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Review of samarium-containing bioactive glasses: Biomedical applications

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A B S T R A C T

Samarium, a rare earth element, has attracted considerable attention in biomaterials due to its distinct physicochemical properties and possible bioactivity. This review focuses on samarium-containing bioactive glasses, highlighting their composition and the role of samarium in enhancing bioactivity, biocompatibility, and antibacterial properties. The incorporation of samarium ions has been shown to influence the structural characteristics of bioactive glasses, promoting superior interaction with biological tissues and improved osteogenic activity. Incorporating samarium into bioactive glasses (BGs) enhances their bioactivity and mechanical strength. Various biomedical applications, including bone regeneration, drug delivery systems, and tissue engineering, are explored, showcasing the versatility and effectiveness of these materials in medical settings. A comprehensive analysis of recent literature reveals ongoing advancements in the properties and application of samarium-containing bioactive glasses, paving the way for future research and clinical applications in regenerative medicine.

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1. Introduction

Biomaterials are artificial or natural materials that complement or replace living tissues [1]. A number of biomaterials have been developed as bone substitutes, given the high frequency of bone abnormalities brought on by illnesses and traumas [2, 3].

L. Hench created the first 45S5 Bioglass in the late 1960s, with a chemical composition of 45 wt.% SiO_2, 24.5 wt.% CaO, 24.5 wt.% Na_2O, and 6.0 wt.% other components. This bioglass has been successfully used in bone regeneration, helping more than 1.5 million patients [4]. Over the years, numerous glass compositions classified as biomaterials have been utilized in human biomedicine, making significant contributions to healthcare [5]. Recent researchers have published a large number of studies on the integration of metallic ions (or bioinorganic) in calcium phosphates and bioactive glasses (BGs) [6-9]. Cations and anions, including Ag^+, Li^+, Co^{2+}, Ca^{2+}, Cu^{2+}, Zn^{2+}, Sr^{2+}, Fe^{2+}, Mg^{2+}, Ga^{3+}, B^{3+}, as well as rare earth elements (REEs) and elements that are not metals such as Ba^{2+}, Bi^{3+}, Cl^-, Cr^{6+}, Dy^{3+}, Eu^{3+}, Gd^{3+}, Yb^{3+}, Th^{3+}, Ge^{2+}, Au^{3+}, Ho^{3+}, La^{3+}, I^-, Mn^{2+}, Ni^{2+}, Nb^{5+}, Mo^{6+}, N^{3-}, Pd^{2+}, Rb^+, Sm^{3+}, Se^{4+}, Ta^{5+}, Te^{4+}, Tb^{3+}, Er^{3+}, Sn^{2+}, W^{6+}, V^{5+}, Zr^{4+}, and Y^{3+}. Phosphate, silicate, and borate-based BG systems have been integrated to enhance functional properties such as osteogenesis, angiogenesis, bioactivity, and bone regeneration while also playing a role in infection control and cancer treatment [10-14]. Several studies have specifically highlighted the application of components of rare earth in advancing applications for biomaterials and biology [15, 16]. Also, lanthanide (Ln) elements, particularly those that can be divalent and are chemical, can be used to dope bioglass [17]. Fig. 1 illustrates Samarium, one of the lanthanides and a rare earth element. Samarium (Sm^{3+}) is a naturally abundant element with an ionic radius similar to calcium (Ca^{2+}), allowing it to integrate well into bone tissue. Its unique radioactive properties make it particularly valuable for biomedical applications, including bone regeneration and therapeutic treatments [18, 19]. Sm^{3+} ions play a vital role in strengthening the Sm_2O_3–SiO_2–Na_2O–CaO–P_2O_5 glass system. With their strong fluorescence, high bending energy levels (135.6 BE/eV), and excellent quantum efficiency, they not only enhance the glass's optical properties but also improve its mechanical strength, making it more suitable for various advanced applications [20].

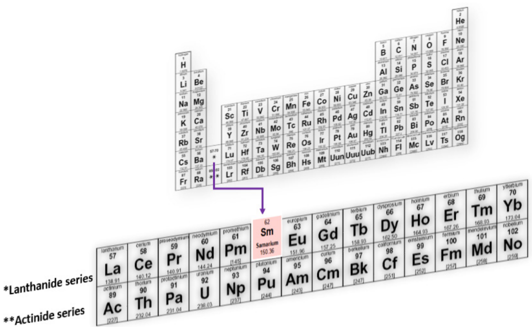

Fig. 1. Periodic table of Elements, Lanthanides.

Sm-doped bioactive glasses are more thermally stable than traditional BGs by reducing their susceptibility to heat shock while being manufactured. Additionally, Sm doping improves its glass's mechanical qualities, increasing its resistance to cracking and breakage [21, 22]. This review aims to comprehensively analyze the role of samarium-doped bioglass, focusing on its synthesis, properties, and biomedical applications, including its potential in bone tissue regeneration, cancer treatment, antimicrobial activity, and other therapeutic advancements.

2. Samarium-containing bioactive glasses

The most commonly used BGs are 45S5 Bioglass, 58S Bioglass, and 77S Bioglass. Each of these has its unique composition and properties, making them valuable for various medical applications [21].In BGs, dopants are tiny quantities of atoms or ions added during manufacturing to modify and enhance their mechanical, biological, and physical properties. Along with rare-earth (RE)ions like cerium (Ce), europium (Eu), and samarium (Sm), these dopants also comprise metallic ions like copper (Cu), zinc (Zn), silver (Ag), strontium (Sr), and iron (Fe) [13, 21, 23]. In recent years, scientists have been exploring the therapeutic potential of rare earth ions, especially lanthanide ions, due to their biological properties, which are primarily attributed to their similarity to calcium ions [24]. Due to their similarity to Ca ions, they have served as the foundation for studies on potential therapeutic applications. However, their larger charge makes them more attractive to Ca^{2+} binding sites on biological molecules. It has been recognized for decades that Ln^{3+} ions have a strong affinity for bone, as they can substitute for Ca^{2+} ions in hydroxyapatite. Lanthanide ions such as La^{3+}, Y^{3+}, In^{3+}, Sm^{3+}, and Gd^{3+} are known to incorporate into the hydroxyapatite matrix, with Ce^{3+}, Ce^{3+} and Sm^{3+} also observed in nanostructured hydroxyapatite [25].

2.1. Chemical composition

Lanthanide oxides are considered excellent candidates for photo-thermal conversion due to their higher photon energy and beneficial properties in biomedical fields [26]. In this glass matrix, Sm^{3+} ions are essential in altering the structure and improving the physical properties of the glass. These ions help to modify the connectivity of the silicate network, which can affect essential properties like thermal stability, viscosity, and optical behavior [27].

2.2. Physical and biological properties

Rare-earth ion-doped biomaterials, such as silica nanoparticles, hydroxyapatite [28], and bioglasses, offer various advantages. Among these, borate glasses stand out due to their reduced absorption coefficient, higher dielectric constant, excellent rare-earth ion solubility, and enhanced mechanical and chemical strength. Additionally, their superior bioactivity, ease of fabrication, and potential for controlled drug delivery make them promising materials for biomedical applications. These properties are attributed to their more incredible phonon energy (~1300 cm^{-1}) compared to silicate, fluoride, tellurite, and phosphate glasses [29]. In lanthanide complexes, organic ligands enhance emission intensity by absorbing light and transferring energy to the lanthanide ion. In nanomaterials based on Ln, hybridization is achieved by combining inorganic materials such as silica, quantum dots, calcium phosphates, fluorides, or polymers like polypropylene and polyvinyl alcohol. This strategy enhances the robustness, stability, mechanical properties, and photophysical characteristics, thereby enhancing the efficiency of bioimaging [30].One of the most significant and critical concerns associated with rare-earth doped glass and glass–ceramics comes from the influence of dopants on the host material's optical and thermal characteristics. These materials are beneficial because they can effectively accommodate different RE ions, making them ideal for various applications. As a result, compared to many other crystalline-based materials, precursor glass, and glass–ceramics may be used to generate optical fibers and solid-state lasers more effectively [31].

The luminescent properties of doped bioactive glasses facilitate the monitoring of the process of deterioration. Variations in the release of ions like Ca, Na, and Si, depending on the samarium ion concentration, highlight how the quantity of dopant influences the glass's biological behavior [28]. Agata Baranowska et al. [32] explored a novel approach for monitoring the mechanism by which bioactive glass fibers degrade using a luminescence-based technique. They characterized the optical and biological properties of 13-93 glass fibers doped with varying amounts (0.2 and 2 mol%) of samarium ions. The result indicated that the Properties of luminescence are beneficial for tracking bioactive glass fibers' deterioration through measures made in vitro. The emission of Sm^{3+} ions played a key role as an active sensing element. The data presented underscored that lanthanide ion-doped bioactive glass fibers could sense while maintaining their biological functionality. The biological properties of the material are altered when rare-earth ion doping is applied to bioactive glasses, and the dopant concentration significantly impacts the development of the hydroxycarbonate apatite (HCA). Compared to dopant-free glasses, this phenomenon may be explained by stronger chemical connections. Rare-earth ion doping of bioactive glasses influences the material's biological properties, and the concentration of the dopant has a significant impact on the development of HCA. The presence of stronger chemical connections than in glasses without dopant is the cause of this phenomena [30, 33]. Sm-doped BGs have demonstrated enhanced bioactivity and accelerated biodegradation rates while simultaneously improving cell differentiation and proliferation, which makes them perfect for applications involving bone tissue engineering [20]. Additionally, Sm-doped BGs exhibit notable antibacterial properties, rendering them highly promising for applications aimed at avoiding and managing infections more than ever. Sm-doped BGs show better thermal stability than other bioactive glasses, decreasing their likelihood of suffering from heat shock in the production process. Additionally, adding Sm fortifies the glass, making it more durable and less prone to cracking or breaking [22, 34]. In the study by Md Ershad et al. [20] Synthesized and characterized bioactive glasses containing a mixture of (45 − X) SiO_2, 24.5 Na_2O, 24.5 CaO, and 6 P_2O_5, where X varied from 0 to 4.0 wt% of Sm_2O_3. They found that increasing Sm_2O_3 concentrations in non-charge balanced (NCB) glasses enhanced Young's modulus, shear modulus, and bulk modulus while Poisson's ratio decreased. Adding Sm_2O_3 also lowered the nucleation and crystallization temperatures. Furthermore, incorporating Sm^{3+} ions improved the physical and biological properties of the glasses. The modified 45S5 glass showed an amorphous phase, formed an HCA layer, and exhibited increased dissolution rates and weight loss with higher samarium concentrations when immersed in simulated body fluid (SBF).

Y. Zhang et al. [24] explored the potential of using samarium-doped mesoporous BG and alginate-containing microspheres (0.5–1 mol% Sm) for drug delivery applications. They demonstrated that incorporating small amounts of samarium (0.5%) into the mesoporous BG microspheres significantly influenced the mesoporous structure, apatite-mineralization capacity, and drug release characteristics. Therefore, the prepared microspheres exhibited multifunctional properties, combining excellent apatite-mineralization ability with controllable doxorubicin (DOX) release, suggesting their promising potential for bone cancer therapy.

3. Biomedical applications

The potential of bioactive glasses with samarium in various biological applications has been investigated, particularly due to their enhanced properties, such as improved bone regeneration, antibacterial activity, and thermal stability. Fig.2 shows the kind of biomedical applications of samarium-containing bioactive glasses.

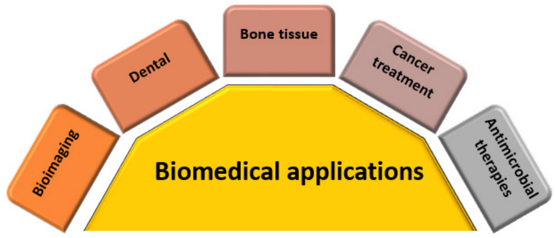

Fig. 2. Biomedical applications samarium-containing bioactive glasses**.**

3.1. Bone tissue

Bone tissue is constantly being remodeled through the coordination between different bone cells, which include osteoblasts forming new bone and osteoclasts resorbing existing bone. Osteocytes, in this process, function as mechanosensory and key regulators of the bone remodeling process [35] . Tissue engineering has emerged as a promising approach to help repair and regenerate tissues and organs lost or destroyed due to illness, aging, injury, and trauma [36, 37]. Bone tissue engineering focuses on encouraging the growth of functional bone by combining biomaterials, cells, and growth factors in a way that works together effectively[37]. Biomaterials for bone regeneration include cements, calcium phosphate-based ceramics, synthetic polymers, and tissue-engineered bone replacements. Calcium phosphates, such as beta-tricalcium phosphate (β-TCP), $Ca_3(PO_4)_2$, and calcium HAp, $Ca_{10}(PO_4)6(OH)_2$, are the most commonly used synthetic grafting materials. These materials are made up of the same ions that make up the majority of the inorganic components of teeth and bones [38]. Lanthanides can replace calcium in bones, leading to the activation of osteoblasts, which are responsible for bone formation [39]. Compounds containing REEs have been developed for their exceptional potential in bone-targeting therapy and disease diagnosis, including elements such as Sm [22], Ce [40], and Er [41]. Nica et al. [42] developed novel, innovative coatings by synthesizing Sm-doped hydroxyapatite nanoparticles via dip-coating. These nanoparticles demonstrated significant antibiofilm activity and high biocompatibility with Human gingival fibroblasts. Additionally, the Sm concentration appeared to influence the antimicrobial properties of the materials. Their study revealed that as the Sm concentration increased, the examined surface's granular structure became more defined, and this change was linked to cytoskeletal remodeling in the 5SmHAp samples. It has been demonstrated by Morais .et al [25] that composites of glass-reinforced HA-based bone with 0.5, 1, or 2 (mol%) Sm_2O_3 can promote osteoblast proliferation, organicity, and gene expression. In addition, S. aureus and S. epidermidis have less adherence to bone substitutes when Sm^{3+} doping is present. Enhanced osteoblastic activity and antibacterial properties were closely related to the levels of Samarium in the composite, particularly noticeable in the composite with increased Sm^{3+} concentration. Similarly, Md Ershad et al. [20] investigated the biological properties of multicomponent bioactive glasses containing SiO_2–Na_2O–CaO–P_2O_5–Sm_2O_3, emphasizing their potential for bone tissue applications. These glasses were more bioactive when their Sm_2O_3 concentrations were higher, stimulating biological processes. Moreover, developing an HCA layer on the samples' surface shows good bone tissue compatibility. Also, Sm_2O_3 reduced nucleation and crystallization temperatures, which could improve the glasses' biological properties. According to this study, bioactive glasses with varying Sm_2O_3 concentrations support bone regeneration and treatment effectively. Another study has demonstrated that samarium can enhance materials' biochemical and biological properties. In a separate study, a bioactive glass with the composition $65.0SiO_2$–$4.5P_2O_5$–$24.0CaO$–$2.5Na_2O$ (mol.%) doped with 1.0% Ag_2O and 3.0% Sm_2O_3 (mol.%) was synthesized using the sol-gel technique for biomedical applications. The results indicated that this bioglass exhibited significant bioactivity following a 28-day SBF immersion and effectively inhibited the growth of Gram-negative bacteria. Furthermore, these materials have potential applications in tissue engineering [21].

3.2. Cancer treatment

Cancer encompasses a wide range of illnesses that have various effects on the human body; it is one of the most fatal and feared diseases, contributing to a significant number of deaths globally, regardless of whether the country is developed or developing [43, 44]. A key feature of the development of bone cancer is the creation of a harmful cycle, including the signaling and molecular connections between the cancer cells in the bone microenvironment, osteoclasts, and osteoblasts [45]. Novel techniques for treating cancer are constantly being developed, and glass ceramics and BGs have much promise in this field [46] . A variety of glass-ceramic types and compositions have been developed and utilized for the treatment of different kinds of cancer cells [44, 47, 48]. Kanika Chandel et al. [49] synthesized bioceramics with the composition x $Sm_2O_3\cdot(43\text{-}x)$ $CaO\cdot42$ $ASiO_2\cdot15$ P_2O_5 (x = 0 and 1 mol%) utilizing the sol-gel process. Analysis results showed the bioactivity of the prepared samples. After the first day of immersion, hydroxyapatite production is observed in the samarium oxide-doped sample. Additionally, in vitro degradation tests were carried out in SBF for 10 days to assess the potential degradation of the samples in the body. The results indicated an essential change in pH and demonstrated excellent sample degradability in bodily fluid simulation. In addition, The MG-63 human osteosarcoma cell line was used in cell culture tests, and the results showed that the samples had a significant cytotoxic impact on the malignant cells. Fig. 3 demonstrates the effects of samarium-containing bioglass as a drug in bone cancer (MG-63 cell line).

Bioceramics, especially those doped with radioactive isotopes, have attracted considerable attention in radiation therapy due to their potential for targeted cancer treatment. Among these materials, samarium-doped bioglass, particularly Sm-153, is a promising candidate for the development of bioactive and biodegradable ceramic seeds. These seeds can be used in internal radiation therapy or brachytherapy, where they are implanted either near or within tumors to deliver localized radiation [50].

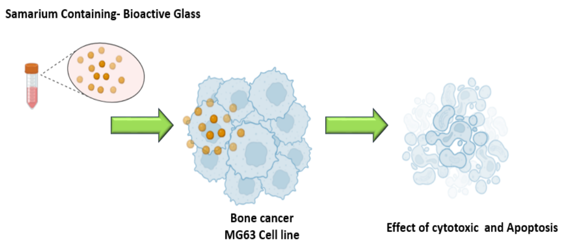

Fig. 3. The effects of samarium-containing bioglass as a drug on bone cancer.

Tarcísio P.R. Campos et al. [51] achieved notable results in their study on the development of Si–Ca–Sm-153 bioglass produced via the sol-gel process. This method ensures high biocompatibility and imparts the necessary radioactive properties for effective cancer treatment Sm-153, a beta-emitting radionuclide, was chosen for its therapeutic potential. The dosimetry analysis performed in the study involved calculating the energy absorption from both the beta and gamma radiation emitted during Sm-153 decay. The results demonstrate that the seed production and implantation procedure were appropriate, fulfilling the research's initial objectives. Moreover, the study conducted by Roberto et al. [52] Investigated the incorporation of samarium atoms into SiO_2 and SiO_2-CaO matrices using sol-gel processing. Successful samarium doping was confirmed, and the materials produced were mostly non-crystalline, with some crystalline phases in higher calcium content samples. The glasses had large surface areas and varied pore sizes based on composition. Additionally, studies identified optimal samarium concentrations in the sol-gel glasses for generating ^{125}I seeds with activities similar to those used in prostate cancer brachytherapy [52]. Although most chemotherapeutic medications are categorized as either kinase inhibitors or molecular target treatment, bioactive glasses have primarily been utilized as drug-delivery vehicles for these two types of medications [45].

Other medications used in bone cancer treatment have also been transported using bioactive glasses. Moreover, they enhance bone regeneration and infection prevention by delivering functional drugs like DOX and bisphosphonates, which influence osteoblast metabolism [53]. Fig. 4 displays a schematic of the potential uses of bioactive glasses, or MBGs, in treating cancer as a drug carrier. Ying Zhang et al. [15] developed a microsphere system to overcome the challenges of targeted DOX delivery for bone cancer treatment. They integrated Sm^{3+} ions into a mesoporous bioactive glass (MBG) through alginate cross-linking with Ca^{2+} ions, forming Sm/MBG/alginate composite microspheres. The study optimized the microspheres' physicochemical and biological properties, demonstrating their superior apatite-mineralization capability and controlled DOX release. The results indicate that Sm incorporation in MBG affects calcium-phosphate mineralization, enhances drug-loading capacity, and refines drug release kinetics. Specifically, a 0.5% Sm concentration was identified as optimal for DOX release, with higher concentrations accelerating release due to material dissolution, while lower concentrations inhibited it. The pH-responsive release behavior of the Sm/MBG/alginate composite microspheres highlights their potential as intelligent carriers for anti-cancer drugs, capable of adapting to pH variations during the healing process.

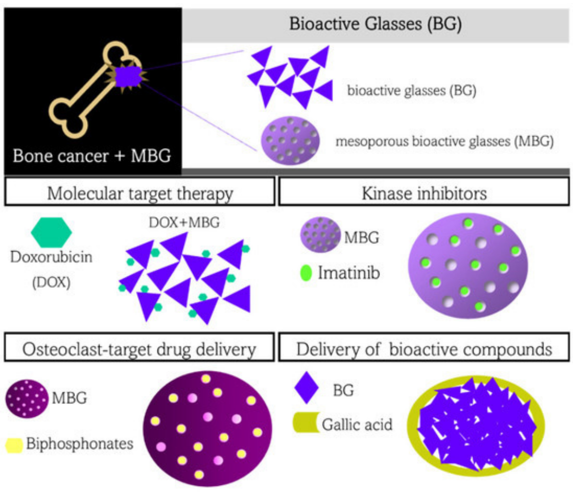

Fig. 4. Utilizing bioactive glasses as medication delivery devices for bone cancer therapy [45].

3.3. Dental

Bioactive materials are employed in dentistry and osteology for tissue repair and regeneration [54]. Bioactive glasses are widely recognized for their use in dentistry, functioning as restorative materials, dental adhesives, intracranial medicaments, and agents for enamel demineralization [55, 56]. Deng et al. [56] examined the impact of 45S5 bioactive glass on the surface characteristics of dental enamel exposed to 35% hydrogen peroxide bleaching. The findings indicated that 45S5 bioactive glass holds potential as a biomimetic supplement to bleaching treatment, helping to avoid damaging enamel caused by bleaching agents.

Rare earth elements, including samarium, have been utilized in aesthetic restorative dental ceramics and dental resins to enhance the fluorescence of natural teeth. Samarium is also known for its bacteriostatic properties and low toxicity. As an essential dopant for bioactive glasses, it plays a key role in enhancing the glass's ability to promote bone regeneration [56]. Aylin M. Deliormanlı et al. [56] conducted a study on Nb_2O_5 and Sm_2O_3-doped bioactive glasses synthesized using the sol-gel method for dental applications. The research examined the physical, structural, and optical properties of these glasses, finding that Sm^{3+} ions preserve the amorphous structure of the silicate glasses. In contrast, Nb^{5+} ions promote the crystallization of the T-Nb_2O_5 phase. In vitro bioactivity tests revealed that the doped glasses facilitated hydroxyapatite layer formation, especially in phosphate-buffered saline, suggesting their potential to enhance dental restorative materials. Moreover, the study assessed the ionizing radiation shielding properties of the glasses, showing that the addition of Nb_2O_5 and Sm_2O_3 significantly improved their radiation attenuation capabilities. These findings suggest that this dual functionality of the doped bioactive glasses could improve the aesthetic qualities of dental ceramics and resins while offering better protection during dental radiology procedures. This research could have a significant impact on advancing restorative dental treatments and improving safety in dental practices [56].

3.4. Antimicrobial therapies

Recently, the emergence of multidrug-resistant microorganisms has raised significant global concern, prompting greater attention towards the development of new and effective antimicrobial agents [22]. The antimicrobial properties of lanthanides are viewed as a multifaceted interplay of various factors, including the nature of the metal ion, its connection with cellular elements, chelation, coordinating sites, the structure of the complex geometry, concentration, hydrophilicity, lipophilicity, steric and pharmacokinetic factors, as well as various environmental factors [42]. The study investigated developing a safe antimicrobial agent that would work against Candida albicans, Staphylococcus aureus, and Escherichia coli using 5Sm-HAp suspensions, targets, and coatings. The antimicrobial mechanism of 5Sm-HAp is thought to involve Sm^{3+} ions affecting microbial cell walls, leading to cell damage, reactive oxygen species (ROS) formation, and DNA damage. Colony-forming unit (CFU) proliferation was inhibited, according to quantitative assays in the early adherence phase (12 hours) for all sample types, indicating effective antimicrobial properties [22].

Ciobanu et al. [57] studied the antimicrobial properties of samarium-doped hydroxyapatite nanoparticles (Sm: HAp-NPs) against both Gram-positive and Gram-negative bacteria. Gram-negative bacteria cause infections such as bloodstream infections, pneumonia, and meningitis. The antibacterial properties of Sm: HAp-NPs were carried out using the coprecipitation method, and the results demonstrated that these nanoparticles possess antibacterial potential for treating wounds and coating medical instruments. The bio properties of Sm: HAp-NPs can be adjusted by varying the samarium concentration in hydroxyapatite. The antibacterial activities of Sm: HAp-NPs could enhance their use in medical or environmental applications. The study emphasizes the need to develop new antimicrobial agents to combat infections caused by resistant bacteria.

Recent investigation highlights that infections during the therapy of prosthetic infections remain a significant issue. In patients undergoing treatment for hip or infections related to knee prosthetics, it is essential to note that infections caused by gram-negative bacilli or fungi are contraindications. To improve patient therapy for infections related to prosthetics, the development of novel substances with antimicrobial properties is crucial. In conclusion, the novel bioceramic Sm: HAp exhibits antimicrobial properties and could be a promising candidate for addressing prosthetic joint infections and bone-targeted drug delivery systems [57].

3.5. Bioimaging

Bioimaging allows depicting biological activities, ranging from subcellular components to entire organisms, improving our understanding [58]. The effectiveness of imaging depends on the physical and chemical properties of the bioimaging agent, including size distribution, solubility, biocompatibility, optical properties, and interactions with biological systems. Recent studies have explored the synthesis, characterization, and biological properties of Eu and Sm-doped HAp nanoparticles for bioimaging applications. These nanoparticles exhibit enhanced fluorescence, minimal toxicity, and efficient cellular uptake, positioning them as potential theragnostic agents [30]. In the study by Mukesh Kumar et al.[59] doping with samarium significantly enhanced the bioactivity of bioceramic systems, which is evident through improved hydroxyapatite phase formation in the samples. Moreover, adding Sm^{3+} enhanced stability and regulated the degradation rate across different environments. The Sm-doped samples also exhibited a lower band gap, enhancing the optical properties of the materials. Furthermore, these materials demonstrated stronger bactericidal effects against E. coli and S. aureus, as well as higher antioxidant properties. Importantly, the systems were designed to promote the growth of MG-63 cell lines while reducing oxidative stress. These results highlight the potential of samarium doping to improve applications in medicine and design bioactive materials with optimized properties for bone regeneration and bioimaging.

4. Challenges and future directions of samarium-containing BGs

Samarium-containing BGs encounter challenges that impede their progress potential. Optimizing glass composition is crucial for desired biological responses. Incorporating samarium ions can affect structural and thermal properties, impacting bioactivity. For example, the ionic radius of Samarium may alter the glass network, influencing the release of beneficial ions that promote osteogenesis [2]. Another challenge lies in the understanding of the mechanisms by which rare earth elements enhance biological activity. While studies have shown that these elements can promote osteointegration and possess antibacterial properties, the specific biological pathways involved remain poorly understood. This gap in knowledge hinders the ability to predict the performance of rare earth-containing bioactive glasses in clinical settings [60, 61]. Additionally, it's important to balance bioactivity and mechanical strength because bioactive glasses need to support physical loads while helping with bone healing. Research indicates that the mechanical properties of bioactive glasses can be significantly influenced by their composition, necessitating a careful design of formulations [62]. However, the high charge density and varied chemical reactivity of rare earth ions lead to their tendency to form stable complexes with a wide variety of ligands (molecules that can attach to a receptor) and organic compounds [25]. The increased reactivity of these ions enhances their attraction to Ca^{2+} sites in biological molecules. This property renders rare earth ions particularly valuable for various biological and biomedical applications, as they can effectively substitute for calcium ions [63]. Future research should focus on elucidating these mechanisms through in vitro and in vivo studies to provide a clearer understanding of how samarium influences cellular behavior and tissue regeneration. Moreover, the scalability and reproducibility of samarium-containing bioactive glass production pose significant hurdles. The synthesis methods, such as sol-gel processes or melt-quenching techniques, must be optimized to ensure consistent quality and performance of the glasses [21].

5. Conclusion

Samarium-containing bioactive glasses represent significant progress in the field of biomedical materials. Their distinct chemical composition, enhanced thermal and mechanical stability, and ability to integrate into bone tissue make them promising candidates for a variety of applications. Sm-BGs show exceptional potential in bone tissue engineering, drug delivery systems, and antimicrobial treatments. However, despite these remarkable properties, challenges persist in optimizing Sm-BGs for clinical use. Future research should focus on their long-term biocompatibility, cost-effective manufacturing methods, and potential environmental effects. Overcoming these challenges could enable Sm-BGs to transform biomedical applications, leading to innovative treatments and better patient outcomes.

Author contributions

Negin Khosravi: Writing – original draft, Writing – review & editing, **Aramis Moradi**: Writing – original draft, Writing – review & editing, Conceptualization, **Fariborz Sharifianjazi:** Writing – review & editing, Supervision, **Ketevan Tavamaishvili**: Writing – original draft, Writing – review & editing, **Ameneh Bakhtiari:** Writing – original draft, Writing – review & editing, **Ali Mohammadi**: Writing – original draft, Writing – review & editing.

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Conflict of interest

Given their role as Editor-in-Chief, Fariborz Sharifianjazi had no involvement in the peer-review of this article and has no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to another journal editor.

Data availability

No data is available.

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