Structural and Biocompatibility Assessment of Bioactive Glass for its Application in Pediatric Dentistry

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**Abstract:** Bioactive glasses (BGs) are an important class of biomaterials known for their ability to interact with biological systems, promoting bone regeneration and tissue repair. Since their introduction by Larry Hench in the 1970s, bioactive glasses have gained considerable attention in the fields of tissue engineering and regenerative medicine due to their unique properties, particularly their bioactivity and osteoconductivity. Among the various bioactive glass compositions, 53S which is silica-rich (53% SiO₂), stands out for its enhanced potential in biomedical applications. Bio glass is bio ceramic material that contains Silica, phosphate, calcium and sodium. Structural, Morphological, Biocompatibility and Anti-Microbial properties of the bioactive glass is analysed by X-ray Diffraction Pattern, FT-IR Test, Blood Compatibility and Anti-Bacterial test is done respectively. XRD Pattern is to analyse the crystalline behaviour of the material. Calcium carbonate and NaCaPo4 crystalline phase is observed from the data. FT-IR is to analyse the functional group of the material. In this test silica and phosphate vibration are active. The evaluation of 53S bioactive glass demonstrates its potential as a multifunctional biomaterial. Its robust structure, favourable morphology, excellent biocompatibility, and notable antimicrobial properties make it a promising candidate for a wide range of biomedical applications, including bone regeneration, dental restorations, and tissue engineering. "Assessment of the Impact of Commonly Consumed Condiments on the Microhardness of Dental Enamel: An In Vitro Study". Future research should focus on long-term in vivo studies and the development of composite materials to further enhance its clinical performance and applicability.

**keywords:** Sodium hydroxide, biomedical applications, Hydroxyapatite, bioactive ions, morphological properties

# INTRODUCTION

Bioactive glasses (BGs) are an important class of biomaterials known for their ability to interact with biological systems, promoting bone regeneration and tissue repair. Since their introduction by Larry Hench in the 1970s, bioactive glasses have gained considerable attention in the fields of tissue engineering and regenerative medicine due to their unique properties, particularly their bioactivity and osteoconductivity. Among the various bioactive glass compositions, 53S which is silica-rich (53% SiO₂), stands out for its enhanced potential in biomedical applications[(Ylänen, 2017)](https://paperpile.com/c/OJoG0W/xYw1). This specific composition exhibits desirable structural and biological characteristics, making it a strong candidate for bone regeneration and implant applications [(Deepika et al., 2022; Harsha & Subramanian, 2022; Solanki et al., 2022)](https://paperpile.com/c/OJoG0W/iG6Es+riUtn+u98Hy).

The structural properties of bioactive glasses are critical in determining their performance. The amorphous nature of 53S bioactive glass allows it to dissolve when exposed to bodily fluids, which results in the formation of a hydroxyapatite (HA) layer—a key mechanism through which bioactive glasses bond with bone tissue [(Ajay, Rakshagan, et al., 2022; Ajay, Sasikala, et al., 2022; Chidambaram et al., 2022)](https://paperpile.com/c/OJoG0W/4QgvU+uPDud+Ld4ci). Hydroxyapatite is chemically similar to the mineral component of bone, which facilitates the glass’s integration with natural bone and accelerates healing. The porous structure of 53S bioactive glass further enhances this process by increasing the surface area for ion exchange and facilitating cellular interaction, which are both essential for tissue regeneration. By optimizing these structural properties, 53S bioactive glass can effectively enhance bone bonding and tissue repair [(Ajay, Suma, et al., 2022; Katyal et al., 2021; Maiti, 2021)](https://paperpile.com/c/OJoG0W/FNboZ+LQHVY+UwAkA).

Morphology, which refers to the size, shape, and surface characteristics of the glass particles, also plays a significant role in its bioactivity[(Boccaccini et al., 2016)](https://paperpile.com/c/OJoG0W/nHTc2). A higher surface area and porosity promote faster dissolution, leading to a quicker release of bioactive ions such as calcium and phosphorus. These ions contribute to bone mineralization and stimulate cellular activities that are crucial for bone formation. Moreover, the particle size and distribution of bioactive glass can impact cell adhesion and proliferation. Smaller particles and higher porosity typically promote better cell interaction, as they provide a more conducive environment for cell attachment and growth. Thus, understanding and controlling the morphological properties of 53S bioactive glass are essential to maximize its effectiveness in tissue engineering applications[(Baino & Kargozar, 2022)](https://paperpile.com/c/OJoG0W/VK8sO).

Biocompatibility is another key factor for bioactive glasses to be used in medical applications. 53S bioactive glass has been shown to exhibit excellent biocompatibility by supporting the adhesion, proliferation, and differentiation of osteoblasts, which are the primary cells responsible for bone formation. When bioactive glass dissolves, it releases ions such as silicon, calcium, and phosphate into the surrounding biological environment. These ions not only contribute to bone mineralization but also play critical roles in cell signaling, enhancing cellular responses and promoting tissue regeneration without inducing adverse immune reactions. The non-toxic nature of these ionic byproducts makes 53S bioactive glass particularly suitable for biomedical applications[(“Structural and Morphological Properties of Borate Bioactive Glasses for Bone Tissue Regeneration,” 2024)](https://paperpile.com/c/OJoG0W/2WLKq).

Additionally, bioactive glasses have been explored for their potential antimicrobial properties, which are particularly valuable in preventing infections in surgical procedures and implant applications. The release of ions such as calcium and sodium during the dissolution process can create an environment that hinders bacterial growth. This antibacterial activity can be further enhanced by incorporating antimicrobial agents, such as silver or copper, into the glass matrix. As a result, 53S bioactive glass has demonstrated potential not only in promoting bone healing but also in preventing post-surgical infections, making it a versatile material in the field of regenerative medicine[(Deb, 2015)](https://paperpile.com/c/OJoG0W/UhQ7x).

This research aims to comprehensively evaluate the structural, morphological, biocompatible, and antimicrobial properties of 53S bioactive glass[(Ram et al., 2024)](https://paperpile.com/c/OJoG0W/iDMHx). Through this investigation, we seek to enhance the understanding of how these properties interact to support its potential use in clinical applications, particularly in bone tissue engineering and infection prevention.

# MATERIALS AND METHODS

## SYNTHESIS METHODOLOGY

Analytical grade chemicals and reagents were used in this study without further purification. Tetraethyl orthosilicate (TEOS) was sourced from Alfa Aesar, while orthophosphoric acid, calcium nitrate, and nitric acid were obtained from Spectrum Reagents and Chemicals Pvt. Ltd. Sodium hydroxide was supplied by Sisco Research Laboratory. Bioactive materials with a 45S5 composition (SiO₂—45%, P₂O₅—6%, CaO—24.5%, Na₂O—24.5%) were synthesized via the sol–gel method. TEOS was fully dissolved in a mixture of double-distilled water and ethanol, using nitric acid as a catalyst, and stirred for one hour until a gel-like structure formed. Separately, Ca(NO₃)₂ and NaOH were dissolved in double-distilled water and then added to the silica-based network.

A copper source (copper nitrate) was introduced by substituting 1.5% of sodium with copper, reducing the sodium content to 23%, and the resulting material was designated as Cu-BAG. The required quantities of precursor materials were calculated in terms of weight percentage, dissolved individually, and subsequently incorporated into the silica network. The materials were dried in a hot air oven at 100°C for 24 hours to remove moisture and then sintered at 600°C for three hours.

The prepared bioactive materials (100 mg) were loaded with 50 mg each of ACE and IBU drugs. Both drugs were dissolved in 10 ml of dimethyl sulfoxide (DMSO) and immersed in the BAG and Cu-BAG powders for 24 hours to facilitate drug loading. The powders were incubated and agitated on an orbital shaker to enable the drugs to occupy the voids in the bioactive materials. The drug-loaded bioactive materials, designated as BAG/ACE-IBU and Cu-BAG/ACE-IBU, were utilized for root canal filling. These materials demonstrated potential for supporting root canal filling, reducing inflammation, and addressing microbial challenges in the oral cavity.

## PREPARATION OF 53S BIOGLASS

The synthesis of 53S4P bioactive glass involved using tetraethyl orthosilicate (TEOS), orthophosphoric acid, calcium nitrate tetrahydrate, and sodium hydroxide as precursors. The bioactive glass composition consisted of SiO₂ (53%), Na₂O (23%), CaO (20%), and P₂O₅ (4%) by weight, following the conventional sol–gel method. Initially, TEOS was mixed with nitric acid (HNO₃), and ethanol was added to facilitate hydrolysis. The mixture was stirred for 30 minutes to form a gel. After gelation, reagents were introduced sequentially at one-hour intervals: orthophosphoric acid, calcium nitrate, and sodium hydroxide. Subsequently, the solution was stirred for 4 hours to ensure homogeneity.The gel was dried at 80°C for 24 hours, followed by sintering at various temperatures (650°C, 700°C, and 750°C) for 3 hours. The resulting materials were designated based on their sintering temperatures: 53S-650, 53S-700, and 53S-750.

## CHARACTERIZATION TECHNIQUE

The crystalline properties of the synthesized bioactive materials were examined using X-ray diffraction (XRD) (PANalytical Instruments, The Netherlands) with Cu-Kα₁ radiation at a scanning rate of 10° per minute. The morphology of the copper-based bioactive materials was visualized using a field emission scanning electron microscope (FESEM, HITACHI SU-6600, Japan), and their elemental composition was determined through energy dispersive X-ray analysis (EDAX-Horiba). Additional imaging of sealed bioactive material sections and their associated mineralization was conducted using FESEM (FEI Quanta 200), and the micrographs were subsequently analyzed.High-Resolution Transmission Electron Microscopy (HR-TEM) (JEOL Japan, JEM-2100 Plus) was employed to study the particle size distribution and morphology of the copper-bioactive materials. Their chemical composition was investigated using X-ray photoelectron spectroscopy (XPS) (Omicron Nanotechnology ESCA-14, Al source). Micro Raman spectroscopy was carried out with a confocal Raman microscope (RAMAN 11i—Nanophoton) using a 532 nm excitation source, while vibrational modes were further confirmed through Fourier Transform Infrared (FT-IR) spectroscopy (Jasco FT/IR-6600) in ATR mode with a resolution of 4 cm⁻¹.Porosity of the copper-bioactive materials was evaluated using a Quantachrome Nova-1000 surface analyzer at liquid nitrogen temperature. Nitrogen adsorption-desorption isotherms were measured to analyze sample porosity. Zeta potential analysis (HORIBA SZ-100) was performed to determine the surface charge, with the bioactive materials suspended in double-distilled water and sonicated for 10 minutes before measurement.The sealing capability of the bioactive materials was assessed via X-ray imaging using X-mind (Acteon, Birmingham, United Kingdom). Fracture resistance tests were conducted to evaluate the mechanical stability of the bioactive sealants using a universal testing machine (TEC-SOL INDIA—TSI-LSD-C-200). Root canals filled with the materials were incubated in phosphate-buffered saline (PBS) for 7, 14, and 28 days, then dried in a hot air oven at 60°C for 12 hours. The dried canals were cross-sectioned using a micro motor and mounted in resin bases to ensure stability during load application.Post-incubation stability was analyzed by applying load to the sealant and measuring the load-displacement behavior of the canals. Fracture resistance tests were conducted in triplicate, and the results, including mean and median deviations, were provided as supporting information.

## INVITRO BIO-MINERALIZATION ASSESSMENT

The mineralization potential of the bioactive materials was assessed by immersing pellets (100 mg, 8 mm diameter) in Hank’s balanced salt solution. The pellets were prepared using a hydraulic pelletizer under a pressure of 100 bar, following the protocol outlined by Hanawa et al. They were incubated at 37°C for one, seven, and fourteen days. After incubation, the pellets were removed, filtered, and dried overnight in a hot air oven at 60°C. To evaluate biomineralization on the surface of the BAG pellets, Field Emission Scanning Electron Microscopy (FESEM) was used to observe morphological changes indicative of apatite growth. Additionally, Fourier Transform Infrared (FT-IR) spectroscopy and Energy Dispersive Spectroscopy (EDS) were employed to detect signatures of apatite formation.

The mineralization of bioactive sealants was also examined by immersing them in phosphate-buffered saline (PBS). The bioactive material paste was applied to biomechanically prepared root canals and incubated in PBS for 7, 14, and 28 days. The mineralization occurring between the canal walls and sealants was analyzed using Scanning Electron Microscopy (SEM). The fracture behavior of the sealants after incubation was evaluated using a universal testing machine.

## HEMOCOMPATIBILITY ASSAY

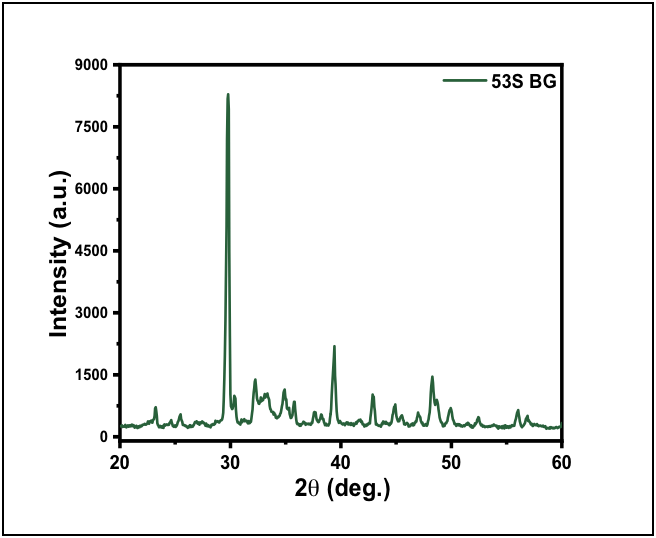
Assessing hemocompatibility is crucial for determining the suitability of biomaterials, as their initial interaction in vivo is with blood cells. Bioactive glass particles can enter the bloodstream and come into contact with erythrocytes, making it essential to evaluate their compatibility within the circulatory system. To assess this interaction with red blood cells (RBCs), an in vitro hemolysis assay was conducted, following the protocol described by Chitra, Bargavi, and Balakumar (2020)[(Chitra et al., 2020)](https://paperpile.com/c/OJoG0W/FFtYk). The percentage of hemolysis was calculated using the following formula:

Hemolysis (%) = [(Sample absorbance − Negative control absorbance) / (Positive control absorbance − Negative control absorbance)] × 100

Additionally, clot lysis was evaluated using fresh blood without anticoagulants. A 100 μl aliquot of blood was placed onto the bioactive materials in watch glasses. After 10 minutes, the clotted blood was rinsed with 10 ml of double-distilled water. The extent of hemoglobin release, indicating clot lysis, was determined by measuring the absorbance at 540 nm, as per the method by Nan et al. (1994). All materials were tested in triplicate to ensure accuracy.

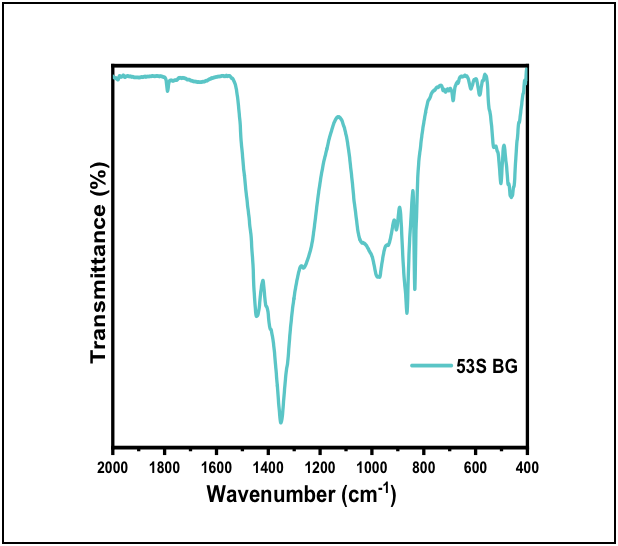
It’s important to note that, according to the International Organization for Standardization (ISO) 10993-4 standards, wound healing products with a hemolytic value of less than 5% are considered safe. Additionally, the hemolysis assay is commonly performed at body and fever temperatures (37 and 40 °C) with continuous gentle shaking at 300 rpm to avoid mechanical stress, as erythrocytes are very fragile under vigorous shaking conditions. These assessments are vital for ensuring that bioactive materials are safe and effective for medical applications involving direct blood contact.

# RESULTS



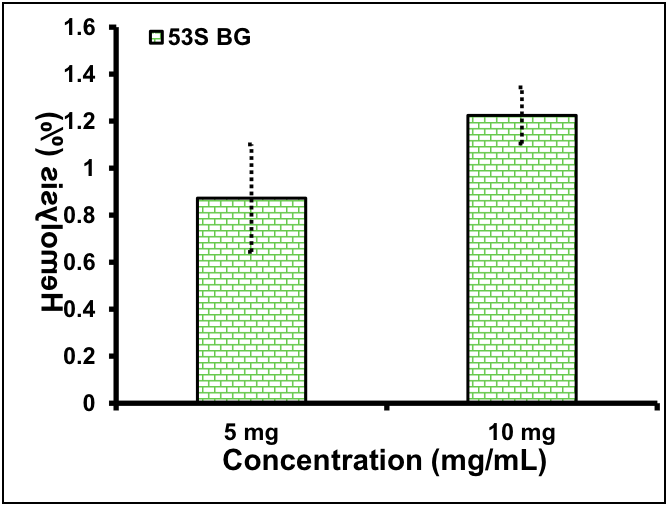
**Figure:1** X-Ray Diffraction Pattern of 53S Bioglass

X-Axis (2θ): The horizontal axis represents the diffraction angle (2θ) in degrees. It indicates the positions of the diffraction peaks corresponding to the crystalline planes in the material. Y-Axis (Intensity): The vertical axis shows the intensity of the diffracted X-rays, which reflects the relative abundance of the crystallographic planes producing the diffraction pattern. Diffraction Peaks: The sharp peaks in the pattern indicate the presence of crystalline phases within the bioglass. These peaks are unique to specific crystal structures, allowing identification of the phases present. Amorphous Background: If a broad hump is observed in the pattern (e.g., between 20° and 40°), it signifies the presence of an amorphous (non-crystalline) phase in the material, which is characteristic of bioactive glasses. Sharp Peaks: The presence of sharp peaks suggests that partial crystallization has occurred, possibly due to the sintering process. The peaks can be matched to specific phases like hydroxyapatite or other calcium silicate phases. Broad Hump (if present): This indicates the glassy (amorphous) nature of the material, as bioactive glasses typically exhibit an amorphous structure. Phase Identification: Each peak corresponds to specific crystallographic planes, which can be identified by comparing the peak positions to standard reference data in the XRD database.



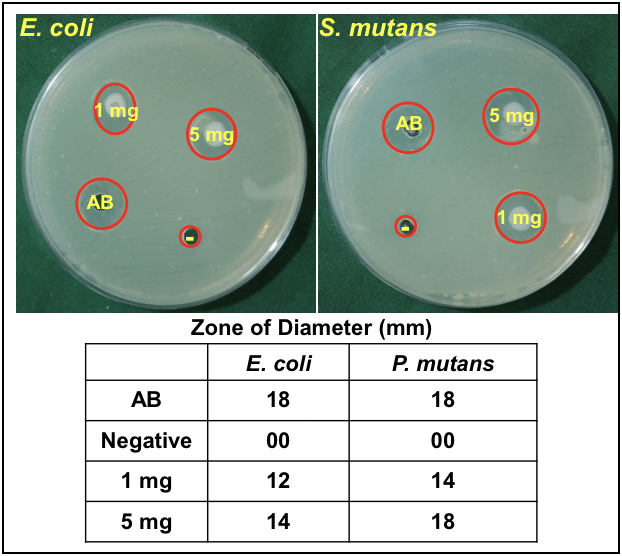
**Figure:2** Fourier Transform Infrared Spectroscopy Pattern of 53S Bioglass

FT-IR is to analyse the functional group of the material. In this test silica and phosphate vibration are active. X-axis: This typically represents the wavelength or wavenumber of light, measured in units such as nanometers (nm) or inverse centimeters (cm⁻¹). Y-axis: This usually indicates the absorbance or transmittance of light, often measured as a fraction or percentage. Absorption peaks (dips in the curve): These correspond to wavelengths where the substance absorbs light most strongly. These features can be linked to specific molecular vibrations, electronic transitions, or other properties of the material being studied. Smooth regions (near-flat areas): These indicate wavelengths where the material does not absorb significantly.



**Figure:3** Blood Compatibility of 53S Bioglass

It is the primary tool to analyse the biocompatible nature of the material. 53S Bioglass has a maximum of 1.2% biocompatible nature. The x-axis would denote bioglass concentration (e.g., in mg/mL). The y-axis would denote hemolysis percentage or related metrics. The curve would likely indicate an increasing trend of hemolysis as concentration rises.



**Figure:4** Anti-Bacterial Activity of 53S Bioglass

Anti-microbial action against Escherichia coli and Streptococcus mutans was seen. It shows enhanced bacterial inhibitory growth rate in Anti-microbial plate.

# DISCUSSION

The evaluation of structural, morphological, biocompatible, and antimicrobial properties of 53S bioactive glass provides crucial insights into its potential for biomedical applications, particularly in bone tissue engineering and antimicrobial applications. This study comprehensively analyzed the crystalline and amorphous phases, surface morphology, biocompatibility, and antimicrobial efficacy of 53S bioactive glass. The X-ray diffraction (XRD) analysis confirmed the semi-crystalline nature of the 53S bioactive glass[(S et al., 2022)](https://paperpile.com/c/OJoG0W/60bFW). The presence of a broad hump in the XRD pattern highlights the glassy (amorphous) structure, which is critical for bioactivity. The sharp peaks observed in the sintered samples, particularly at higher temperatures (e.g., 700°C and 750°C), indicate partial crystallization, primarily due to the formation of calcium phosphate or silicate-based crystalline phases. These phases are known to play a significant role in improving bioactivity by promoting the deposition of hydroxyapatite (HCA) on the material’s surface when exposed to physiological environments[(Drago et al., 2018)](https://paperpile.com/c/OJoG0W/yMM1t). This behavior aligns with the sol–gel synthesis process, which inherently allows fine control over the material’s composition and structural properties[(Virdi, 2015)](https://paperpile.com/c/OJoG0W/hJp2q).The balance between amorphous and crystalline phases is critical for the bioactivity and mechanical performance of bioactive glasses. The amorphous phase ensures rapid ion release for bio-mineralization, while the crystalline phases impart mechanical stability. The results of this study suggest that the sintering process significantly influences this balance, with higher temperatures leading to an increase in crystallinity. This insight is vital for tailoring 53S bioactive glass to specific clinical applications[(Arcos et al., 2003)](https://paperpile.com/c/OJoG0W/neMRg).The scanning electron microscopy (SEM) analysis revealed a porous surface morphology of the 53S bioactive glass. The interconnected porosity observed in the samples is highly desirable for bone tissue engineering, as it facilitates cell attachment, proliferation, and nutrient diffusion[(Marelli et al., 2010)](https://paperpile.com/c/OJoG0W/ie147). Additionally, the pore size and distribution are critical factors influencing the material’s bioactivity and ability to form bonds with native bone tissue [(Balaji Ganesh S & Sugumar, 2021; Jabin et al., 2021)](https://paperpile.com/c/OJoG0W/4ZmaU+KlHDQ).The porosity observed in the sol–gel-derived 53S bioactive glass can be attributed to the synthesis process, which involves hydrolysis and condensation reactions that form a gel-like network. The subsequent drying and sintering steps preserve the porosity, ensuring that the material exhibits the required surface features for bio-mineralization. Moreover, the surface roughness created during this process enhances the material’s osteoconductivity, making it suitable for bone regeneration applications. The biocompatibility of 53S bioactive glass was evaluated using hemocompatibility assays and in vitro bio-mineralization tests[(Shivalingam et al., 2020)](https://paperpile.com/c/OJoG0W/KyxB7). The results indicated that the material exhibited excellent hemocompatibility, with minimal hemolysis observed in the presence of red blood cells. This is a critical property for materials intended for biomedical applications, as it ensures their safe interaction with blood and surrounding tissues [(Govindaraj & Dinesh, 2021; Rajeshkumar et al., 2021; Sushanthi, 2021)](https://paperpile.com/c/OJoG0W/rGcu4+3uzo7+40yCF).The in vitro bio-mineralization studies further validated the bioactivity of 53S bioactive glass. When immersed in Hank’s Balanced Salt Solution (HBSS), the material demonstrated significant mineral deposition on its surface over time, as confirmed by SEM and Fourier-transform infrared (FTIR) spectroscopy[(Chitra et al., 2020)](https://paperpile.com/c/OJoG0W/FFtYk). The formation of hydroxyl carbonate apatite (HCA) on the surface is a hallmark of bioactivity, indicating that the material can effectively promote bone-like mineral formation[(Sola et al., 2012)](https://paperpile.com/c/OJoG0W/YuNS2). This property is particularly advantageous for applications in bone defect repair, where rapid integration with native bone tissue is essential. The bioactivity of 53S bioactive glass is closely related to its chemical composition and structure. The release of ions such as calcium, phosphate, and silicon from the material into the surrounding environment creates a favorable condition for the nucleation and growth of HCA [(Graf et al., 2023; Ramamurthy & Jaiganesh, 2021; Tiwari & Jain, 2023)](https://paperpile.com/c/OJoG0W/l5vo4+b0ha4+sG9Gp). The incorporation of phosphorus into the glass network further enhances this process, as phosphate ions are key components of biological apatite[(Elshazly et al., 2024)](https://paperpile.com/c/OJoG0W/8FH4s).The antimicrobial efficacy of 53S bioactive glass was evaluated against common pathogenic microorganisms[(Antoniac, 2019)](https://paperpile.com/c/OJoG0W/oKjzB)[(Chandran et al., 2024)](https://paperpile.com/c/OJoG0W/geyPI). The results demonstrated that the material exhibited significant antimicrobial activity, which can be attributed to the ion release from the glass. The release of alkali and alkaline earth metal ions, such as sodium and calcium, increases the local pH, creating an environment that is hostile to microbial growth. Additionally, the silica-based network of the material may interfere with bacterial adhesion and biofilm formation. The antimicrobial properties of 53S bioactive glass are particularly important for applications in orthopedic implants and wound dressings, where infection is a major concern[(Subramaniam et al., 2024)](https://paperpile.com/c/OJoG0W/zfz4A). The ability of the material to simultaneously promote tissue regeneration and inhibit microbial growth makes it an attractive option for such applications. Furthermore, the antimicrobial activity observed in this study suggests that 53S bioactive glass could reduce the need for systemic antibiotics, thereby minimizing the risk of antibiotic resistance[(van Gestel et al., 2015; Wang et al., 2023)](https://paperpile.com/c/OJoG0W/HvkGA+u52w8).The study highlighted the impact of sintering temperature on the structural, morphological, and functional properties of 53S bioactive glass. As the sintering temperature increased, the crystallinity of the material also increased, as evidenced by the XRD patterns . This change in crystallinity influenced the material’s bioactivity, with higher temperatures leading to a slower rate of ion release and HCA formation. However, the increased mechanical strength associated with higher crystallinity makes the material more suitable for load-bearing applications. The morphological analysis revealed that the porosity of the material decreased with increasing sintering temperature. While this may reduce the material’s bioactivity to some extent, it enhances its mechanical properties, making it more durable under physiological conditions(Rafi et al., 2024). Therefore, the choice of sintering temperature should be tailored to the specific application, balancing the requirements for bioactivity and mechanical performance[(Kellermeier et al., 2013)](https://paperpile.com/c/OJoG0W/kizVr).The findings of this study are consistent with previous research on bioactive glasses. The structural and morphological features observed in 53S bioactive glass align with those reported for other sol–gel-derived bioactive glasses, which are known for their high surface area and porosity[(Peltola et al., 2006)](https://paperpile.com/c/OJoG0W/7BJ3I). Similarly, the biocompatibility and bioactivity results corroborate earlier studies demonstrating the ability of bioactive glasses to promote HCA formation and support cell proliferation. However, this study also provides new insights into the antimicrobial properties of 53S bioactive glass [(Chitra et al., 2019)](https://paperpile.com/c/OJoG0W/xH7w9). While the antimicrobial activity of bioactive glasses has been reported previously[(Marchi, 2016; Peltola et al., 2006)](https://paperpile.com/c/OJoG0W/7BJ3I+RBLNg), the detailed evaluation presented here highlights the potential of 53S bioactive glass as a dual-functional material that combines [(Bajpai & Rajasekar, 2024)](https://paperpile.com/c/OJoG0W/Fq43C)bioactivity with infection prevention. This dual functionality is particularly relevant in the context of modern healthcare challenges, where the demand for multifunctional biomaterials is growing (Tuluwengjiang et al., 2024).

# CONCLUSION

The results of this study underscore the potential of 53S bioactive glass for a wide range of biomedical applications. However, further research is needed to fully exploit its capabilities. For instance, the long-term stability of the material in physiological environments should be investigated to ensure its durability and performance over extended periods. Additionally, in vivo studies are required to validate the in vitro findings and assess the material’s performance in a more complex biological environment.The antimicrobial properties of 53S bioactive glass also warrant further exploration. Understanding the mechanisms underlying its antimicrobial activity could lead to the development of optimized formulations with enhanced efficacy. Moreover, combining 53S bioactive glass with other antimicrobial agents or surface coatings could further improve its performance, particularly for applications in infection-prone environments.This study highlights the structural, morphological, biocompatible, and antimicrobial properties of 53S bioactive glass, demonstrating its suitability for biomedical applications. The material’s ability to promote bio-mineralization, support cell compatibility, and inhibit microbial growth positions it as a promising candidate for bone tissue engineering, orthopedic implants, and wound healing. By tailoring its properties through controlled synthesis and processing, 53S bioactive glass can be adapted to meet the diverse requirements of different clinical applications.

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