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Evolving Trends in Bioactive Glass Coatings: A Systematic Review of Global Research and Applications

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Abstract

Bioactive glass (BG) coatings are essential in advancing regenerative medicine, enhancing interactions with biological tissues and improving the performance of medical and dental implants. Since their discovery in the late 1960s, BGs have evolved to meet the demands of biomedical applications, particularly in orthopedics and dentistry. This systematic review examines the development and recent advancements in BG coatings, focusing on innovative techniques that address mechanical and biological challenges. Utilizing VOSviewer software, the review conducts a bibliometric analysis to map research networks and identify influential studies shaping BG technology. It highlights promising research directions, emphasizing nanotechnology and composite materials. These innovations aim to overcome existing limitations of BGs, unlocking new possibilities for bone regeneration and other therapeutic areas. The review underscores significant progress in BG coatings and points to future breakthroughs that could redefine their role in modern medicine, making them vital for next-generation medical treatments.

Keywords: Bioactive glass coating, Bioceramic implants, Biomedical application, Surface modification, Advanced coating techniques.

1. Introduction

Bioceramics, particularly BGs, have gained prominence in the field of biomaterials due to their exceptional ability to bond with living tissues, making them highly suitable for a wide range of medical applications, especially in implants and tissue regeneration [1]. The inception of BGs traces back to the pioneering work of Larry L. Hench in the late 1960s, who developed Bioglass 45S5, a material capable of forming a direct chemical bond with bone and soft tissues [2].

This discovery has since evolved into a significant area of research and development, particularly in biomedical implants and tissue engineering [3]. Over the past decades, BGs have been modified and refined to enhance their mechanical properties and biological performance, meeting the growing demands of modern clinical applications [4]. A key characteristic of BGs is their bioactivity—defined as the ability to elicit specific biological responses at the material-tissue interface, promoting the formation of a strong bond with surrounding tissues [5]. This makes them invaluable in applications such as bone grafting, where they not only act as scaffolds but also actively participate in the healing process. Despite their impressive bioactivity, BGs often exhibit mechanical limitations, including brittleness and a limited ability to bear load, which restricts their use in load-bearing implants [6]. Addressing these limitations has become a focus for researchers, leading to the development of advanced surface modification and coating techniques aimed at enhancing the mechanical performance and durability of BGs when applied to more robust bioinert substrates like titanium [7]. This systematic review encompasses studies published from 1975 to 2024, using bibliometric data extracted from the Scopus database. The inclusion criteria were specifically designed to target peer-reviewed articles, reviews, and patents that address the synthesis, modification, and application of BG coatings. By focusing on a time frame that spans nearly five decades, this review captures both the foundational research in BGs and recent innovations, including nanoscale modifications and hybrid materials [8]. These innovations are shaping the next generation of bioactive coatings, which aim to optimize the balance between bioactivity and mechanical strength, offering better integration with biological tissues and improved outcomes in regenerative medicine [9]. As research in this field progresses, there has been a growing emphasis on the integration of BGs with newer biocompatible materials and nanotechnology. Such developments not only promise to improve the performance of medical implants but also open new avenues for patient-specific treatments, particularly in the fields of orthopedics and dentistry [10]. The convergence of material science, coating technologies, and nanotechnology marks a transformative phase in the application of BG coatings, making them essential in addressing the challenges of modern medicine. This review systematically evaluates the current literature, highlighting advancements, challenges, and future directions in the use of BG coatings for medical and dental implants.

2. Methods

2.1. Search Strategy

The bibliometric data for this review was collected from the Scopus database, one of the most comprehensive repositories for academic literature. An advanced search was conducted on 11th October 2024 using the following keywords: "bioactive glass," "biomaterials," "bioglass," "coating," "surface modification," and "hydroxyapatite." The search query was structured to include these terms in the title, abstract, or keywords of relevant papers. The exact query used is as follows: TITLE-ABS-KEY ("bioactive glass") OR, TITLE-ABS-KEY ("bioactive ceramics") OR , TITLE-ABS-KEY ("biomaterials") OR, TITLE-ABS-KEY (bioglass) AND, TITLE-ABS-KEY (coating) OR, TITLE-ABS-KEY ("coating technique") OR, TITLE-ABS-KEY ("Surface modification") AND , TITLE-ABS-KEY ("hydroxyapatite").

This search yielded a total of 3370 documents, spanning from 1984 to 2024, and including articles from various subject areas such as materials science, engineering, physics, and chemistry.

2..2. Eligibility Criteria

Studies were included based on the following criteria: Must be published in peer-reviewed journals between 1984 and 2024, Relevant to BG, biomaterials, coating techniques, and surface modifications in biomedical applications, Studies focused on hydroxyapatite coatings were included, Non-English language articles, conference abstracts, and duplicate studies were excluded.

2.3. Data Extraction

The data was extracted from Scopus, focusing on bibliometric indicators such as Total Papers (TP), Total Citations (TC), and Citations Per Paper (CPP). The extracted dataset included information on authors, publication year, country, journal title, and affiliation. These indicators were utilized to assess the impact and influence of the studies on BG coatings over time.

2.4. Bibliometric Analysis

Several performance indicators were employed to assess the impact of publications: TP (Total Papers): Reflects the total number of papers published on the topic each year, TC (Total Citations): Refers to the total number of citations that each publication received, CPP (Citations per Paper): The average number of citations per publication, calculated by dividing the TC by the TP. These indicators were used to construct a column bar plot illustrating the distribution of publications and citations over time.

3. Results

3.1. Overview of Publications and Time Trends

The development of BG coatings has evolved significantly over the decades, beginning with the initial discovery of BG in 1969. This innovation laid the groundwork for future research into bioactive materials capable of bonding with human tissue, a property that has profound implications for medical and dental implants and regenerative medicine. A chart overview of the publications and citations is listed in Fig. 1.

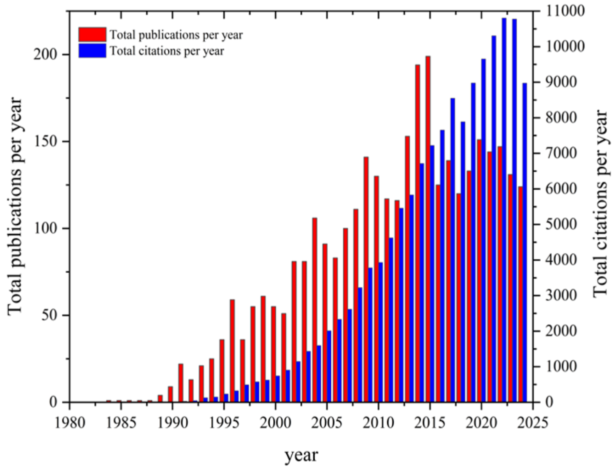

Figure 1. Total Number of Publications and Citations per year in Scopus database.

The significance of BGs became increasingly evident in the 1980s and 1990s as research began to uncover their potential, especially in bone regeneration [11]. By the early 2000s, attention shifted from merely understanding their inherent properties to improving their functionality through surface modifications. This era saw a growing number of studies investigating different types of BGs and ceramics, exploring how surface treatments could enhance clinical outcomes. A notable turning point occurred between 2005 and 2010 when advancements in nanotechnology and materials allowed for greater precision in developing coating techniques [12]. These innovations enabled more effective integration of BG coatings into complex implant systems, leading to enhancements in durability and functionality [13]. Techniques like plasma spraying, cold gas spraying, and aerosol deposition were refined during this period, contributing to significant progress in implant technology [14]. Since 2010, there has been a clear trend toward customizing bioactive coatings to address specific clinical needs. Incorporating doping agents such as magnesium, copper, and zinc has become more prevalent, as these elements enhance osteoconductivity, bioactivity and ultimately bone-bonding ability, while simultaneously improving the mechanical strength of the fabricated coatings. In addition, composite materials were further developed to optimize the performance of BGs in various medical applications. This growing body of research reflects a consensus on the importance of tailored bioactive materials for diverse clinical uses [15].

The importance of BGs became particularly pronounced in the 1980s and 1990s as researchers began to delve deeper into their potential applications, particularly in bone regeneration [16]. By the early 2000s, the focus expanded from merely understanding the material's properties to enhancing its functionality through surface modifications. This period saw an increase in studies exploring different types of BGs and ceramics and how their surfaces could be modified to improve outcomes in clinical applications. A significant leap occurred in the mid-2000s, especially around 2005-2010, when advances in nanotechnology and materials science provided new tools and methodologies to develop sophisticated coating techniques [17]. These advancements facilitated more precise control over the properties of coatings, allowing for the development of BGs coatings that could be more effectively integrated into complex implant systems [18]. Techniques such as plasma spraying, cold gas spray, and aerosol deposition were refined during this time, leading to improved durability and functionality of implants. From 2010 onwards, there was a clear trend towards the customization of bioactive coatings to address specific clinical needs. Research publications surged, reflecting a growing consensus on the importance of tailored bioactive materials for diverse medical applications [19]. Most recently, the past decade has been crucial for the integration of cutting-edge technologies with traditional BG research. The rise of additive manufacturing and 3D printing technologies has given new stems for the application of BGs in more complex and patient-specific implant designs. This period has also seen an increasing focus on sustainability and the environmental impact of material production, driving research towards more eco-friendly manufacturing processes. Throughout these years, the continuous advancements in BGs coatings have been documented in a wealth of scientific literature, with significant spikes in publications during periods of technological breakthroughs and clinical application refinements. This ongoing research effort not only highlights the historical importance of key developments but also sets the stage for future innovations in BGs applications in medicine.

3.2. Patent Trends in Bioactive Glass Technology

The analysis of patent trends is further illustrated in Fig. 2, which shows the annual numbers of total patents and total research papers related to BGs from 1975 to 2024. The plot highlights the parallel growth in both patent filings and academic publications, emphasizing the strong relationship between research activity and technological innovation in the field. This visual representation demonstrates periods of heightened innovation, such as the notable increase in patent filings and research output from 2000 onwards, reflecting the maturation of BG technologies into marketable solutions. This systematic analysis not only maps the academic contributions to the field but also highlights the practical applications and technological advancements as seen through patenting trends.

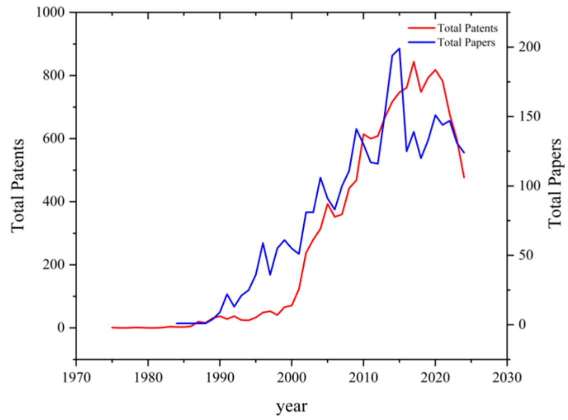

Figure 2. Annual Trends in Total Patents and Research Papers Related to BGs (1975–2024).

The patenting activity for BG technologies began modestly in the late 1970s and 1980s, with just a few patents each year. This period corresponds to the early stages of research into BGs, where academic interest in their potential for bone regeneration and other biomedical applications was first emerging. The number of patents remained low throughout the 1980s, aligning with a period of foundational research that laid the groundwork for later technological applications. A notable increase in patent filings occurred in the mid-1990s, coinciding with a rise in published research on the topic. This trend accelerated significantly from the early 2000s onwards, as research focus shifted from understanding the basic properties of BGs to exploring surface modifications and coating techniques that could improve their integration with medical and dental implants. Between 2000 and 2010, the number of patents grew rapidly, reflecting advancements in both the materials science and biomedical engineering aspects of BGs. Key patents during this period include innovations in surface coating methods, which enhanced the performance of BGs in clinical settings. The correlation between the rise in patents and the increase in published papers suggests a strong synergy between academic research and technological innovation. For example, the early 2000s saw a rise in studies on coating techniques such as plasma spraying, which translated into patents that improved the durability and biocompatibility of BG coatings for implants. This period also saw the emergence of patents focused on the synthesis of novel BG compositions and their use in specific applications like bone graft substitutes. This synergy is evident in the parallel increase in both patent filings and research publications from 2005 to 2020, where patent numbers climbed from around 393 in 2005 to over 800 annually by 2020. Such growth reflects the academic community's efforts to address practical challenges—such as improving the mechanical properties of BGs and expanding their applications beyond traditional bone regeneration—and the industry's interest in protecting these innovations as intellectual property. It highlights the transition of BG technologies from the lab to commercially viable products.

3.2.1. Recnt Patenting Activity and Emerging Innovations

In recent years, patent filings have continued to be a significant indicator of innovation in the field of BGs, albeit with some fluctuations. The data from 2020 to 2024 shows a decline in annual patent filings, dropping from 818 in 2020 to to 477 in 2024. This decline could be attributed to market saturation or shifts in research focus towards more niche applications of BGs, such as in tissue engineering and personalized medicine. However, the sustained activity suggests ongoing interest in refining existing technologies and exploring new avenues, such as nanocrystalline materials and advanced 3D printing techniques. Recent patents, such as US12115072 for an implant with a porous outer cortical layer, reflect continued efforts to improve the performance and integration of BGs in complex medical applications. Other patents like US20240335592, which focuses on nanocrystalline hydroxyapatite/ polyurethane hybrid polymers, indicate the exploration of hybrid materials that enhance the mechanical properties and bioactivity of BGs. This trend towards hybrid and composite materials shows how the industry is adapting research findings into next-generation products that cater to evolving clinical needs.

3.2.2.Role of Patents in Start-Ups and Market Development

Patents play a crucial role in the formation and growth of start-ups centered around BG technologies. Several startups make use of patented inventions to produce specialized products that target specific markets for dental and medical implants. For example, Poriferous, LLC and Tenon Medical, Inc., both of which hold recent patents related to BG-based implants, are likely utilizing their intellectual property to secure a competitive advantage in the medical device market. These patents not only protect technological advancements but also attract investment by demonstrating the unique value of the start-up's offerings. Start-ups focused on BG technologies often emphasize the commercial applications of their patents, ranging from improved coatings for dental implants to advanced scaffolds for tissue engineering. For instance, Vanderbilt University's patent on hybrid polymers reflects the academic-to-commercial pathway, where university research is translated into marketable solutions through licensing agreements or spin-off companies. This process underscores the importance of patents in bridging the gap between academic discoveries and real-world applications.

3.2.3. Patents as a Measure of Market Interest and Innovation

The analysis of patent trends reveals that patents serve as a barometer of industry interest and investment in BG technologies. Periods with high patent activity often align with heightened commercial interest and market opportunities, as companies seek to secure a stake in the emerging applications of BGs. This is particularly true in regions like the United States and China, which dominate both the research output and patent filings in the field. As companies seek to differentiate themselves through innovation, patents become a critical tool for protecting new methods of synthesis, coating, and application of BGs.

3.3. Subject Area Distribution

The retrieved documents were also categorized by subject area, as shown in Table 1. This categorization allowed for further analysis of the interdisciplinary nature of the research on BGs: The interdisciplinary nature of BG research is evident from its wide distribution across several subject areas, as demonstrated by the bibliometric analysis. The majority of publications stem from the fields of materials science and engineering, which highlights the crucial role these disciplines play in understanding and optimizing the structural and surface properties of BGs. With 2344 publications, materials science leads in this area, underscoring its importance in investigating the composition and development of BGs for various biomedical applications.

Table 1. Distribution of BG Research by Subject Area

No.	Subject Area	Doc.
1	Materials Science	2344
2	Engineering	1683
3	Physics and Astronomy	804
4	Chemical Engineering	724
5	Biochemistry, Genetics, Molecular Biology	679
6	Chemistry	521
7	Medicine	395
8	Dentistry	201

Engineering follows closely behind 1683 publications, focusing on developing and refining the techniques required to apply BG coatings effectively, such as plasma spraying and other surface modification technologies. The field of physics also makes a significant contribution, with 804 publications. Research in this domain often explores the physical properties of BGs, such as their porosity, mechanical strength, and thermal behavior, all of which are critical for their application in medical implants and regenerative medicine. Chemical engineering, with 724 publications, complements this by focusing on the synthesis and processing techniques for BGs, including the incorporation of doping agents such as magnesium, zinc, and copper to enhance their bioactivity and mechanical properties. Additionally, the biological sciences contribute to a growing body of research, with biochemistry, genetics, and molecular biology accounting for 679 publications. These studies are essential for understanding the interactions between BGs and biological tissues, including their effects on cell proliferation, differentiation, and osteointegration. This is particularly relevant for their use in tissue engineering and regenerative medicine. The medical and dental fields have also significantly contributed, with 395 and 201 publications, respectively, focusing on the clinical applications of BGs, particularly in bone regeneration, dental restorations, and implant technologies. Emerging fields such as pharmacology and toxicology, environmental science, and neuroscience, although contributing fewer publications, indicate the expanding potential of BG applications beyond traditional biomedical fields. Research in these areas explores innovative uses of BGs, such as in drug delivery systems, environmental protection, and even neural regeneration, which opens up new avenues for their development.

3.4. Geographical Distribution and Collaboration

The geographical distribution of BG research shows a global effort, with China leading the field with 617 publications, followed by the United States with 436. Both countries have made significant contributions to advancing BG technologies for medical applications, such as bone regeneration and implant coatings. European countries, including Germany (227), the United Kingdom (186), and Italy (180) play a critical role, often collaborating across borders to drive innovations in BG coatings and materials science. Japan (259) and India (241) are also key contributors, with their research focusing on nanotechnology and novel coating techniques. Emerging contributors such as Brazil (125), South Korea (151), and Iran (133) are expanding their research output through international collaborations, while countries like France (123), Spain (118), and Australia (103) continue to play important roles in the field.

through international collaborations, while countries like France (123), Spain (118), and Australia (103) continue to play important roles in the field.

Smaller but notable contributions come from countries like Turkey (101), Poland (84), and Romania (97), emphasizing the growing interest in BG research worldwide. The global nature of this research is highlighted by a map showing the distribution of articles across different countries, displayed in Fig. 3. below. This map provides a visual representation of the widespread geographical collaboration that is key to advancing the field of BG coatings for medical applications.

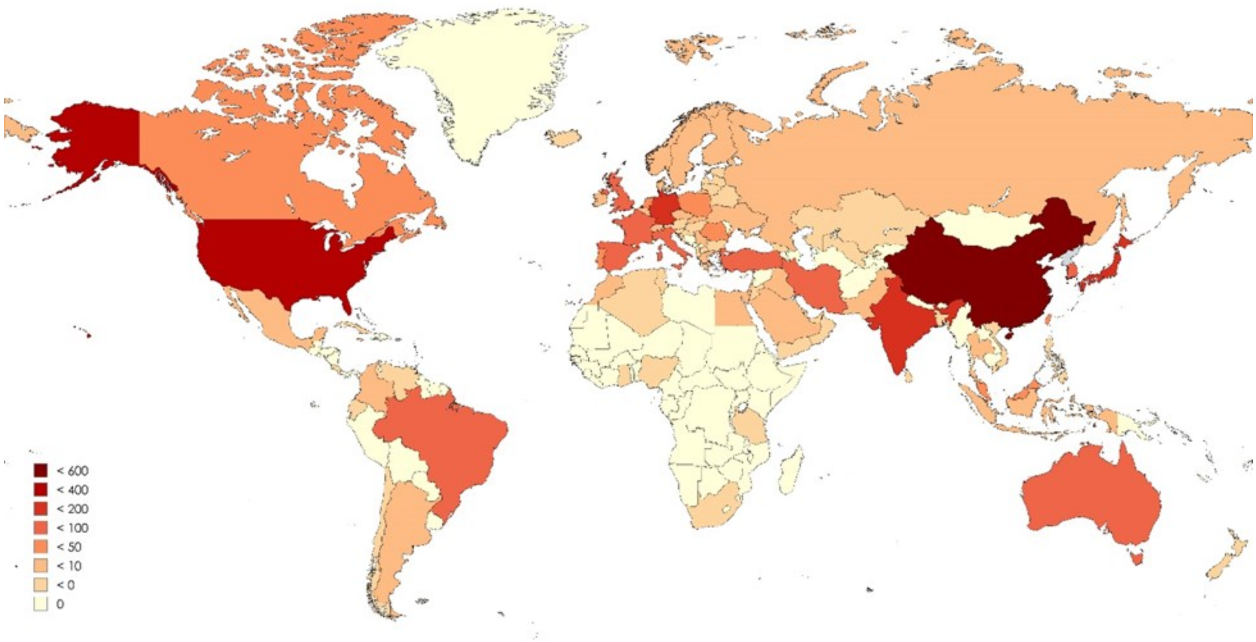

Figure 3. Global Distribution of BG Research Publications (1984–2024).

3.5. Most Productive and Highly Cited Authors

The most prolific authors on Scopus were identified and ranked according to their publication count. In cases where authors had the same number of publications, they were further ranked by their total number of citations. Table 3 displays the top 15 most prolific authors, with Aldo R. Boccaccini leading with 86 publications. Following him, Khiam Aik Khor is the next most prolific, boasting 28 publications. Additionally, the ranking of the most influential authors was determined based on the total citations their publications received. Aldo R. Boccaccini not only tops the list in terms of productivity but also leads as the most influential author with 6,074 citations in Scopus. Fig. 4 visually represents the links between the most influential authors, where the size of each node indicates the impact from a citation perspective.

3.5.1. Country-wise Analysis

This section details the top 15 countries that have produced the most publications in the field. Table 4 lists these countries, ranked by their total number of publications and considering both the total citations received and citations per publication. In Scopus, China stands out as the leading country, holding the first position with a total of 605 publications and also topping the chart from the perspective of total citations. Fig. 5 depicts the connections between the most influential countries in the area of BG coating. As noted in earlier sections, the node size in this figure reflects the citation count.this figure reflects the citation count.

Table 3. Top 15 most productive authors in Scopus [20–22].

Rank	Authors	Total Publications	Total Citations	Citations Per Publications
1	Boccaccini,	86	6074	70.62
2	Khor, K.A.	28	1958	69.92
3	Jansen, J.A.	27	1280	47.40
4	Wolke, J.G.C.	23	1612	70.086
5	Kim, H.E.	22	1725	78.40
6	Kim, H.W.	18	1420	78.88
7	Mihailescu, I.N.	18	1167	64.83
8	Gross, K.A.	18	921	51.16
9	Reis, R.L.	18	783	43.5
10	Cannillo, V.	17	670	39.41
11	Ong, J.L.	16	1639	102.43
12	Roether, J.A.	16	1337	83.56
13	Stan, G.E.	16	672	42
14	Cheang, P.	15	1271	84.73
15	Ben-Nissan, B.	15	661	44.06

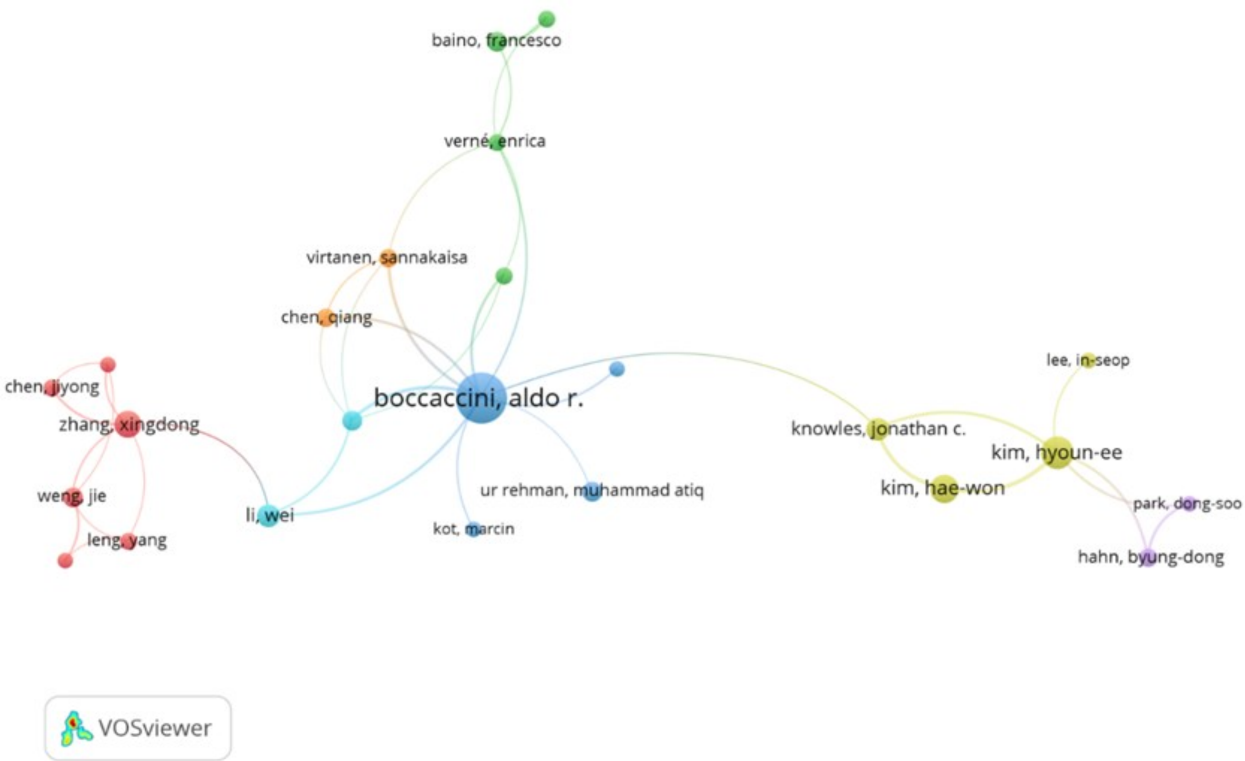

Figure 4. The connection among the most influential authors.

Table 4. Top 15 countries publishing work on BG coating Scopus

Rank	*Countries*	*Total Publications*	*Total Citations*	*Citations Per Publications*
1	China	605	18784	31.04
2	United State	435	309800	70.80
3	Japan	255	7548	29.6
4	Germany	226	9723	43.02
5	India	224	5914	26.40
6	United Kingdom	184	14804	80.45
7	Italy	179	9116	50.92
8	South Korea	148	7746	52.33
9	Iran	126	5018	39.82
10	France	123	4769	38.77
11	Brazil	122	2843	23.30
12	Spain	117	4514	38.58
13	Australia	103	6805	66.06
14	Turkey	96	2277	23.71
15	Romania	94	2811	29.90

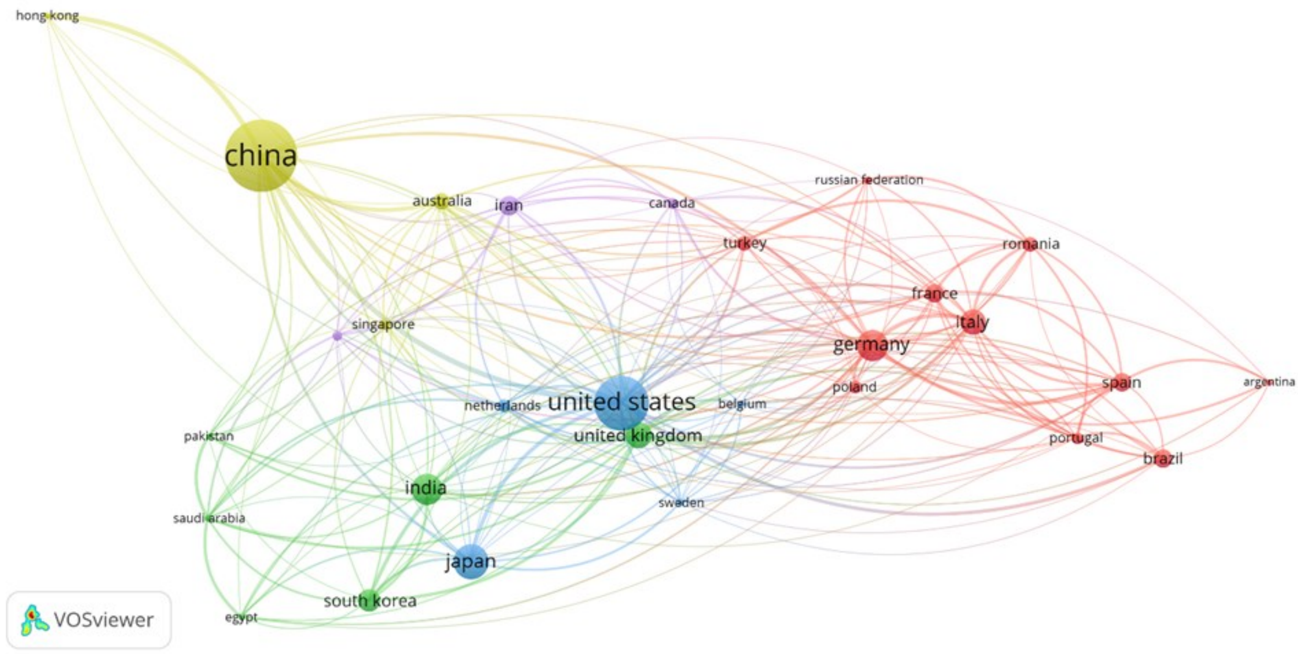

Figure 5. The connection among the documents published along countries.

3.5.2. Top Keywords in Scopus

In this part of the systematic review, we highlight the most influential keywords that frequently appear in the literature concerning BGs coatings. Using VOSviewer, we have identified and analyzed the top keywords that define the scope and focus of research within this field. The following keywords have been most prominent: Hydroxyapatite, Biomaterials, Titanium, Coated Materials, Human, Surface Property, Biocompatibility, Coatings, Calcium Phosphate, and Bone Regeneration and other keywords are listed in Table 5.

Fig. 6 displays a connected network of these keywords, as indexed in Scopus, demonstrating how they are interrelated and often co-occur in various studies. This visualization helps in understanding the thematic concentration of the field and underscores the critical areas of research that are currently driving innovations in BGs coatings. By examining these keywords, we gain insights into the material properties researchers prioritize, the biological interactions they investigate, and the specific applications they target in the realm of regenerative medicine and implant technology.

Table 5. Top 15 keywords and their link strength based on the Scopus database.

Rank	*Keywords*	*Total Link Strength*
1	Hydroxyapatite	68048
2	Biomaterials	39245
3	Titanium	26362
4	Coated Materials	25471
5	Surface Property	24125
6	Biocompatibility	22168
7	Surface Properties	20414
8	Human	19940
9	Coatings	18990
10	Calcium phosphate	17808
11	Bone regeneration	14576
12	Cell proliferation	13883
13	Cell Adhesion	13224
14	Osteoblast	13037
15	Cell culture	12688

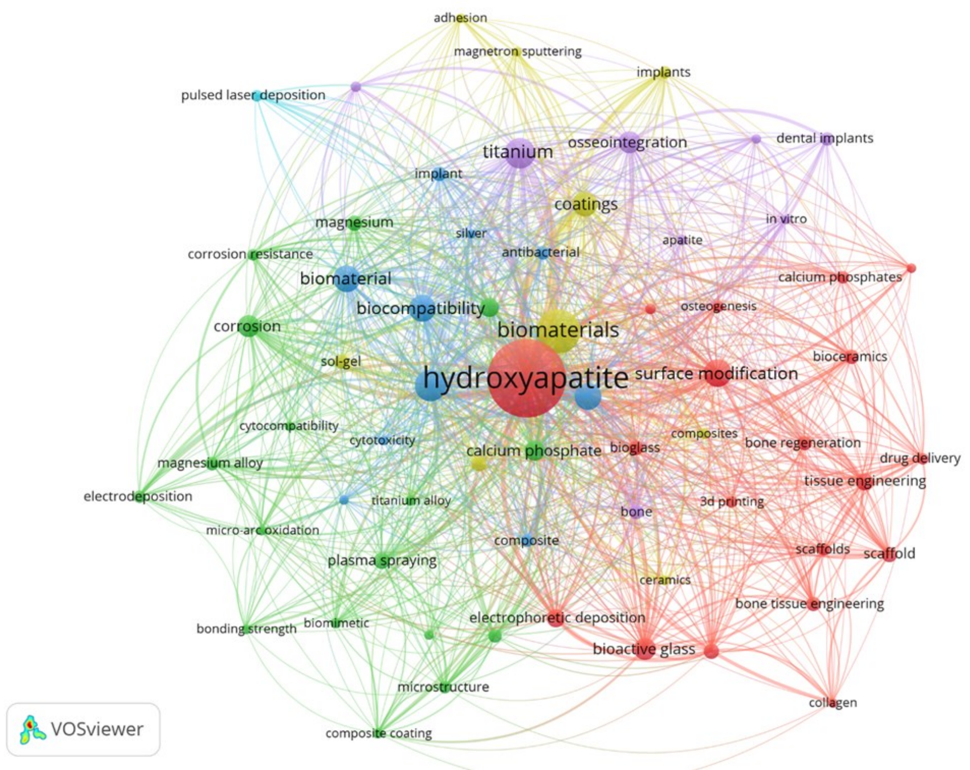

Figure 6. The connection among the most repeated Keywords.

3.5.3. Recent Research Trends

The visualization reveals that several key topics have gained prominence in recent years. Notably, "Hydroxyapatite" remains a central theme, reflecting ongoing interest in its applications for bone regeneration and biocompatibility. "Titanium alloys" have also emerged as a significant area of research, particularly in the context of enhancing implant materials through surface modifications and coatings to improve their performance and longevity. Another recent trend is the focus on "Corrosion resistance" and "Surface modification" techniques, which are crucial for developing durable bioactive coatings that can withstand the physiological environment, thereby extending the lifespan of implants. Researchers have also been exploring "Composite coatings," which combine different materials to leverage their strengths, creating more effective and versatile coatings. The topic of "Electrophoretic deposition" has also seen increased attention, underscoring its utility in applying uniform and controlled bioactive coatings on various substrates. Additionally, "Plasma electrolytic oxidation" and "Nanostructures" have been highlighted as innovative approaches to improving the properties of BGs coatings, facilitating better integration with biological tissues. All other connections on this topic are shown in Fig. 7

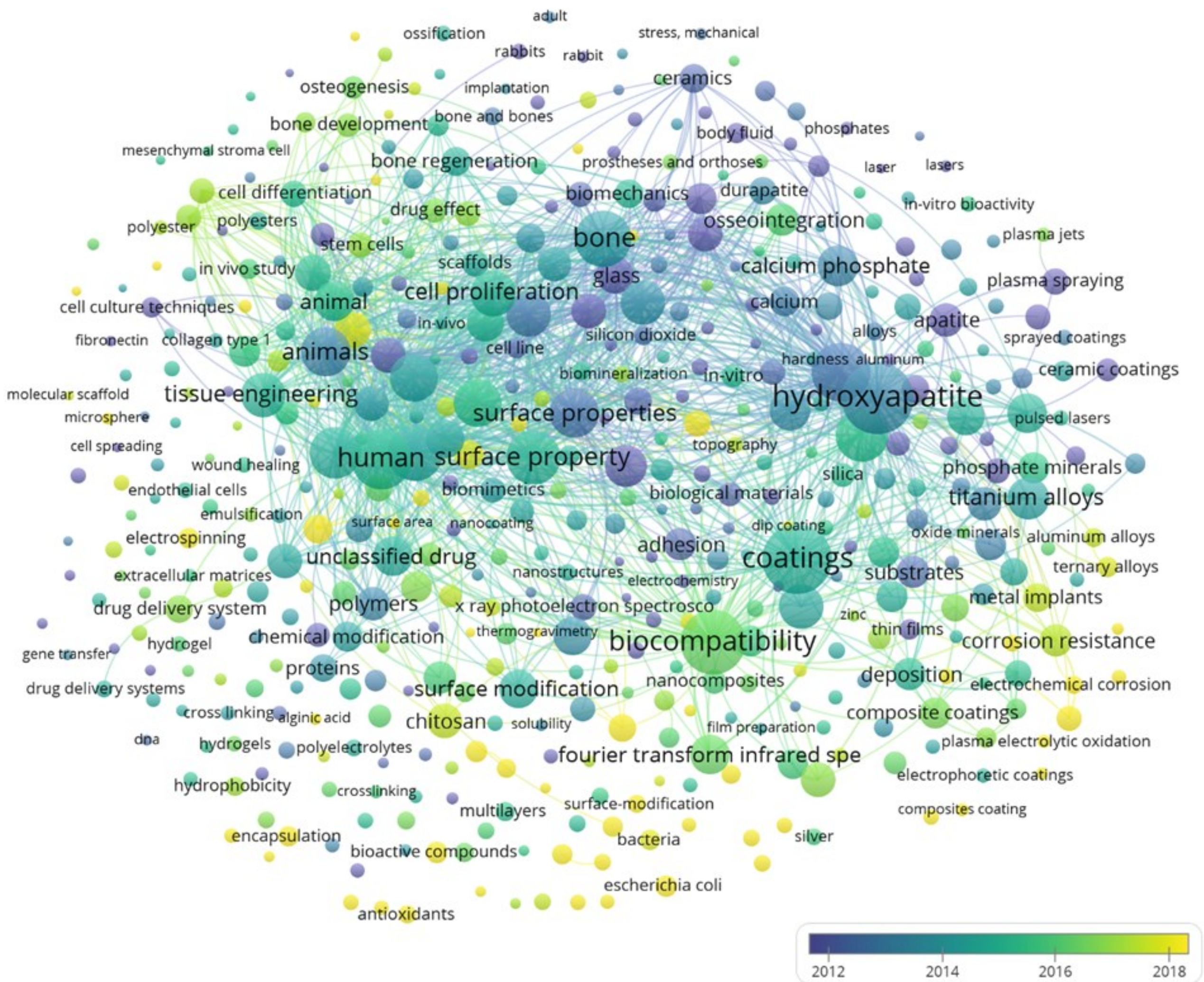

Figure 7. Connection between the keywords based on time trends.

3.5.4. Top Highly Influential Papers

In this segment of the systematic review, we present a compilation of the top 15 most highly cited papers spanning from 1993 to 2024, as recorded in Scopus. Table 6 showcases these influential papers, ranking them by the number of citations received. Included in the table are the names of the authors, the year of publication, and the sources where these papers were published. This detailed listing provides a clear overview of the key scholarly contributions that have significantly impacted the field of BGs coatings over the past decades.

Table 6. The most influential papers from 1993 to 2024

Rank	*Authors & Year*	*Title*	*Source Title*	*Total Citations*
1	Larry L. Hench-1998	Bioceramics: From Concept to Clinic [23]	The American Ceramic Society	6693
2	Larry L. Hench-1998	Bioceramics [24]	The American Ceramic Society	2834
3	Julian R. Jones-2013	Review of bioactive glass: From Hench to hybrids [6]	Acta Biomaterialia	2654
4	LeGeros, Racquel-2002	Properties of Osteoconductive Biomaterials: Calcium Phosphates [25]	Clinical Orthopaedics and Related	2625
5	Hongjian Zhou-2011	Nanoscale hydroxyapatite particles for bone tissue engineering [26]	Acta Biomaterialia	1741
6	Sergey V. Dorozhkin-2010	Bioceramics of calcium orthophosphates [27]	Biomaterials	1573
7	LeGeros, Racquel-2008	Calcium Phosphate-Based Osteoinductive Materials [28]	American Chemical Society	1562
8	Riccardo A.A. Muzzarelli-2009	Chitins and chitosans for the repair of wounded skin, nerve, cartilage and	Carbohydrate Polymers	1335
9	Jafar Hasan-2013	Antibacterial surfaces: the quest for a new generation of biomaterials [30]	Trends in Biotechnology	1125
10	Lingzhou Zhao-2009	Antibacterial coatings on titanium implants [31]	Journal of biomedical Materials Research	1067
11	E. Boanini-2010	Ionic substitutions in calcium phosphates synthesized at low temperature [32]	Acta Biomaterialia	962
12	Jiwoon Jeong-2019	Bioactive calcium phosphate materials and applications in bone regeneration [33]	Biomaterials Research	898
13	A. R. Boccaccini-2010	Electrophoretic deposition of biomaterials [34]	Journal of the royal society interface	866
14	Jungki Ryu-2010	Mussel-Inspired Polydopamine Coating as a Universal Route to Hydroxyapatite Crystallization [35]	Advanced Functional Materials	812
15	Rachit Agarwal-2015	Biomaterial strategies for engineering implants for enhanced osseointegration and bone repair [36]	Advanced Drug Delivery Reviews	780

4. Challanges and Gaps

4.1. Challenges of BGs Coatings

In the processing conditions of thermal spraying or sol-gel methods, the thermal expansion coefficients of the coating and substrate materials must be compatible; otherwise, differences in thermal expansion during cooling can induce stresses that lead to cracking or delamination. Finding a suitable processing method that allows for the deposition of BGs coatings without compromising the mechanical integrity of the implant is a complex challenge. Undoubtedly, BGs treated medical and dental implants enhance osseointegration and promote healing. However, so far, the development of BGs has not provided a balance between bioactivity and mechanical strength. That is; the mechanical stability and adhesion of BG coatings to the implant substrate still remain significant challenges [37]. Mechanical stability is critical for BGs coating applied to implants because it must endure a variety of stresses during and after implantation [38]. However, BGs coatings are generally brittle, which can cause cracking or delamination when subjected to mechanical stress. This brittleness results from the intrinsic characteristics of BGs, which may not have the toughness needed for load-bearing applications even while they offer bioactivity. Studies have indicated that the composition and processing techniques of BG can affect its mechanical characteristics. However, optimizing these compositions while maintaining bioactivity remains a substantial challenge. That is; while changes might increase mechanical qualities, they may also modify the bioactive behavior of the BGs, resulting in a trade-off between mechanical strength and bioactivity [6]. Furthermore, the firm adherence of BGs coatings to the underlying implant material, which is often pure titanium or titanium alloy, leads to increased physician satisfaction. For example, in the field of dental implantology, the surgeon must examine if there is a guarantee that the coating will remain on the implant surface during the torque of the implant into the bone [39].

4.2. Gaps and Future Directions

Despite tremendous advances in improving the bioactivity of BGs treated implants, several gaps in the research remain. That is; whereas the bioactivity of BGs is extensively reported, the particular methods and mechanisms by which these materials interact with biological tissues are not well known and remain inadequately understood. Further research is needed to understand the function of ion release and hydroxyapatite transformation [40]. The long-term durability and degradation behavior of BGs coatings in physiological situations must be thoroughly explored. The research focused on short-term in vitro findings, leaving little information on how these coatings operate over time in vivo. Preclinical models are the only focus of the majority of current research, and the shift to clinical settings is frequently gradual. There is a noteworthy lack of clinical trials that confirm the effectiveness of BGs coatings in real-world applications. To evaluate the effectiveness of BGs coatings in human subjects and to find any possible issues or failures related to their usage, more thorough clinical trials are required [41]. On the other hand, whereas BGs are predominantly explored for their osteoconductive capabilities, there has been little study into producing multifunctional coatings with antibacterial or anti-inflammatory effects. The incorporation of drugs into BGs coatings to improve their functioning is an area ripe for examination. The analysis also reveals several gaps and opportunities for future research in the field of BG coatings:

- **Advanced Composite Materials**: There is potential for further exploration into hybrid materials that combine BGs with biodegradable polymers, enhancing both mechanical stability and bioactivity, particularly for load-bearing applications.
- **Customization for Patient-Specific Implants**: Developing BG coatings tailored for specific patient needs, such as those with compromised healing abilities or specific anatomical requirements, could improve implant integration and therapeutic outcomes.
- **Enhanced Drug Delivery Systems**: The use of BGs as carriers for targeted drug delivery presents an opportunity for localized therapies in bone infections and cancer treatments. Research could focus on optimizing the release profiles and ensuring the stability of bioactive molecules.
- **Regenerative Applications Beyond Bone**: Expanding the use of BGs in regenerative medicine beyond bone and dental applications to include areas like cartilage regeneration and nerve repair could open new avenues for clinical use.

Sustainable Synthesis Methods: Investigating more environmentally friendly synthesis methods for BGs could address sustainability concerns, making production processes more efficient and reducing the environmental footprint of BG manufacturing.

Surface Functionalization Techniques: Further research into surface modifications using advanced techniques like plasma spraying or laser treatment could enhance the performance of BG coatings, improving their adhesion and durability on various substrates.

5. Conclusion and recommendation

Bioactive glass (BG) coatings have evolved dramatically since their introduction in the late 1960s, thanks to interdisciplinary research and technical innovation. Bibliometric analysis indicates a significant increase in publications after 2000, reaching a zenith between 2005 and 2010, coinciding with advancements in plasma spraying and nanoscale changes (Fig. 1, 2). This growth coincided with an increase in patent applications, indicating a strong collaboration between academics and industry focused on converting BG technologies into therapeutic applications. China (605 publications) and the United States (435 publications) emerged as worldwide leaders, while materials science (2344 documents) and engineering (1683 documents) predominated research topic fields (Table 1). Important publications, like Hench's foundational research on bioceramics and Jones' analysis of hybrid BGs, highlight the discipline's progression from fundamental bioactivity investigation to sophisticated applications in metallic implant coatings and drug delivery mechanisms.

The trend of BG research has changed significantly over time. During the initial period (1970s–1990s), research predominantly concentrated on elucidating the essential mechanisms of bioactivity and osseointegration, as demonstrated by Hench's groundbreaking contributions. During the 2000s and 2010s, the focus shifted to the development of metallic implant coatings to improve osseointegration, utilizing breakthroughs in deposition techniques like as plasma spraying. Over the past decade, nanotechnology and hybrid materials have prevailed in the sector, with advancements like nanostructured coatings and BG-polymer composites overcoming persistent mechanical constraints and broadening applications in soft tissue regeneration. Keyword analysis of contemporary literature highlights this advancement, with phrases such as hydroxyapatite, titanium, and biocompatibility indicating the emphasis on osteoconductivity and implant efficacy. Despite these advancements, significant obstacles persist in converting laboratory achievements into clinical use.

To address the gap between research and clinical implementation, numerous strategic measures are necessary. Initially, consistent testing protocols must be created to systematically assess long-term mechanical stability, encompassing adhesion strength and degradation behavior, under physiologically relevant environments. Secondly, the discipline must progress beyond preclinical models to execute extensive human trials that confirm the safety and efficacy of BG coatings in varied patient demographics. Third, future designs must emphasize multifunctionality by incorporating antibacterial agents, anti-inflammatory substances, or drug-delivery systems to reduce infection risks and facilitate tailored therapy. Sustainable manufacturing techniques must be refined to minimize production expenses and ecological consequences, while ensuring scalability. The future of BG coatings depends on interdisciplinary collaboration to integrate bioactivity with mechanical strength, thereby initiating a new era of customized, maintaining medical implants.[42][43][44]

This review highlights five decades of advancements in BG coatings, from Hench's groundbreaking contributions to contemporary developments driven by nanotechnology. Bibliometric statistics indicate a significant increase in patents and publications after 2000; however, clinical implementation is constrained by mechanical instability and a lack of extensive long-term investigations. To overcome these obstacles, we advocate for a double approach: (1) establishing standardized testing methodologies for adhesion and degradation, and (2) emphasizing translational research via industry-academia collaborations. By addressing these deficiencies, BG coatings can transition from experimental applications to conventional clinical instruments.

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