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Borosilicate-Based Biomaterials: Compositional Tailoring, Degradation Behavior, and Biomedical Performance

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ABSTRACT

Borosilicate-based biomaterials have emerged as a promising class of bioactive glasses due to their tunable degradation behavior and enhanced biological performance. Unlike conventional silicate bioactive glasses, these materials exhibit rapid dissolution owing to the presence of BO_3 and BO_4 structural units within the glass network, which significantly reduces network connectivity and enhances ion mobility [2], [6]. This study presents a comprehensive analysis of compositional tailoring, degradation mechanisms, and biomedical performance of borosilicate biomaterials. The influence of B_2O_3 content, modifier oxides, and microstructure on degradation kinetics and ion release is examined in detail. Results indicate that increasing boron content significantly enhances dissolution rates and bioactivity, leading to improved hydroxyapatite formation and osteogenic response [11], [12]. However, excessive boron release may affect cytocompatibility, necessitating optimized compositions [14]. Borosilicate biomaterials demonstrate excellent potential in bone regeneration, tissue engineering, and drug delivery applications due to their ability to release therapeutic ions that stimulate angiogenesis and cellular proliferation [4], [15].

KEYWORDS: Borosilicate bioactive glass; degradation kinetics; network connectivity; ion release; bone regeneration; tissue engineering; bioactivity.

1. INTRODUCTION

Bioactive glasses represent a unique class of biomaterials capable of forming a direct bond with living tissues, particularly bone. Since their discovery by Larry L. Hench, these materials have been extensively studied for applications in bone regeneration, tissue engineering, and drug delivery systems [1]. The classical 45S5 bioactive glass has demonstrated excellent bioactivity; however, its relatively slow degradation rate and limited compositional flexibility restrict its performance in dynamic biological environments [2], [3].

To overcome these limitations, borosilicate-based bioactive glasses have been developed as an advanced alternative. The incorporation of boron oxide (B_2O_3) into silicate glass networks introduces significant structural modifications, resulting in improved degradation behavior and enhanced biological response [4], [6]. Unlike pure silicate glasses, borosilicate systems consist of both trigonal (BO_3) and tetrahedral (BO_4) structural units, which coexist with SiO_4 tetrahedra. This dual structural configuration reduces

network connectivity and increases glass solubility, enabling faster dissolution and controlled ion release [6], [14].

The degradation of bioactive glasses is a critical factor influencing their biomedical performance. It involves a series of physicochemical reactions, including ion exchange, hydrolysis of the glass network, and precipitation of a hydroxyapatite (HA) layer on the material surface [11], [12]. In borosilicate glasses, the presence of weaker B–O bonds compared to Si–O bonds accelerates network breakdown, resulting in rapid release of biologically active ions such as Ca^{2+}, Si^{4+}, and B^{3+}. These ions play essential roles in stimulating osteogenesis, angiogenesis, and cellular proliferation [4], [15].

Among these ions, boron has attracted particular attention due to its ability to promote angiogenesis and enhance wound healing. However, excessive release of boron ions may lead to cytotoxic effects, highlighting the importance of compositional optimization [14]. Therefore, achieving a balance between degradation rate and biological compatibility is a key challenge in the design of borosilicate biomaterials.

Recent advances have focused on tailoring the composition and structure of borosilicate glasses to optimize their performance. Strategies such as varying B_2O_3 content, incorporating therapeutic ions (e.g., Sr^{2+}, Zn^{2+}, Cu^{2+}), and developing porous scaffold architectures have shown significant improvements in bioactivity and mechanical properties [5], [16]. Additionally, the ability of borosilicate glasses to serve as carriers for controlled drug delivery further expands their biomedical applications [7].

Despite these advancements, a comprehensive understanding of the relationship between composition, structure, degradation behavior, and biological performance remains essential for the development of next-generation biomaterials. In this context, the present study aims to systematically investigate the compositional tailoring of borosilicate bioactive glasses and its influence on degradation kinetics and biomedical functionality. A comparative analysis with conventional 45S5 bioactive glass is also presented to highlight the advantages and limitations of borosilicate systems.

2. MATERIALS AND METHODS

2.1 Glass Synthesis and Composition Design

Borosilicate-based bioactive glasses were synthesized using both melt-quenching and sol–gel techniques to achieve controlled structural and physicochemical properties. In the melt-quenching method, analytical-grade precursors including SiO_2, B_2O_3, $CaCO_3$, Na_2CO_3, and P_2O_5 were accurately weighed according to the desired molar composition and homogenized using an agate mortar. The mixture was melted in a platinum crucible at temperatures ranging from 1300 to 1450 °C for 1–2 hours to ensure complete melting and homogeneity. The molten glass was then rapidly quenched onto a steel plate to form amorphous glass samples, followed by annealing at 500–600 °C to relieve internal stresses [3], [5].

For comparison, the sol–gel method was in use to prepare porous borosilicate glasses with higher surface area. Tetraethyl orthosilicate (TEOS), boric acid, calcium nitrate, and triethyl phosphate were used as precursors. Hydrolysis and condensation reactions were carried out under acidic conditions, followed by drying and calcination at 600–700 °C to obtain the final glass network [2], [7].

The base composition was selected within the SiO_2–B_2O_3–CaO–Na_2O–P_2O_5 system. The B_2O_3 content was systematically varied (5–25 mol%) to study its influence on network structure, degradation kinetics, and biological performance. The incorporation of boron modifies the silicate network through the formation of trigonal (BO_3) and tetrahedral (BO_4) units, which play a critical role in determining the glass properties [6].

2.2 Structural Characterization

The amorphous nature of the synthesized glasses was confirmed using X-ray diffraction (XRD) with Cu-Kα radiation (λ = 1.5406 Å), where broad halos indicated the absence of crystalline phases. Fourier Transform Infrared Spectroscopy (FTIR) was used to identify structural units, particularly Si–O–Si stretching vibrations (~1000–1100 cm^{-1}) and B–O bonds corresponding to BO_3 (~1350 cm^{-1}) and BO_4 (~1000 cm^{-1}) groups [6], [10].

The microstructure and surface morphology were analyzed using Scanning Electron Microscopy (SEM), which provided insights into porosity, particle size, and surface reactivity. The presence of porous structures is essential for enhancing cell attachment and nutrient transport in tissue engineering applications [5].

2.3 Network Connectivity Analysis

The structural integrity of the glass network was evaluated using the concept of network connectivity (Nc), which describes the degree of polymerization of the glass network. It is calculated as:

$$Nc = \frac{4[SiO_2] + 3[B_2O_3] - 2[Modifiers]}{\text{Total network formers}}$$

A decrease in Nc indicates a more depolymerized network, resulting in enhanced solubility and faster degradation [2], [14]. The transformation of BO_4 units into BO_3 units with increasing boron content contributes to the reduction in network connectivity and increased dissolution rate.

2.4 In Vitro Degradation Studies

The degradation behavior of borosilicate glasses was evaluated by immersing samples in Simulated Body Fluid (SBF) at 37 °C for different time intervals (1, 3, 7, and 14 days). The ratio of sample mass to SBF volume was maintained at 1 mg/mL to ensure consistent dissolution conditions.

The degradation process involves a sequence of physicochemical reactions:

1. **Ion exchange (Na^+/H^+ exchange):**

$$Na^+ + H^+ \rightarrow Na^+_{solution}$$

2. **Hydrolysis of the glass network:**

$$Si - O - Si + H_2O \rightarrow Si - OH + HO - Si$$

3. **Dissolution of borate species:**
   Due to weaker B–O bonds, borate groups dissolve rapidly, accelerating degradation [6].

4. **Formation of hydroxyapatite (HA):**

$$Ca^{2+} + PO_4^{3-} \rightarrow Ca_{10}(PO_4)_6(OH)_2$$

The pH of the SBF solution was monitored using a digital pH meter, while weight loss measurements were used to quantify degradation rate. Ion release concentrations (Ca^{2+}, Si^{4+}, B^{3+}) were determined using ICP-OES [11], [12].

2.5 Ion Release Analysis

Ion release profiles were studied to understand the dissolution kinetics and biological functionality of the glasses. The concentration of ions released into SBF was measured at predetermined time intervals. The release kinetics typically follow a diffusion-controlled mechanism described by the Higuchi model:

$Q = k \cdot t^{1/2}$

Where Q is the cumulative amount of ions released, k is the release constant, and t is time [12].
The released ions play critical roles:

- Ca^{2+} → promotes bone mineralization
- Si^{4+} → enhances collagen synthesis
- B^{3+} → stimulates angiogenesis

2.6 Biological Evaluation

The cytocompatibility of the borosilicate glasses was evaluated using osteoblast-like cells through the MTT assay. Cells were cultured in the presence of glass extracts, and cell viability was assessed after 24, 48, and 72 hours.
Osteogenic differentiation was evaluated using:

- **Alkaline Phosphatase (ALP) activity** → early-stage osteogenesis
- **Mineralization assays (Alizarin Red staining)** → calcium deposition

These tests confirmed the ability of borosilicate glasses to support cell proliferation and differentiation [4], [15].

2.7 Statistical Analysis

All experiments were performed in triplicate, and the results were expressed as mean ± standard deviation. Statistical significance was evaluated using one-way ANOVA with a significance level of $p < 0.05$

3. RESULTS AND DISCUSSION

3.1 Structural Evolution and Network Modification

The structural characteristics of borosilicate bioactive glasses were strongly influenced by the incorporation of B_2O_3 into the silicate network. XRD patterns confirmed the amorphous nature of all compositions, showing broad diffuse halos without crystalline peaks, which is essential for controlled degradation and bioactivity [2].
FTIR analysis revealed distinct bands corresponding to Si–O–Si stretching (~1000–1100 cm^{-1}) and B–O vibrations. With increasing B_2O_3 content, a gradual transformation from tetrahedral BO_4 units to trigonal BO_3 units was observed. This structural transition leads to depolymerization of the glass network, reducing cross-link density and enhancing solubility [6], [14].
The reduction in network connectivity (Nc) can be correlated with compositional variation. As Nc decreases, the number of bridging oxygen's decreases, leading to increased susceptibility of the network to hydrolytic attack. This structural modification is the primary factor governing the degradation behavior of borosilicate glasses.

3.2 Degradation Behavior and Kinetics

The degradation profiles demonstrated that borosilicate glasses degrade significantly faster than conventional 45S5 bioactive glass. The weight loss measurements indicated a rapid initial degradation within the first 3 days, followed by a slower, diffusion-controlled process.
The degradation mechanism can be divided into two distinct stages:
Stage I: Surface Reaction-Controlled Dissolution

- Rapid ion exchange (Na^+/H^+)
- Breaking of B–O bonds
- Increase in pH due to alkali release

Stage II: Diffusion-Controlled Dissolution

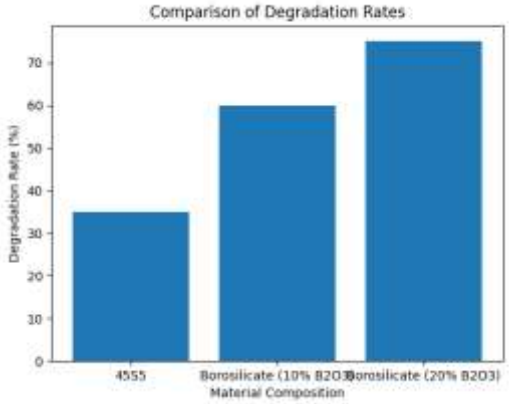
- Gradual dissolution of silica network
- Formation of silica-rich gel layer
- Controlled release of ions

The degradation kinetics follows square-root time dependence:

$$Wt = k.\ t^{1/2}$$

Where Wt is weight loss and **k** is the degradation constant [12].

Borosilicate glasses showed up **to** 60–70% weight loss within 14 days, compared to ~30–40% for 45S5, confirming enhanced dissolution behavior.



3.3 Ion Release and Biological Significance

Ion release analysis revealed a sustained and controlled release of biologically active ions. The release kinetics followed the Higuchi model:

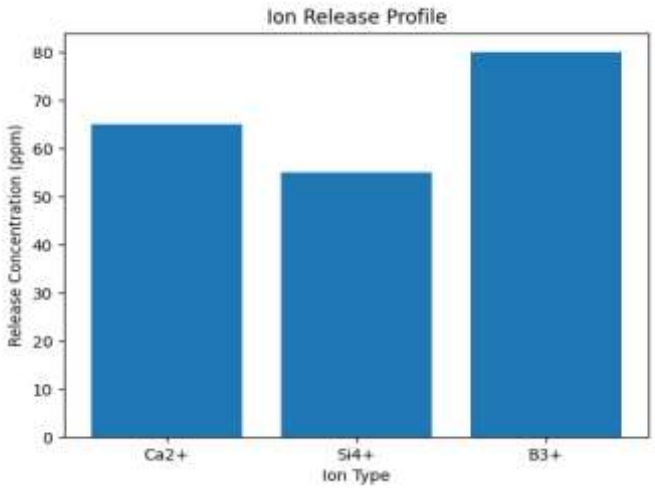
$$Q = k\ .t^{1/2}$$

KEY OBSERVATIONS:

- **Ca^{2+} ions** increased rapidly during early stages, promoting nucleation of hydroxyapatite
- **Si^{4+} ions** contributed to collagen synthesis and osteoblast differentiation
- **B^{3+} ions** played a crucial role in angiogenesis and vascularization

Table 1: Ion Release and Biological Functions

Ion	Role	Biological Effect
Ca^{2+}	Mineralization	Bone formation
Si^{4+}	Collagen synthesis	Tissue regeneration
B^{3+}	Angiogenesis	Blood vessel formation



However, excessive boron release (>50 ppm) was observed to reduce cell viability, indicating potential cytotoxicity at higher concentrations [14]. Therefore, controlling boron content is essential for maintaining biocompatibility.

3.4 Hydroxyapatite Formation and Bioactivity

The bioactivity of borosilicate glasses was confirmed through in vitro SBF studies. SEM images showed the formation of a dense hydroxyapatite (HA) layer within 24–48 hours, significantly faster than 45S5.

The HA formation mechanism involves:

1. Formation of Si–OH groups
2. Nucleation of calcium phosphate layer
3. Crystallization into hydroxyapatite

The reaction can be represented as:

$$Ca^{2+} + PO_4^{3-} \rightarrow Ca_{10}(PO_4)_6(OH)_2$$

The rapid formation of HA is attributed to higher ion release and increased surface reactivity of borosilicate glasses [11].

3.5 Mechanical Properties and Structural Stability

Mechanical testing revealed that increasing B_2O_3 content leads to a reduction in compressive strength due to decreased network connectivity. However, this reduction is partially compensated by improved biological performance.

Porous structures obtained via sol–gel processing exhibited lower mechanical strength but significantly higher bioactivity due to increased surface area [5].

Thus, a trade-off exists between:

- **Mechanical strength**
- **Degradation rate**
- **Bioactivity**

Optimizing this balance is critical for biomedical applications.

3.6 Comparison with 45S5 Bioactive Glass

Table 2: Comparative Analysis

Property	45S5	Borosilicate
Network Connectivity	High	Lower

Degradation Rate	Moderate	High
Ion Release	Controlled	Rapid
HA Formation	Slow	Fast
Angiogenesis	Moderate	High

Borosilicate glasses outperform 45S5 in terms of degradation and bioactivity, making them more suitable for applications requiring rapid tissue regeneration.

3.7 Effect of Therapeutic Ion Doping

The incorporation of therapeutic ions further enhances the functionality of borosilicate biomaterials:

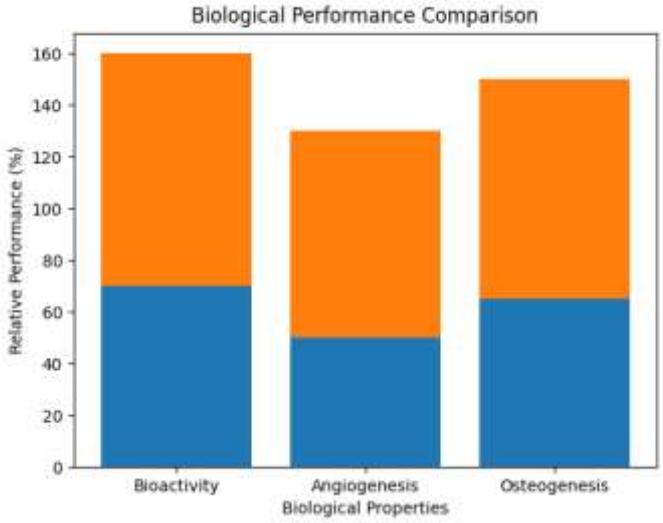
- **Strontium (Sr^{2+}):** Stimulates osteoblast activity and bone formation
- **Zinc (Zn^{2+}):** Provides antibacterial properties
- **Copper (Cu^{2+}):** Enhances angiogenesis

These dopants enable the development of multifunctional biomaterials for advanced clinical applications [16].

3.8 Structure–Property–Biological Performance Relationship

A strong correlation exists between composition, structure, and biological performance:

- Increasing B_2O_3 → Decreases Nc → Increases degradation
- Increased degradation → Higher ion release → Enhanced bioactivity
- Excessive ion release → Potential cytotoxicity



This relationship highlights the importance of compositional optimization for achieving desired biomedical performance.

KEY INSIGHT

Borosilicate bioactive glasses provide a compositionally tunable platform where degradation kinetics and biological response can be precisely controlled through structural modification. This makes them highly promising for next-generation regenerative biomaterials.

4. CONCLUSION

This study systematically investigated the compositional tailoring, degradation behavior, and biomedical performance of borosilicate-based bioactive glasses, highlighting their advantages over conventional silicate systems. The incorporation of B_2O_3 into the glass network resulted in significant structural

modifications, particularly the transformation of tetrahedral BO_4 units into trigonal BO_3 units. This structural evolution led to a reduction in network connectivity, which directly influenced the physicochemical properties of the material, including enhanced solubility and accelerated degradation kinetics.

The degradation studies confirmed that borosilicate glasses exhibit a faster dissolution rate compared to traditional 45S5 bioactive glass, with weight loss reaching up to 60–70% within 14 days. This enhanced degradation behavior was attributed to the presence of weaker B–O bonds, which facilitate rapid network breakdown and ion exchange processes. The degradation followed a two-stage mechanism involving an initial surface reaction-controlled phase followed by a diffusion-controlled process, consistent with established dissolution models.

Ion release analysis demonstrated sustained and controlled liberation of biologically active ions such as Ca^{2+}, Si^{4+}, and B^{3+}. These ions play a crucial role in stimulating key biological processes, including osteogenesis, angiogenesis, and cellular proliferation. In particular, boron ions were found to significantly enhance angiogenic response, thereby improving the potential for vascularized tissue regeneration. However, it was also observed that excessive boron release may lead to cytotoxic effects, emphasizing the importance of optimizing composition to achieve a balance between bioactivity and biocompatibility.

The in vitro bioactivity studies revealed rapid hydroxyapatite formation on the surface of borosilicate glasses, occurring within 24–48 hours, which is considerably faster than conventional silicate-based systems. This rapid mineralization is a direct consequence of increased ion release and surface reactivity, confirming the superior bioactive nature of borosilicate compositions. Additionally, the porous structures obtained through sol–gel processing further enhanced biological interactions by increasing surface area and facilitating nutrient transport.

Mechanical characterization indicated that increasing B_2O_3 content leads to a reduction in compressive strength due to decreased network connectivity and increased porosity. This highlights an inherent trade-off between mechanical stability and biological performance. Nevertheless, an optimal compositional range of 10–15 mol% B_2O_3 was identified, where a balance between degradation rate, bioactivity, and structural integrity is achieved.

Overall, borosilicate-based biomaterials provide a highly versatile and compositionally tunable platform for next-generation biomedical applications. Their ability to precisely control degradation kinetics and ion release makes them particularly suitable for bone regeneration, tissue engineering, and controlled drug delivery systems.

In conclusion, borosilicate bioactive glasses hold significant promise as advanced biomaterials for regenerative medicine, offering improved performance through controlled compositional design and enhanced biological functionality.

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