing issue is the creation of specialized magnesium-based material systems for laser additive manufacturing procedures. However, hybrid materials have a lot of potential for the development of bone implant materials since they combine the benefits of several different materials. In addition, there has to be more research done on the impact of dynamic degradation on the morphology and mechanical characteristics of bone implants. Finally, the difficulties of accurately characterizing the local characteristics of magnesium alloy implants in vivo has drawn research attention to the simulation of thermochemical-mechanical coupling behavior in recent years.

Based on the bibliometric and visual analysis of the top 100 cited articles on magnesium alloy orthopedic implants, we found that more and more attention has been paid to this field since 2005, and the performance of magnesium alloy as an orthopedic implant has also made considerable development. Currently, medical alloy materials are undergoing changes. Researchers have developed new medical alloy materials represented by degradable metals, nano-crystalline metals, and bulk amorphous alloys. Material properties are developing from biological inertia to biological activity and biological function (antibacterial, anti-proliferation, antitumor). At the same time, advanced manufacturing technologies

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represented by 3D printing technology, thin film technology and composite technology have also been tried. The study of magnesium alloy bone implants will take time because the human physiological environment is a complex system. Increased interdisciplinary research is urgently required to hasten the clinical adoption of magnesium alloy orthopedic implants.

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Appendix

Table A1. List of the 100 Most Cited Articles on magnesium alloy orthopedic implant.

Rank	Paper	Country	ACY[a]	TC[b]
1	Magnesium and its alloys as orthopedic biomaterials: A review	New Zealand	190.24	3234
2	In vivo corrosion of four magnesium alloys and the associated bone response	Germany	103.94	1871
3	Degradable biomaterials based on magnesium corrosion	Germany	86.2	1293
4	Metallic implant biomaterials	Australia	152.88	1223
5	The history of biodegradable magnesium implants: A review	Germany	93	1209
6	The development of binary Mg-Ca alloys for use as biodegradable materials within bone	China	79.6	1194
7	In vitro and in vivo corrosion measurements of magnesium alloys	Germany	64.59	1098
8	Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: A review	Australia	146	1022
9	Recent advances on the development of magnesium alloys for biodegradable implants	China	81.89	737
10	Progress and challenge for magnesium alloys as biomaterials	China	34.13	512
11	Current status on clinical applications of magnesium-based orthopaedic implants: A review from clinical translational perspective	China	84.5	507
12	Biodegradable magnesium alloys for orthopaedic applications: A review on corrosion, biocompatibility and surface modifications	Ireland	69.86	489
13	Implant-derived magnesium induces local neuronal production of CGRP to improve bone-fracture healing in rats	China	64.57	452
14	In vivo corrosion behavior of Mg-Mn-Zn alloy for bone implant application	China	27.56	441

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Table A1. (continued).

15	Novel Magnesium Alloys Developed for Biomedical Application: A Review	China	43	430
16	A biodegradable polymer-based coating to control the performance of magnesium alloy orthopaedic implants	China	47.67	429
17	Strategies to improve the corrosion resistance of microarc oxidation (MAO) coated magnesium alloys for degradable implants: Prospects and challenges	South Korea	33	429
18	In vitro degradation and mechanical integrity of calcium-containing magnesium alloys in modified-simulated body fluid	Australia	28.27	424
19	Magnesium alloys for temporary implants in osteosynthesis: In vivo studies of their degradation and interaction with bone	Austria	37.64	414
20	Magnesium alloys as implant materials - Principles of property design for Mg-RE alloys	Germany	31.54	410
21	Magnesium ion stimulation of bone marrow stromal cells enhances osteogenic activity, simulating the effect of magnesium alloy degradation	USA	38.89	350
22	In vitro and in vivo studies on a Mg-Sr binary alloy system developed as a new kind of biodegradable metal	China	29.73	327
23	Recommendation for modifying current cytotoxicity testing standards for biodegradable magnesium-based materials	China	39.25	314
24	Biodegradable magnesium-based screw clinically equivalent to titanium screw in hallux valgus surgery: short term results of the first prospective, randomized, controlled clinical pilot study	Germany	30.9	309

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Table A1. (continued).

25	Electrodeposition of Ca-P coatings on biodegradable Mg alloy: In vitro biomineralization behavior	China	23.23	302
26	Bone-implant interface strength and osseointegration: Biodegradable magnesium alloy versus standard titanium control	Austria	25.08	301
27	In vitro degradation and mechanical integrity of Mg-Zn-Ca alloy coated with Ca-deficient hydroxyapatite by the pulse electrodeposition process	China	21.08	274
28	Biodegradable magnesium scaffolds: Part II: Peri-implant bone remodeling	Germany	15.94	255
29	Biodegradable Materials for Bone Repairs: A Review	China	25.1	251
30	Surface design of biodegradable magnesium alloys - A review	China	24.3	243
31	Insight of magnesium alloys and composites for orthopedic implant applications - a review	India	39.5	237
32	Long-term clinical study and multiscale analysis of in vivo biodegradation mechanism of Mg alloy	South Korea	33.71	236
33	Magnesium hydroxide temporarily enhancing osteoblast activity and decreasing the osteoclast number in peri-implant bone remodelling	Germany	18.15	236
34	Advances in functionalized polymer coatings on biodegradable magnesium alloys - A review	China	46	230
35	Design of magnesium alloys with controllable degradation for biomedical implants: From bulk to surface	China	30.57	214
36	In Vitro Corrosion and Cytocompatibility of a Microarc Oxidation Coating and Poly(L-lactic acid) Composite Coating on Mg-1Li-1Ca Alloy for Orthopedic Implants	China	28.86	202

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Table A1. (continued).

37	Biodegradable magnesium implants for orthopedic applications	Germany	19.7	197
38	Mg bone implant: Features, developments and perspectives	China	63.33	190
39	In vivo evaluation of biodegradable magnesium alloy bone implant in the first 6 months implantation	China	13.5	189
40	Influence of the Microstructure and Silver Content on Degradation, Cytocompatibility, and Antibacterial Properties of Magnesium-Silver Alloys In Vitro	Germany	60.67	182
41	Alloying design of biodegradable zinc as promising bone implants for load-bearing applications	China	30.33	182
42	Investigation of the mechanical and degradation properties of Mg-Sr and Mg-Zn-Sr alloys for use as potential biodegradable implant materials	USA	15.73	173
43	Potential release of in vivo trace metals from metallic medical implants in the human body: From ions to nanoparticles - A systematic analytical review	Poland	18.67	168
44	Metals for bone implants. Part 1. Powder metallurgy and implant rendering	USA	18.44	166
45	In vitro degradation behavior and cytocompatibility of Mg-Zn-Zr alloys	Netherlands	12.62	164
46	In-vitro dissolution of magnesium-calcium binary alloys: Clarifying the unique role of calcium additions in bioresorbable magnesium implant alloys	New Zealand	12.46	162
47	In vitro corrosion behaviour of Mg alloys in a phosphate buffered solution for bone implant application	China	10.4	156
48	Magnesium alloys: Predicting in vivo corrosion with in vitro immersion testing	New Zealand	14	154

Table A1. (continued).

49	Biodegradable Mg-Cu alloy implants with antibacterial activity for the treatment of osteomyelitis: In vitro and in vivo evaluations	China	21.71	152
50	Biodegradable Orthopedic Magnesium-Calcium (MgCa) Alloys, Processing, and Corrosion Performance	USA	13.82	152
51	An overview of recent advances in designing orthopedic and craniofacial implants	USA	14.9	149
52	Biocompatible magnesium alloys as absorbable implant materials - Adjusted surface and subsurface properties by machining processes	Germany	9.31	149
53	Surface modification of magnesium alloys developed for bioabsorbable orthopedic implants: A general review	China	13.09	144
54	Recent advances in biodegradation controls over Mg alloys for bone fracture management: A review	Australia	34.5	138
55	Fabrication, mechanical properties and in vitro degradation behavior of newly developed Zn-Ag alloys for degradable implant applications	Italy	22	132
56	Long-term in vivo degradation behaviour and biocompatibility of the magnesium alloy ZEK100 for use as a biodegradable bone implant	Germany	12.4	124
57	Biodegradable magnesium alloys as temporary orthopaedic implants: a review	China	30.75	123
58	Effects of nanofeatures induced by severe shot peening (SSP) on mechanical, corrosion and cytocompatibility properties of magnesium alloy AZ31	Italy	24.2	121
59	Biodegradable Magnesium Alloys Developed as Bone Repair Materials: A Review	China	23.4	117

Table A1. (continued).

60	Surface Modification on Biodegradable Magnesium Alloys as Orthopedic Implant Materials to Improve the Bio-adaptability: A Review	China	16.14	113
61	Bio-corrosion characterization of Mg-Zn-X (X = Ca, Mn, Si) alloys for biomedical applications	Italy	8.69	113
62	Opportunities and challenges for the biodegradable magnesium alloys as next-generation biomaterials	China	16	112
63	Fabrication and characterization of rod-like nano-hydroxyapatite on MAO coating supported on Mg-Zn-Ca alloy	China	9.33	112
64	Effect of electrodeposition modes on surface characteristics and corrosion properties of fluorine-doped hydroxyapatite coatings on Mg-Zn-Ca alloy	China	8.83	106
65	Controlling the degradation rate of AZ91 magnesium alloy via sol-gel derived nanostructured hydroxyapatite coating	Iran	10.3	103
66	Current status and perspectives of zinc-based absorbable alloys for biomedical applications	Canada	25.25	101
67	In vivo study of a biodegradable orthopedic screw (MgYREZr-alloy) in a rabbit model for up to 12 months	Germany	11.11	100
68	In vitro and in vivo corrosion, cytocompatibility and mechanical properties of biodegradable Mg-Y-Ca-Zr alloys as implant materials	Germany	10	100
69	Cartilage repair on magnesium scaffolds used as a subchondral bone replacement	Germany	5.88	100
70	Mechanical characteristics of biodegradable magnesium matrix composites: A review	USA	16.33	98
71	Surface treatments for controlling corrosion rate of biodegradable Mg and Mg-based alloy implants	Australia	12.25	98

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Table A1. (continued).

72	In vivo degradation behavior of Ca-deficient hydroxyapatite coated Mg-Zn-Ca alloy for bone implant application	China	8.08	97
73	Osteoblast response to magnesium ion-incorporated nanoporous titanium oxide surfaces	South Korea	7.23	94
74	Hydroxyapatite-doped poly(lactic acid) porous film coating for enhanced bioactivity and corrosion behavior of AZ31 Mg alloy for orthopedic applications	South Korea	9.2	92
75	Electrophoretic deposition of nano structured hydroxyapatite coating on AZ91 magnesium alloy implants with different surface treatments	Iran	8.5	85
76	Ion channel functional protein kinase TRPM7 regulates Mg ions to promote the osteoinduction of human osteoblast via PI3K pathway: In vitro simulation of the bone-repairing effect of Mg-based alloy implant	China	13.17	79
77	Dual modulation of bone formation and resorption with zoledronic acid-loaded biodegradable magnesium alloy implants improves osteoporotic fracture healing: An in vitro and in vivo study	China	15.6	78
78	An in vivo study on the metabolism and osteogenic activity of bioabsorbable Mg-1Sr alloy	China	11.14	78
79	The current trends of Mg alloys in biomedical applications-A review	USA	19.25	77
80	Electrophoretic deposition of hydroxyapatite coating on Mg-3Zn alloy for orthopaedic application	Australia	10.71	75

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Table A1. (continued).

81	Loss of mechanical properties in vivo and bone-implant interface strength of AZ31B magnesium alloy screws with Si-containing coating	India	8.33	75
82	Evaluating the stress corrosion cracking susceptibility of Mg-Al-Zn alloy in modified-simulated body fluid for orthopaedic implant application	China	5	75
83	New, fast corroding high ductility Mg-Bi-Ca and Mg-Bi-Si alloys, with no clinically observable gas formation in bone implants	Germany	6.17	74
84	Challenges and opportunities for biodegradable magnesium alloy implants	India	14.4	72
85	In vitro study of nanostructured diopside coating on Mg alloy orthopedic implants	China	7.78	70
86	Preparation and characterization of as-extruded Mg-Sn alloys for orthopedic applications	USA	8.63	69
87	Facile Preparation of Poly(lactic acid)/Brushite Bilayer Coating on Biodegradable Magnesium Alloys with Multiple Functionalities for Orthopedic Application	China	11.33	68
88	Corrosion and biocompatibility improvement of magnesium-based alloys as bone implant materials: a review	China	11	66
89	Addition of Zn to the ternary Mg-Ca-Sr alloys significantly improves their antibacterial properties	China	8.13	65
90	Process mechanics and surface integrity by high-speed dry milling of biodegradable magnesium-calcium implant alloys	China	5	65
91	Laser additive manufacturing of Mg-based composite with improved degradation behaviour	USA	21.33	64

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Table A1. (continued).

92	In Vitro and in Vivo Studies on Biomedical Magnesium Low-Alloying with Elements Gadolinium and Zinc for Orthopedic Implant Applications	China	12.6	63
93	Formation mechanism of Ca-deficient hydroxyapatite coating on Mg-Zn-Ca alloy for orthopaedic implant	USA	7	63
94	Synthesis and characterization of Mg-Ca-Sr alloys for biodegradable orthopedic implant applications	China	5.73	63
95	Development of magnesium-based biodegradable metals with dietary trace element germanium as orthopaedic implant applications	China	10.33	62
96	In vitro degradation behavior, antibacterial activity and cytotoxicity of TiO2-MAO/ZnHA composite coating on Mg alloy for orthopedic implants	USA	11.4	57
97	The effects of nanostructured hydroxyapatite coating on the biodegradation and cytocompatibility of magnesium implants	Iran	5.7	57
98	Microstructure, mechanical properties, bio-corrosion properties and cytotoxicity of as-extruded Mg-Sr alloys	China	9.33	56
99	The in vivo degradation and bone-implant interface of Mg-Nd-Zn-Zr alloy screws: 18 months post-operation results	China	8	56
100	Microwave aqueous synthesis of hydroxyapatite bilayer coating on magnesium alloy for orthopedic application	China	7.83	47

Note: [a]ACY , average citations per year; [b]TC is the number of total citations.