

# 1 Shaping the Future of Peri-Implant Health: Insights into 2 Bioceramic Implant Materials .

## 4 Abstract

5 Bioceramic implant materials have evolved significantly beyond traditional passive  
6 biocompatibility concepts, with contemporary research focusing on bioactive,  
7 antimicrobial, and immunomodulatory functionalities to enhance peri-implant tissue  
8 stability and long-term clinical success. This review examines recent advances in  
9 bioceramic implant technology across five key domains. Additive manufacturing enables  
10 patient-specific implant designs with optimized macro- and micro-architectures that  
11 enhance bone ingrowth and stress distribution. Surface biofunctionalization strategies,  
12 including calcium phosphate coatings, bioactive glass layers, and ion-doped ceramic  
13 modifications (strontium, magnesium, zinc), demonstrate enhanced osteogenic potential  
14 and accelerated mineralized tissue formation. Antimicrobial approaches targeting  
15 biofilm-mediated peri-implantitis include nanostructured ceramic coatings and  
16 photocatalytic zirconia surfaces that reduce bacterial adhesion while preserving host cell  
17 compatibility. Hybrid implant systems combining metallic cores with ceramic outer layers  
18 address mechanical limitations while maintaining aesthetic and biological advantages.  
19 Emerging immunomodulatory surface concepts aim to engineer macrophage  
20 polarization toward pro-healing phenotypes, potentially reducing chronic inflammatory  
21 reactions associated with peri-implantitis. While preclinical data support the biological  
22 promise of these advanced bioceramic systems, long-term randomized clinical trials  
23 remain essential to validate their efficacy in reducing peri-implant disease incidence and  
24 improving implant survival rates. The integration of digital manufacturing, bioactive  
25 surface engineering, and immunomodulation represents a paradigm shift toward  
26 biologically optimized, patient-specific implant solutions.

## 28 Keywords

29 Bioceramics; Dental implants; Additive manufacturing; Surface biofunctionalization;  
30 Antimicrobial coatings; Osseointegration; Peri-implantitis; Immunomodulation; Zirconia;  
31 Bioactive surfaces

## 33 Introduction

34 Dental implant therapy is widely regarded as a predictable treatment modality for the  
35 rehabilitation of edentulism; however, long-term success depends not only on osseointegration  
36 but also on the maintenance of peri-implant health. Biological complications, particularly peri-  
37 implant mucositis and peri-implantitis, remain prevalent and represent major causes of late  
38 implant failure.<sup>1,2</sup> Contemporary understanding emphasizes that peri-implant disease is  
39 multifactorial, involving host immune response, microbial biofilm accumulation, and implant  
40 surface characteristics.<sup>3</sup>

41 While titanium implants remain the gold standard because of their mechanical reliability and  
42 well-documented clinical performance, concerns related to esthetics, hypersensitivity, and  
43 corrosion have stimulated interest in metal-free alternatives.<sup>4</sup> Bioceramic materials, especially  
44 yttria-stabilized zirconia (Y-TZP), have gained attention due to their favorable biocompatibility,  
45 low plaque affinity, and excellent optical properties.<sup>5</sup> In addition to bulk material advantages,  
46 surface chemistry and topography significantly influence protein adsorption, fibroblast adhesion,  
47 and early osteogenic cell activity.<sup>6</sup>

48 Recent research has therefore shifted toward optimizing bioceramic implant surfaces through  
49 micro- and nano-scale modifications and bioactive coatings aimed at enhancing bone-to-implant  
50 contact and promoting stable peri-implant tissue integration.<sup>7</sup> From a periodontal perspective,  
51 these material innovations are particularly relevant, as improved soft-tissue sealing and reduced  
52 bacterial colonization may contribute to long-term peri-implant stability.<sup>8</sup> Consequently,  
53 understanding the biological behavior of bioceramic implant materials is critical for shaping  
54 future strategies in peri-implant disease prevention and management.

## 55 **Bioceramic Materials in Dental Implants**

### 56 Overview

57 Bioceramic materials are increasingly utilized in implant dentistry because they can be  
58 engineered to actively interact with surrounding tissues rather than functioning solely as  
59 structural replacements. In implant applications, bioceramics most commonly appear as  
60 zirconia-based implants and abutments or as bioactive ceramic coatings such as calcium  
61 phosphate or bioactive glass applied to metallic cores. Modern surface science emphasizes  
62 biofunctional interfaces capable of influencing early protein adsorption, cellular attachment,  
63 inflammatory modulation, and bone apposition. This paradigm shift moves implant design  
64 beyond macro-mechanics toward biologically responsive surfaces that directly affect peri-  
65 implant tissue behavior.<sup>10,12</sup>

### 66 Zirconia as a Bioceramic Implant Material

67 Zirconia implants and components, particularly zirconia abutments, have gained popularity due  
68 to aesthetic advantages and favorable biologic response. Recent systematic analyses report  
69 promising short- to medium-term survival rates and acceptable marginal bone stability with  
70 zirconia implants, while acknowledging that long-term data remain more limited compared with  
71 titanium systems. Importantly, zirconia's clinical performance depends significantly on surface  
72 characteristics, including micro- and nano-topography and wettability, which influence host  
73 tissue response and biofilm formation at the transmucosal interface.<sup>9</sup>

### 74 Calcium Phosphate Bioceramics as Bioactive Coatings

75 Calcium phosphate coatings represent one of the most studied bioactive ceramic strategies for  
76 enhancing osseointegration. These coatings combine the mechanical strength of metallic  
77 substrates with the osteoconductive properties of ceramic surfaces. Their composition and  
78 crystallinity influence ion release and apatite formation, facilitating early bone-implant contact  
79 and supporting osteogenic cell activity. Properly engineered calcium phosphate layers have  
80 been shown to accelerate bone healing and improve interfacial stability during early integration  
81 phases.<sup>11</sup>

## 82 Bioactive Glass and Antibacterial Potential

83 Bioactive glasses represent another important bioceramic class for implant modification. These  
84 materials release therapeutic ions that stimulate apatite formation while potentially exerting  
85 antibacterial effects. Recent developments in multi-element–doped porous bioactive glass  
86 coatings demonstrate efforts to simultaneously enhance osseointegration and reduce bacterial  
87 colonization. Such dual functionality is particularly relevant in the prevention of peri-implantitis,  
88 where biofilm control and tissue compatibility are equally critical.<sup>13</sup>

## 89 Soft-Tissue Integration Around Zirconia Abutments

90 Long-term peri-implant health depends heavily on the integrity of the soft-tissue seal  
91 surrounding the implant-abutment complex. Emerging evidence indicates that nano-engineered  
92 zirconia surfaces enhance protein adsorption and promote epithelial and fibroblast attachment.  
93 Experimental findings demonstrate improved soft-tissue integration and stronger mucosal  
94 sealing features compared with non-modified surfaces. These results suggest that surface  
95 engineering of zirconia may improve the biological barrier against bacterial ingress and support  
96 marginal bone preservation.<sup>14</sup>

## 97 Microbial Ecology and Peri-Implant Health

98 Material composition influences early microbial colonization and subsequent biofilm maturation.  
99 Comparative peri-implantitis models evaluating titanium and zirconia-based materials  
100 demonstrate differences in anaerobic enrichment and pathogenic complex development. Some  
101 ceramic compositions exhibit reduced dysbiotic shifts under experimental conditions. While  
102 translational interpretation requires caution, these findings reinforce the concept that bioceramic  
103 surface properties can influence peri-implant microbial ecology and potentially modulate disease  
104 susceptibility.<sup>15</sup>

## 105 Osseointegration and Bone-Implant Interface

### 106 Biological Basis of Osseointegration

107 Osseointegration is defined as the formation of a direct structural and functional interface  
108 between living bone and the surface of a load-bearing implant, without the interposition of  
109 fibrous connective tissue.<sup>16</sup> This intimate bone–implant contact is fundamental for achieving  
110 primary and secondary stability and is a prerequisite for long-term implant success. At the  
111 microscopic level, successful osseointegration is characterized by newly formed mineralized  
112 bone in direct apposition to the implant surface. Following implant placement, a cascade of  
113 biological events is initiated, beginning with blood clot formation and the adsorption of plasma  
114 proteins onto the biomaterial surface. These proteins mediate the recruitment of mesenchymal  
115 stem cells and osteoprogenitor cells, which subsequently differentiate into osteoblasts.  
116 Osteoblasts synthesize osteoid matrix that progressively undergoes mineralization, leading to  
117 the formation of woven bone that is later remodeled into lamellar bone.<sup>17</sup> Surface properties—  
118 including chemical composition, surface energy, hydrophilicity, and micro-/nanotopography—  
119 critically regulate protein adsorption and cellular adhesion. These factors ultimately influence  
120 the percentage of bone-to-implant contact (BIC), a  
121 histomorphometric parameter widely used to assess osseointegration.<sup>17</sup> Enhanced early  
122 osteoblastic attachment and proliferation contribute to improved biomechanical stability during  
123 the critical healing period.

### 124 Surface Engineering and Bioactivity

125 Surface engineering strategies have substantially advanced implant integration outcomes.  
126 Techniques such as acid etching, sandblasting, plasma spraying, and laser modification  
127 increase surface roughness and surface energy, thereby enhancing osteoblastic adhesion and  
128 differentiation.<sup>18</sup> Clinical and experimental studies have consistently demonstrated that  
129 modified implant surfaces achieve significantly higher BIC values compared with machined  
130 surfaces, resulting in accelerated secondary stability.<sup>18</sup>  
131 Bioactive coatings incorporating calcium phosphate, hydroxyapatite, collagen matrices, or  
132 growth factors further stimulate osteogenic signaling pathways at the interface.<sup>17</sup> These  
133 coatings enhance early mineral deposition and facilitate faster maturation of peri-implant bone.  
134 Additionally, nanostructured surfaces that replicate the architecture of the extracellular matrix  
135 improve integrin-mediated cell attachment and promote osteogenic gene expression.<sup>16</sup> Such  
136 biofunctionalization approaches are particularly relevant for bioceramic materials, which  
137 inherently exhibit osteoconductive properties and chemical affinity for biological apatite.

### 138 **Nanoscale Interface and Bioceramic Integration**

139 Recent advances in bioceramic implant materials have highlighted the importance of nanoscale  
140 interfacial phenomena. Ceria-stabilized tetragonal zirconia polycrystal (Ce-TZP) has  
141 demonstrated favorable nanoscale bonding with newly formed hydroxyapatite, facilitating direct  
142 mineral attachment without the need for additional surface modification.<sup>20</sup> This intrinsic  
143 bioactivity supports early interfacial mineralization and enhances mechanical interlocking at the  
144 bone-implant junction.

145 Bioceramic composites and functionally graded materials are increasingly being developed to  
146 minimize elastic modulus mismatch between the implant and surrounding bone.<sup>16</sup> Reducing  
147 this mismatch mitigates stress shielding effects and promotes more physiological load  
148 transfer, which is critical for maintaining long-term peri-implant bone stability.

149 Furthermore, osteoimmunological interactions at the interface have gained attention, as the  
150 early immune response plays a regulatory role in bone regeneration.<sup>21</sup> Modulating macrophage  
151 polarization toward a pro-healing phenotype may further optimize osseointegration outcomes in  
152 bioceramic systems.

### 153 **Mechanical Adaptation and Re-Osseointegration**

154 Osseointegration represents a dynamic biological equilibrium between bone formation and  
155 resorption rather than a static endpoint. Mechanical loading influences peri-implant bone  
156 remodeling through mechanotransduction pathways. Controlled functional loading enhances  
157 bone density and maturation, whereas excessive or premature loading may compromise  
158 integration.

159 Experimental evidence indicates that re-osseointegration is possible following mechanical  
160 disruption. In controlled animal models, implants subjected to induced loosening demonstrated  
161 renewed bone formation and restoration of stability after appropriate healing periods.<sup>19</sup> These  
162 findings underscore the regenerative capacity of the bone–implant interface and highlight the  
163 importance of optimized loading protocols in clinical implantology.

### 164 **Peri-Implant Soft Tissue and Microbial Considerations**

#### 165 **Soft-tissue considerations**

166 Peri-implant soft tissue forms the first-line seal that separates a highly contaminated oral

167 environment from the osseointegrated portion of the implant. Compared with the periodontal  
168 barrier around natural teeth, peri-implant mucosa has structural disadvantages that reduce  
169 bonding efficiency at the transmucosal region, making the seal easier to disrupt. Once the seal  
170 is compromised, bacteria can penetrate the interface and trigger peri-implant mucositis; without  
171 timely management, this may progress to peri-implantitis with marginal bone loss.<sup>22</sup>

172 The transmucosal surface is now treated as an “engineered interface,” not an afterthought.  
173 Current strategies to strengthen soft-tissue attachment focus on improving surface wettability,  
174 creating micro/nano-topographies, altering surface chemistry, and adding bioactive coatings.  
175 Importantly, the field is moving toward multifunctional designs—surfaces that simultaneously  
176 enhance soft-tissue bonding while adding antibacterial and/or immunomodulatory features to  
177 reduce early inflammatory breakdown.<sup>22</sup>

178 Zirconia abutments are widely used in esthetic zones, but achieving consistently strong soft-  
179 tissue attachment remains a challenge. Evidence synthesized in recent reviews shows that soft-  
180 tissue integration around zirconia depends heavily on both micro-design (surface modification  
181 methods) and macro-design (abutment/contour factors) that influence epithelial closure and  
182 connective tissue behavior. Practical takeaways include matching zirconia surface processing to  
183 the intended tissue response and ensuring post-restoration maintenance supports long-term  
184 sealing.<sup>23</sup>

## 185 **Microbial considerations**

186 Microbial biofilms are central to peri-implant disease biology. Systematic evidence comparing  
187 peri-implantitis biofilms with those from healthy implants and periodontitis sites shows that no  
188 single organism uniquely defines peri-implantitis across studies; rather, disease reflects complex  
189 community shifts. Meta-analytic findings indicate certain species (for example, *Aggregatibacter*  
190 *actinomycetemcomitans* and *Prevotella intermedia*) may show higher prevalence in peri-  
191 implantitis compared with health, while many taxa are shared across conditions—supporting a  
192 dysbiosis-based model rather than a single-pathogen model.<sup>24</sup>

193 Sequencing-based systematic reviews further reinforce that peri-implant disease is  
194 characterized by dysbiotic communities that vary between individuals and differ in composition  
195 and relative abundance compared with periodontal sites. These studies highlight that peri-  
196 implantitis can include well-known periodontopathogens but may also show enrichment of  
197 organisms less emphasized in classic periodontal patterns, and that diversity/composition shifts  
198 are seen when comparing healthy versus diseased peri-implant sites. Clinically, this supports  
199 prevention strategies that focus on disrupting biofilm maturation and maintaining a stable peri-  
200 implant ecological balance rather than targeting a narrow microbial list.<sup>25</sup>

201 Implant material and surface physicochemistry can shape the peri-implant microbial “signature.”  
202 In a controlled preclinical model, microbial communities shifted differently across titanium,  
203 zirconia, and ceria-stabilized alumina-reinforced zirconia, suggesting the implant substrate can  
204 predispose sites toward or away from dysbiotic evolution under inflammatory challenge. The  
205 study also highlights the anaerobic-to-aerobic balance as a potentially useful surrogate marker  
206 for monitoring disease trajectory, reinforcing the concept that material choice may influence

207 plaque evolution and peri-implantitis risk at a biological level.<sup>26</sup>

## 208 **Peri-Implant Health Outcomes**

209 Clinical assessment of peri-implant health around bioceramic implants, particularly zirconia-  
210 based systems, has increasingly incorporated standardised parameters including bleeding on  
211 probing (BOP), probing depth (PD), and radiographic marginal bone loss (MBL). A systematic  
212 review and meta-analysis by Roehling and colleagues, which pooled data from six observational  
213 cohort studies with a minimum five-year follow-up, estimated mean MBL of 1.1 mm (95% CI: 0.9  
214 to 1.3 mm) and mean PD of 3.0 mm (95% CI: 2.5 to 3.4 mm) around commercially available  
215 zirconia implants after five years of loading, findings broadly comparable with titanium  
216 benchmarks reported in the parallel literature.<sup>27</sup> A separate systematic review restricted to  
217 randomised controlled trials and comparing titanium, titanium-zirconium, and zirconia implants  
218 reported BOP values of approximately 16.4% for zirconia, overlapping with the 10 to 20% range  
219 observed for titanium, and noted that no statistically significant between-group differences in  
220 peri-implant mucositis or peri-implantitis incidence were observed across the included studies,  
221 although the small number of RCTs limits firm conclusions [28]. Soft tissue outcomes, including  
222 mucosal stability and esthetic performance, appear to favour zirconia in the anterior zone,  
223 where the tooth-coloured subgingival profile minimises the risk of visible greyish discolouration  
224 through thin gingival phenotypes, a clinically relevant consideration that titanium systems do not  
225 share.<sup>28</sup>

226 The material properties of zirconia are mechanistically relevant to peri-implant tissue  
227 behaviour. The lower surface energy and reduced surface roughness of polished zirconia  
228 surfaces are associated with diminished bacterial adhesion compared with rougher titanium  
229 surfaces in in vitro models, and this has been proposed as a contributing factor to the  
230 comparable or slightly lower BOP values observed in some clinical studies.<sup>28,29</sup> A network  
231 meta-analysis by Pesce and colleagues, which included 18 prospective studies comparing  
232 abutment materials, found that zirconia abutments were associated with a statistically  
233 significant reduction in MBL of 0.20 mm (95% CI: 0 to 0.40 mm) compared with titanium  
234 abutments, alongside numerically lower BOP and PD values, suggesting that the soft tissue  
235 integration profile of zirconia at the transmucosal level may confer a measurable biological  
236 advantage.<sup>28</sup> Wettability and surface chemistry also influence the early soft tissue attachment  
237 response; zirconia surfaces with moderate roughness and appropriate surface energy have  
238 been shown to support fibroblast  
239 adhesion and connective tissue orientation, though the long-term clinical translation of these in  
240 vitro observations into meaningful differences in recession or mucosal thickness has not been  
241 consistently demonstrated in controlled trials.<sup>29</sup>

242 The available evidence must be interpreted with caution given substantial methodological  
243 limitations. Most published studies comparing zirconia and titanium implants are observational  
244 in design, often with small sample sizes, heterogeneous surgical and prosthetic protocols, and  
245 follow-up periods that rarely exceed five years; the most recent systematic review and meta-  
246 analysis of RCTs by Morena and colleagues, which included only six trials and 448 implants,  
247 found no statistically significant differences in MBL, BOP, or PD between zirconia and titanium,

248 but noted high heterogeneity across studies and significant variability in implant designs,  
249 surface treatments, and outcome definitions.<sup>30</sup> This variability in protocols and the absence of  
250 standardised outcome reporting make cross-study synthesis unreliable. Furthermore, patient-  
251 selection data across included studies are often insufficient to assess how factors such as  
252 periodontal history, bone density, and gingival phenotype modify outcomes specifically for  
253 bioceramic materials. Longer follow-up data, larger multicentre RCTs, and harmonised outcome  
254 reporting frameworks are needed before definitive clinical recommendations regarding the peri-  
255 implant health advantages of zirconia over titanium can be made.

## 256 **Emerging Trends and Future Directions**

257 The evolution of bioceramic implant materials is increasingly driven by advances in biomaterials  
258 science, nanotechnology, and digital manufacturing. Contemporary research no longer focuses  
259 solely on passive biocompatibility but aims to develop bioactive, antimicrobial, and  
260 immunomodulatory implant surfaces capable of enhancing peri-implant tissue stability and long-  
261 term success.<sup>31</sup>

## 262 **Additive Manufacturing and Personalized Implant Design**

263 Additive manufacturing (3D printing) has enabled the fabrication of customized zirconia and  
264 other ceramic-based implants with controlled macro- and micro-architectures. This technology  
265 allows optimization of implant geometry, porosity, and surface texture to enhance stress  
266 distribution and bone ingrowth.<sup>32</sup> Experimental studies suggest that porous ceramic scaffolds  
267 can improve vascularization and early bone formation by mimicking trabecular bone morphology  
268.<sup>33</sup> Although still emerging in routine implant dentistry, these strategies represent a promising  
269 shift toward patient-specific, biologically optimized implants.

## 270 **Bioactive Surface Engineering**

271 Surface biofunctionalization is a major area of development in bioceramic implants. Calcium  
272 phosphate coatings, bioactive glass layers, and ion-doped ceramic modifications are being  
273 investigated to stimulate osteoblast differentiation and accelerate mineralized tissue  
274 formation.<sup>34</sup> Incorporation of biologically active ions such as strontium, magnesium, and zinc  
275 into ceramic matrices has demonstrated enhanced osteogenic potential and improved bone-  
276 to-implant contact in preclinical models.<sup>35</sup>  
277 Such bioactive modifications aim not only to promote osseointegration but also to enhance early  
278 peri-implant bone stability, which is critical in reducing susceptibility to inflammatory bone loss.

## 279 **Antimicrobial and Anti-Biofilm Strategies**

280 Given that peri-implantitis is a biofilm-mediated disease, research increasingly targets  
281 antimicrobial implant surfaces. Nanostructured ceramic coatings and photocatalytic zirconia  
282 surfaces are being explored to reduce bacterial adhesion while maintaining compatibility with  
283 host cells.<sup>36</sup> Some experimental surfaces incorporate antimicrobial agents or ions within  
284 ceramic layers to inhibit colonization by peri-implant pathogens without impairing osteoblastic  
285 activity.<sup>37</sup>

286 While in vitro data are promising, long-term randomized clinical trials are still required to  
287 determine whether these innovations significantly reduce peri-implant disease incidence.

## 288 **Hybrid and Composite Implant Systems**

289 To address concerns regarding ceramic brittleness and aging phenomena, hybrid systems  
290 combining metallic cores with ceramic outer layers are under investigation.<sup>38</sup> These designs  
291 aim to preserve mechanical strength while benefiting from the favorable soft tissue response  
292 and aesthetics associated with zirconia-based materials. Ongoing research is evaluating  
293 fracture resistance, low-temperature degradation, and long-term clinical stability of such  
294 systems.

## 295 **Immunomodulatory Surface Concepts**

296 A paradigm shift in implant biomaterials involves the development of surfaces capable of  
297 modulating the host immune response. Studies exploring macrophage polarization around  
298 implant materials suggest that surface chemistry and topography can influence inflammatory  
299 pathways.<sup>39</sup> Future bioceramic implants may be engineered to promote a pro-healing (M2)  
300 macrophage phenotype, thereby enhancing tissue integration and reducing chronic  
301 inflammatory reactions associated with peri-implantitis.

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