Metal Ions and Bioactive Glasses

Subjects: Chemistry, Medicinal
Contributor: Irina Atkinson

Bioactive glasses (BGs) are of great interest in the field of medical implants due to their osteoinductive, osteoproductive, osteoconductive, and antimicrobial properties. Metal ions with bactericidal action can be incorporated into the glass structure in order to improve the antibiofilm activity of the BGs.

Keywords: bacterial biofilm ; bioactive glass ; metal ions

1. Bioactive Glasses

Bioactive glasses (BGs) are of great interest in the field of medical implants due to their osteoinductive, osteoproductive, osteoconductive, and antimicrobial properties [1]. L. Hench, who revolutionized the field of biomaterials with his invention of 45S5 BG, known as Bioglass® (wt. %: 45SiO_2-24.5Na_2O-24.5CaO-6P_2O_5), in the early 1970s, classified a bioactive material as one that causes a biological reaction at its interface and promotes a bond to develop between the tissues and the material [2]. He discovered that the composition of 45S5 bioactive glass bonded with the bone through the formation of hydroxyapatite (HAP), an analog to the mineral phase of bones when it was in contact with biological fluids. The Bioglass® composition has received the approval of the US Food and Drug Administration. Currently, it is used for middle ear treatment and periodontal repair and augmentation [3].

Since then, the research on BGs has provided very good results through the conversion of traditional glasses into glasses with added properties that address healthcare needs. BGs can bond to and integrate with the bone tissue without promoting inflammation and toxicity or forming fibrous tissue [4][5].

The main advantage of BGs for tissue engineering applications is their surface reactivity. The reaction products resulting from the interaction between BGs and the physiological fluids lead to the formation of the HAP-like phase, similar to the crystalline HAP of bones. When these glasses are exposed to an aqueous environment, they undergo several surface reactions that have been described as the bioactivity of BGs [6]:

I. Rapid exchange of Ca^{2+} with a proton or hydrate proton;

II. Generation of silanols (Si–OH) at the site of the breakdown of the silica network. Solution interface for BG. In this stage, soluble silica [Si(OH)4] is also produced and released to the bodily fluid;

III. Condensation and repolymerization of the silica-rich layer take place on the BGs'surface. Consumption of Si–OH;

IV. Ca^{2+} and PO_4^{3-} migrate to the surface and form Ca–PO_4^{3-} clusters on the top of the SiO_2-rich layer, and the crystallization of the amorphous CaP takes place;

V. Finally, the hydroxycarbonate apatite layer (HAC) is formed by the incorporation of OH^- and CO_3^{2-} anions from the solution.

Furthermore, the release of ions makes the surrounding environment hostile to microbial development through the generation of osmotic and acid-base imbalance without being dependent on antibiotics and without harming the host tissues.

BGs can be obtained either by the traditional melt-quenching or the modern sol-gel method [7].

Melt-derived BGs are prepared at temperatures higher than 1000 °C, with a procedure analogous to that used to melt common window glasses. The resulting material does not have any porosity at all, and the surface area depends only on the particle size obtained by grinding up the powders.

In the 1990s, the sol–gel method, which involves the hydrolysis and polymerization of metal hydroxides, alkoxides, and/or inorganic salts, was used for the first time to create BGs [8]. Contrary to the melt-derived BGs, the sol–gel glasses are not prepared at elevated processing temperatures. The surface and structural properties (such as the surface area and porosity) can be finely modulated depending on the composition and synthesis conditions. The BGs obtained by the sol–gel method can have different types of pores, such as nanopores, macropores, or mesopores [9]. At the very end, controlled nanostructured materials can be obtained. Due to their outstanding textural properties, HAP is deposited much faster on the sol–gel BGs than on the melt-derived ones, and the materials exhibit higher bone-bonding rates, together with excellent degradation/resorption properties [10][11][12].

Furthermore, the sol–gel processes can be combined with the supramolecular chemistry of surfactants, resulting in the third-generation class of BGs referred to as ordered mesoporous bioactive glasses (MBGs), with the values of the surface and porosity up to five times higher than those obtained by the sol–gel method [13][14]. The surfactants for preparing MBGs mainly include CTAB, P123 (EO20-PO70-EO20), and F127 (EO106-PO70-EO106) [15]. MBGs exhibit the highest in vitro bioactivity and their ordered mesoporous structure allows for the incorporation of antimicrobial agents, etc., thereby having a huge potential in the therapy of bacteria-associated infection.

Moreover, BGs can be used to produce three-dimensional scaffolds, which are an advantage in tissue-engineering applications. Thus, a bioactive, biodegradable, and highly porous matrix that could resemble the cancellous bone is obtained.

The introduction of the sol–gel method opened the research to new types of materials for medical applications. One of the advantages of this method, in comparison with the conventional melting technique, is the possibility of easy chemical doping. Moreover, the traditional melting method's higher processing temperature causes some components, including P_2O_5, to evaporate throughout the process, decreasing the overall bioactive potential of the glass, as well as other properties [16].

The antibacterial property of the BGs is an intriguing characteristic. In some cases, BG compositions have demonstrated antibacterial properties without any addition to their composition of metal ions or antibiotics.

Zhou et al. [17] compared the efficacy of 45S5 and S53P4 ($53SiO_2$-$23Na_2O$-20%CaO- 4% P_2O_5, wt. %) BGs against the biofilm generated by *MRSA* and *V. parvula*. They found that 45S5 BG particles exhibited a higher reduction of the biofilm than the S53P4 BG particles, suggesting the potential of 45S5 BG for eradicating mature biofilm. They emphasized the influence of the BGs particle size on the effectiveness against biofilms. Smaller particles reduced biofilms significantly more than larger particles across the experiment. Other researchers have demonstrated the strong activity of S53P4 BG to reduce the biofilm produced by a wide variety of bacteria, including *S. aureus*, *P. aeruginosa*, *K. pneumoniae*, and *S. epidermidis* [18][19].

Considering that bacteria can evolve defensive mechanisms against antibiotics through mutation and selection, an alternative to treating bone infections is the use of biocide metal ions. Low-bacterial resistance is one of the advantages of these ions.

Moreover, the concentration of the dopant should be determined, because the low dopant concentrations sometimes may not produce the desired properties, and on the contrary, high dopant concentrations may have cytotoxic and carcinogenic effects [20].

2. Metal Ions Incorporated Bioactive Glasses with Antibiofilm Efficiency

In recent years, several studies have demonstrated the effective antibiofilm activity of different formulations of BGs. Ag^+, $Cu^{2+/+}$, Ga^{3+}, Ti^{4+}, and Zn^{2+} are some examples of ions that can be used in doped BGs to target the inhibition and disruption of bacterial biofilm [21][22][23][24].

A recent study [25] reported that F18 glass, synthesized by the melting method, belonging to the SiO_2-Na_2O-K_2O-MgO-CaO-P_2O_5 system, is a promising material for preventing and controlling bacterial biofilm. The bacterial strains *S. aureus* and *methicillin-resistant S. aureus (MRSA)* were used to evaluate the reduction of the biofilm.

One of the most efficient ions against bacterial biofilm is zinc (Zn) [26][27]. Zn is a multifunctional therapeutic ion. Zn can stimulate bone formation because it is a cofactor in many enzymes and is involved in DNA replication [26]. Zn can also leak from the BG, causing oxidative stress in the intracellular medium or damage to cell membranes [28].

Zn-containing BGs have been shown to have antimicrobial properties against *S. aureus* and *E. coli* in the planktonic form [29].

In their investigation, Esfahanizadeh et al. [22] discovered that BG doped with 5 mol % of Zn significantly reduced the ability of Gram-negative anaerobic periodontal pathogens such as *P. gingivalis, A. actinomycetemcomitans,* and *P. intermedia* to develop a biofilm.

Zn (2.39 wt. %)-doped nano-BG particles ($55SiO_2$-$40CaO$-$5P_2O_5$ mol %) were obtained by Paramita et al. [30] using the sol–gel method.

Silver (Ag) exhibits powerful antibacterial activity against a range of bacterial species [31][32][33], including antibiotic-resistant strains [34]. Incorporating Ag into BG has been proposed as a possible alternative to antibiotics for reducing infection in clinical applications [35][36][37]. Wilkinson et al. [35] aimed to elucidate the antibiofilm efficacy of Ag-doped BG (TheraGlass^{TM}) against the opportunistic pathogens *P. aeruginosa* and *S. aureus*.

In a recent publication [38], the antibacterial activity of Ag-doped borate glasses with compositions of $60B_2O_3$-$36CaO$-$(4-x)P_2O_5$-$(x)Ag_2O$, where x = 0.0, 0.3, 0.5, and 1 (mol %), was examined in vitro.The dose-dependent antibacterial activity of the Ag-doped BG was demonstrated against *P. aeruginosa* preformed biofilms, with up to a 99.7% reduction in the bacterial cell counts.

Additionally, several studies [39][40] proved that Ag has an antimicrobial activity only against bacteria and fungus, but not against epithelial cells, indicating its clinical use without adverse side effects on human health.

Fan et al. [41] showed that Ag-containing MBGs (molar ratio Si:Ca:P = 80:15:5) presented an antibacterial activity against *E. faecalis* biofilm in the root canal of human teeth.

Copper (Cu) has also been used as a therapeutic ion due to its biocidal action against Gram-positive and Gram-negative bacteria and its low cytotoxicity to human cells. It is a necessary element for both human and animal existence [42]. Additionally, by enhancing angiogenesis and promoting osteogenesis, it plays a significant role in the metabolism of bone formation [42].

In 2008, the United States Environmental Protection Agency classified Cu as a metallic antimicrobial agent against many disease-causing bacteria [43].

Using poly(styrene)-block-poly(acrylic acid) (PS-b-PAA) and hexadecyltrimethylammonium bromide (CTAB) as structure-directing agents, Holquin et al. [44] produced Cu-doped hallo BG nanoparticles with the following composition: $79.5SiO_2$-$(18-x)CaO$-$2.5P_2O_5$-$xCuO$ (x = 0, 2.5 or 5 mol % of CuO).

Their study showed that the composition with a greater amount of Cu was able to degrade the biofilm formed by *S. aureus* at a minimal concentration, indicating its suitability as a bactericide agent [44].

Furthermore, Bari et al. [24], demonstrated that Cu-containing MBG (2 mol %) prepared by an ultrasound-assisted one-pot synthesis inhibited bacterial growth and was also able to restrain the formation of a biofilm produced by *S. epidermidis*, and even favored its dispersion. It is known that *S. epidermidis* produces considerable quantities of polysaccharide intercellular adhesions that induce biofilm formation [45].

Gallium (Ga) is another interesting element to be used as a therapeutic ion due to its broad-spectrum activity and immunity to the conventional resistance mechanism of bacteria associated with antibiotics. All these characteristics are linked with gallium's pathway in bacteria metabolism. Ga acts as a "Trojan horse", disrupting the bacterial Fe metabolism. Since the ionic radii of Ga^{3+} and Fe^{3+} are nearly identical, many biologic systems cannot discriminate between them [46].

According to the study [21], melt-derived Ag- and Ga-doped phosphate glass with the following composition $10CaO$-$37Na_2O$-$45P_2O_5$-$3Ga_2O_3$-$5Ag_2O$ (mol %) contributed to the biofilm growth inhibitory effect on *P. aeruginosa* (up to 2.68 reductions in log10 values of the viable counts compared with controls). The composition may offer a successful choice to combat opportunistic pathogens such as *P. aeruginosa*-associated infections due to the controlled release of antibacterial Ga and Ag ions at the site of infection. The melt-derived Ag- and Ga-doped phosphate glass was also tested in terms of the inhibition of biofilm formation against *P. gingivalis* and *S. gordonii* periodontal pathogens [47]. The glass developed in the study [47] reduced biofilm formation of *P. gingivalis* after 7 days of exposure by combining the actions of Ga and Ag synergistically. Ag ions destabilize the biofilm matrix to increase the biofilm's contact area, hence enhancing the chances of the Ag and Ga ions subsequently killing the bacteria.

Recently, Tellurium (Te), an element from the chalcogens group that exhibits several oxidation states, has been studied for biological applications due to its antimicrobial, antioxidant, and antitumoral properties [48][49][50][51]. Telluride (Te^{2-})→elemental tellurium (Te^{0})→tellurite (TeO_3^{2-})→tellurate (TeO_4^{2-}) are only a few of the redox states in which Tellurium can be found. The tellurite (TeO_3^{2-}) is highly toxic for most bacteria (e.g., *Escherichia coli*) even at concentrations of 1 μg mL^{-1} [52].

This opens a new perspective for the Te element in terms of biomaterials to prevent bacterial infections in tissue engineering applications.

A recent study [48] analyzed the antibacterial activity against bacterial biofilm of Te-doped BGs. The investigated Te-doped BG showed a significant biofilm metabolic reduction for both *S. aureus* and *S. epidermidis*, the most frequent strains involved in orthopedics infections [53].

The antibacterial activity of Te is due to a combination of different mechanisms that are likely not yet fully disclosed. Turner et al. [54] gave an explanation of some events. Briefly, tellurite can exceed the outer membrane due to the environmental pH variation and then exert its toxic action in the cytoplasmic compartment by triggering an increase in the generation of reactive oxygen species (ROS) [55]. The tellurite influences the activity of the superoxide dismutase (SOD) that is necessary to counteract the oxygen species (ROS) formed.

References

1. Chen, Q.Z.; Li, Y.; Jin, L.Y.; Quinn, J.M.W.; Komesaroff, P.A. A new sol-gel process for producing Na2O-containing bioactive glass ceramics. Acta Biomater. 2010, 6, 4143–4153.
2. Hench, L.L.; Splinter, R.J.; Allen, W.C.; Greenlee, T.K. Bonding mechanisms at the interface of ceramic prosthetic materials. J. Biomed. Mater. Res. 1971, 5, 117–141.
3. Hench, L.L. Bioceramics. J. Am. Ceram. Soc. 1998, 81, 1705–1728.
4. Rainer, A.; Giannitelli, S.M.; Abbruzzese, F.; Traversa, E.; Licoccia, S.; Trombetta, M. Fabrication of bioactive glass–ceramic foams mimicking human bone portions for regenerative medicine. Acta Biomater. 2008, 4, 362–369.
5. Ma, J.; Chen, C.Z.; Wang, D.G.; Meng, X.G.; Shi, J.Z. Influence of the sintering temperature on the structural feature and bioactivity of sol–gel derived SiO2–CaO–P2O5 bioglass. Ceram. Int. 2010, 36, 1911–1916.
6. Xynos, I.D.; Edgar, A.J.; Buttery, L.D.K.; Hench, L.L.; Polak, J.M. Ionic products of bioactive glass dissolution increase proliferation of human osteoblasts and induce insulin-like growth factor II mRNA expression and protein synthesis. Biochem. Biophys. Res. Commun. 2000, 276, 461–465.
7. Boccaccini, A.R.; Erol, M.; Stark, W.J.; Mohn, D.; Hong, Z.; Mano, J.F. Polymer/bioactive glass nanocomposites for biomedical applications. A Review. Compos. Sci. Technol. 2010, 70, 1764–1776.
8. Li, R.; Clark, A.E.; Hench, L.L. An investigation of bioactive glass powders by sol-gel processing. J. Appl. Biomater. 1991, 2, 231–239.
9. Baino, F.; Fiorilli, S.; Vitale-Brovarone, C. Bioactive glass-based materials with hierarchical porosity for medical applications: Review of recent advances. Acta Biomater. 2016, 42, 16–32.
10. Zheng, K.; Boccaccini, A.R. Sol-gel processing of bioactive glass nanoparticles: A review. Adv. Colloid Interface Sci. 2017, 249, 363–373.
11. Yan, X.; Yu, C.; Zhou, X.; Tang, J.; Zhao, D. Highly ordered mesoporous bioactive glasses with superior in vitro bone-forming bioactivities. Angew. Chem. Int. Ed. 2004, 43, 5980–5984.
12. Ben-Nissan, B.; Choi, A.H.; Macha, I.J.; Cazalbou, S. Sol-Gel Nanocoatings of Bioceramics. In Handbook of Bioceramics and Biocomposites; Antoniac, I.V., Ed.; Springer: Cham, Switzerland, 2015.
13. Wu, C.J.; Chang, J. Mesoporous bioactive glasses: Structure characteristics, drug/growth factor delivery and bone regeneration application. Interface Focus 2012, 2, 292–306.
14. Wu, C.; Chang, J. Multifunctional mesoporous bioactive glasses for effective delivery of therapeutic ions and drug/growth factors. J. Control. Release 2014, 193, 282–295.
15. Wu, C.; Chang, J.; Xiao, Y. Mesoporous bioactive glasses as drug delivery and bone tissue regeneration platforms. Ther. Deliv. 2011, 2, 1189–1198.
16. Lucas-Girot, A.; Mezahi, F.Z.; Mami, M.; Oudadesse, H.; Harabi, A.; Le Floch, M. Sol–gel synthesis of a new composition of bioactive glass in the quaternary system SiO2–CaO–Na2O–P2O5. Comparison with melting method. J.

Non-Cryst. Solids 2011, 357, 3322–3327.

17. Zhou, P.; Garcia, B.L.; Kotsakis, G.A. Comparison of antibacterial and antibiofilm activity of bioactive glass compounds S53P4 and 45S5. BMC Microbiol. 2022, 22, 212.
18. Bortolin, M.; De Vecchi, E.; Romano, C.L.; Toscano, M.; Mattina, R.; Drago, L. Antibiofilm agents against MDR bacterial strains: Is bioactive glass BAG-S53P4 also effective? J. Antimicrob. Chemother. 2016, 71, 123–127.
19. Coraca-Huber, D.C.; Fille, M.; Hausdorfer, J.; Putzer, D.; Nogler, M. Efficacy of antibacterial bioactive glass S53P4 against S. aureus biofilms grown on titanium discs in vitro. J. Orthop. Res. 2014, 32, 175–177.
20. Oliver, J.N.; Akande, O.; Ecker, M. Incorporation of Novel Elements in Bioactive Glass Compositions to Enhance Implant Performance. Book chapter in Current Concepts in Dental Implantology—From Science to Clinical Research; IntechOpen: London, UK, 2022; ISBN 978-1-83969-864-4.
21. Valappil, S.P.; Higham, S.M. Antibacterial effect of gallium and silver on Pseudomonas aeruginosa treated with gallium–silver–phosphate-based glasses. Bio-Med. Mater. Eng. 2014, 24, 1589–1594.
22. Esfahanizadeh, N.; Nourani, M.R.; Bahador, A.; Akhondi, N.; Montazeri, M. The Anti-biofilm Activity of Nanometric Zinc doped Bioactive Glass against Putative Periodontal Pathogens: An in vitro Study. Biomed. Glasses. 2018, 4, 95–107.
23. Neel, E.A.A.; Hossain, K.M.Z.; Abuelenain, D.; Abuhaimed, T.; Ahmed, I.; Valappil, S.P.; Knowles, J.C. Antibacterial effect of titanium dioxide-doped phosphate glass microspheres filled total-etch dental adhesive on S. mutans biofilm. Int. J. Adhes. Adhes. 2021, 108, 102886.
24. Bari, A.; Bloise, N.; Fiorilli, S.; Novajra, G.; Vallet-Regí, M.; Bruni, G.; Torres-Pardo, A.; González-Calbet, J.M.; Visai, L.; Vitale-Brovarone, C. Copper-containing mesoporous bioactive glass nanoparticles as multifunctional agent for bone regeneration. Acta Biomater. 2017, 55, 493–504.
25. Kim, J.Y.; Choi, W.; Mangal, U.; Seo, J.Y.; Kang, T.Y.; Lee, J.; Kim, T.; Cha, J.Y.; Kim, K.-M.; Kim, D.; et al. Multivalent network modifier upregulates bioactivity of multispecies biofilm-resistant polyalkenoate cement. Bioact. Mater. 2022, 14, 219–233.
26. Wu, C.; Labrie, J.; Tremblay, Y.; Haine, D.; Mourez, M.; Jacques, M. Zinc as an agent for the prevention of biofilm formation by pathogenic bacteria. J. Appl. Microbiol. 2013, 115, 30–40.
27. Hutchings, C.; Rajasekharan, S.K.; Reifen, R.; Shemesh, M. Mitigating Milk-Associated Bacteria through Inducing Zinc Ions Antibiofilm Activity. Foods 2020, 9, 1094.
28. Shruti, S.; Salinas, A.J.; Ferrari, E.; Malavasi, G.; Lusvardi, G.; Doadrio, A.L.; Menabue, L.; Vallet-Regi, M. Curcumin release from cerium, gallium and zinc containing mesoporous bioactive glasses. Microporous Mesoporous Mater. 2013, 180, 92–101.
29. Heras, C.; Holguín, J.J.; Doadrio, A.L.; Vallet-Regí, M.; Sánchez-Salcedo, S.; Salinas, A.J. Multifunctional antibiotic and zinc containing mesoporous bioactive glass scaffolds to fight against bone infection. Acta Biomater. 2020, 114, 395–406.
30. Paramita, P.; Ramachandran, M.; Narashiman, S.; Nagarajan, S.; Sukumar, D.K.; Chung, T.W.; Ambigapathi, M. Sol–gel based synthesis and biological properties of zinc integrated nanobioglass ceramics for bone tissue regeneration. J. Mater. Sci. Mater. Med. 2021, 32, 5.
31. Ruparelia, J.P.; Chatterjee, A.K.; Duttagupta, S.P.; Mukherji, S. Strain specificity in antimicrobial activity of silver and copper nanoparticles. Acta Biomater. 2008, 4, 707–716.
32. Kazemian, Z.; Varzandeh, M.; Labbaf, S. A facile synthesis of mono dispersed spherical silver doped bioactive glass nanoparticle. J. Mater. Sci. Mater. Med. 2021, 32, 29.
33. Palza, H.; Escobar, B.; Bejarano, J.; Bravo, D.; Diaz-Dosque, M.; Perez, J. Designing antimicrobial bioactive glass materials with embedded metal ions synthesized by the sol-gel method. J. Mater. Sci. Eng. C 2013, 33, 3795–3801.
34. Mekkawy, A.I.; El-Mokhtar, M.A.; Nafady, N.A.; Yousef, N.; Hamad, M.A.; El-Shanawany, S.M. In vitro and in vivo evaluation of biologically synthesized silver nanoparticles for topical applications: Effect of surface coating and loading into hydrogels. Int. J. Nanomed. 2017, 12, 759–777.
35. Wilkinson, H.N.; Iveson, S.; Catherall, P.; Hardman, M.J. A Novel Silver Bioactive Glass Elicits Antimicrobial Efficacy Against Pseudomonas aeruginosa and Staphylococcus aureus in an ex Vivo Skin Wound Biofilm Model. Front. Microbiol. 2018, 9, 1450.
36. Da Silva Buriti, J.; Barreto, M.E.V.; Barbosa, F.C.; de Brito Buriti, B.M.A.; de Lima Souza, J.W.; de Vasconcelos Pina, H.; de Luna Rodrigues, P.; Fook, M.V.L. Synthesis and characterization of Ag-doped 45S5 bioglass and chitosan/45S5-Ag biocomposites for biomedical applications. J. Therm. Anal. Calorim. 2020, 145, 39–50.

37. Bellantone, M.; Coleman, N.J.; Hench, L.L. Bacteriostatic action of a novel four-component bioactive glass. J. Biomed. Mater. Res. Part A 2000, 51, 484–490.
38. Naseri, S.; Griffanti, G.; Lepry, W.C.; Maisuria, V.B.; Tufenkji, N.; Nazhat, S.N. Silver-doped sol-gel borate glasses: Dose-dependenteffect on Pseudomonas aeruginosa biofilms and keratinocyte function. J. Am. Ceram. Soc. 2021, 105, 1711–1722.
39. Hoppe, A.; Mourino, V.; Boccaccini, A.R. Therapeutic inorganic ions in bioactive glasses to enhance bone formation and beyond. Biomater. Sci. 2013, 1, 254–256.
40. El-Kady, A.M.; Ali, A.F.; Rizk, R.A.; Ahmed, M.M. Synthesis, characterization and microbiological response of silver doped bioactive glass nanoparticles. Ceram. Int. 2012, 38, 177–188.
41. Fan, W.; Wu, D.; Ma, T.; Fan, B. Ag-loaded mesoporous bioactive glasses against Enterococcus faecalis biofilm in root canal of human teeth. Dent. Mater. J. 2015, 34, 54–60.
42. Gomes, S.; Vichery, C.; Descamps, S.; Martinez, H.; Kaur, A.; Jacobs, A.; Nedelec, J.M.; Renaudin, G. Cu-doping of calcium phosphate bioceramics: From mechanism to the control of cytotoxicity. Acta Biomater. 2018, 65, 462–474.
43. Zambanini, T.; Borges, R.; Kai, K.C.; Marchi, J. Bioactive Glasses for Treatment of Bone Infections. Book chapter in Biomedical, Therapeutic and Clinical Applications of Bioactive Glasses; Woodhead Publishing Series in Biomaterials; Woodhead Publishing: Cambridge, UK, 2019; pp. 383–415.
44. Copper Development Associtaion Inc. U.S. EPA Approves Registration of Antimicrobial Copper Alloys. Available online: https://www.copper.org/about/pressreleases/2008 (accessed on 16 August 2022).
45. Jiménez-Holguín, J.; Sánchez-Salcedo, S.; Cicuéndez, M.; Vallet-Regí, M.; Salinas, A.J. Cu-Doped Hollow Bioactive Glass Nanoparticles for Bone Infection Treatment. Pharmaceutics 2022, 14, 845.
46. Raffi, M.; Mehrwan, S.; Bhatti, T.M.; Akhter, J.I.; Hameed, A.; Yawar, W.; Masood Hasan, M. Investigations into the antibacterial behavior of copper nanoparticles against Escherichia coli. Ann. Microbiol. 2010, 60, 75–80.
47. Valappil, S.P.; Coombes, M.; Wright, L.; Owens, G.J.; Lynch, R.J.M.; Hope, C.K.; Higham, S.M. Role of gallium and silver from phosphate-based glasses on in vitro dual species oral biofilm models of Porphyromonasgingivalis and Streptococcus gordonii. Acta Biomater. 2012, 8, 1957–1965.
48. Miola, M.; Massera, J.; Cochis, A.; Kumar, A.; Rimondini, L.; Verne, E. Tellurium: A new active element for innovative multifunctional bioactive glasses. Mater. Sci. Eng. C 2021, 123, 111957.
49. Matharu, R.K.; Charani, Z.; Ciric, L.; Illangakoon, U.E.; Edirisinghe, M. Antimicrobial activity of tellurium-loaded polymeric fibre meshes. J. Appl. Polym. Sci. 2018, 135, 46368.
50. Morena, A.G.; Bassegoda, A.; Hoyo, J.; Tzanov, T. Hybrid Tellurium–Lignin Nanoparticles with Enhanced Antibacterial Properties. ACS Appl. Mater. Interfaces 2021, 13, 14885–14893.
51. Zonaro, E.; Lampis, S.; Turner, R.J.; Qazi, S.J.S.; Vallini, G. Biogenic selenium and tellurium nanoparticles synthesized by environmental microbial isolates efficaciously inhibit bacterial planktonic cultures and biofilms. Front. Microb. 2015, 6, 584.
52. Taylor, D.E. Bacterial tellurite resistance. Trends Microbiol. 1999, 7, 111–115.
53. Sorrentino, R.; Cochis, A.; Azzimonti, B.; Caravaca, C.; Chevalier, J.; Kuntz, M.; Porporati, A.A.; Streicher, R.M.; Rimondini, L. Reduced bacterial adhesion on ceramics used for arthroplasty applications. J. Eur. Ceram. Soc. 2018, 38, 963–970.
54. Turner, R.J.; Borghese, R.; Zannoni, D. Microbial processing of tellurium as a tool in biotechnology. Biotechnol. Adv. 2012, 30, 954–963.
55. Borsetti, F.; Francia, F.; Turner, R.J.; Zannoni, D. The disulfide binding protein DsbB allows the transfer of oxidizing equivalents from the toxic metalloid tellurite (TeO32−) to the plasma membrane electron transport system of Rhodobactercapsulatus. J. Bacteriol. 2007, 189, 851–859.