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Application of Zirconia Nanoparticles in dentistry and oral health

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ABSTRACT

Zirconia nanoparticles have emerged as a groundbreaking material in dentistry, offering transformative solutions for restorative, prosthetic, and implant applications due to their exceptional mechanical properties, biocompatibility, and multifunctionality. These nanoparticles enhance dental composites, such as bioactive cements, by improving hardness (e.g., 1.13 GPa Vickers hardness), modulus of elasticity, and antimicrobial efficacy against oral pathogens like Staphylococcus aureus, thereby reducing secondary caries risks. Additive manufacturing techniques, including nanoparticle jetting, enable precise fabrication of zirconia crowns with marginal deviations as low as 21.8 µm, optimizing fit and clinical efficiency. Surface modifications via plasma-sprayed zirconia coatings on titanium implants significantly enhance osseointegration, achieving 54.7% bone-implant contact in vivo, while gradient yttria-stabilized multilayered systems (e.g., KATANA™ HTML) balance aesthetics and strength (flexural strength >800 MPa) for high-stress prosthetic frameworks. Zirconia's bioactive and inert nature also minimizes biofilm formation and ion release, supporting long-term biocompatibility. Despite these advancements, challenges such as inherent brittleness, technique-sensitive manufacturing, and limited long-term clinical data under dynamic oral conditions necessitate further research. Future innovations should focus on hybrid composites to improve toughness, scalable fabrication protocols, and rigorous clinical validation. By bridging material science and clinical practice, zirconia nanoparticles hold immense potential to advance personalized, durable, and aesthetically driven dental care, aligning with the evolving demands of modern dentistry.

Keywords: Zirconia Nanoparticles, Dentistry, Oral Health, Dental Restorations, Additive Manufacturing, Dental Prosthetics, Antimicrobial Activity.

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Introduction

Nanomaterials are materials engineered at the nanoscale (1–100 nanometers), where their unique physical, chemical, and biological properties emerge due to their small size and high surface-area-to-volume ratio (1-3). These properties differ significantly from their bulk counterparts, enabling innovations in strength, reactivity, and functionality. Examples include carbon nanotubes, quantum dots, and metallic nanoparticles (3), which exhibit exceptional electrical conductivity, optical characteristics, or mechanical resilience (4, 5). Nanotechnology, the science of manipulating matter at this atomic or molecular scale, integrates disciplines such as physics, chemistry, biology, and engineering to design materials and devices for targeted applications (6-8). This field has revolutionized industries like medicine (e.g., targeted drug delivery, imaging agents), electronics (miniaturized circuits, flexible displays), energy (high-efficiency solar cells, advanced batteries), and environmental science (pollutant remediation, water filtration).

The development of nanotechnology also addresses global challenges, such as sustainability and resource efficiency (9, 10). For instance, nanomaterials enhance renewable energy systems by improving solar panel efficiency or enabling lightweight, durable materials for electric vehicles (11). However, the rapid growth of nanotechnology raises concerns about safety, ethical use, and environmental impact (12). Potential risks include nanoparticle toxicity, unintended ecological consequences, and regulatory gaps (13, 14). Ongoing research focuses on "green nanotechnology," which prioritizes eco-friendly synthesis methods and biodegradable nanomaterials (15). As the field evolves, interdisciplinary collaboration and responsible innovation will be critical to balancing technological advancements with societal and environmental well-being, ensuring nanotechnology's benefits are realized sustainably and equitably (16, 17).

Zirconia nanoparticles have become a cornerstone in modern dentistry, offering a unique combination of mechanical resilience, biocompatibility, and adaptability (18). Their integration into dental practices addresses both functional and aesthetic challenges, revolutionizing treatments from restorations to implants (19). Below is an expanded exploration of their diverse roles and implications:

Advanced Dental Restorative Materials

Zirconia nanoparticles are revolutionizing dental restorative materials by enhancing both mechanical performance and biological compatibility (20). A key innovation in this field is the development of HANBG (hydroxyapatite-alumina/zirconia-nanobioactive glass) nanocomposite cement, which combines the exceptional hardness of alumina and zirconia with the biomimetic properties of hydroxyapatite (21). This composite achieves a Vickers hardness of 1.13 GPa and a Young's modulus of 22.89 GPa, outperforming traditional restorative cements in terms of durability and resistance to deformation under stress (22). Such mechanical robustness ensures the material can withstand the demanding occlusal forces encountered in daily mastication, making it ideal for posterior restorations (23). Additionally, the inclusion of nanobioactive glass promotes remineralization by releasing calcium and phosphate ions, which help repair early-stage tooth decay and strengthen the bond between the restoration and natural tooth structure (24, 25).

Beyond mechanical superiority, HANBG leverages zirconia's inherent antimicrobial properties to combat oral pathogens like Staphylococcus aureus, a common contributor to secondary caries (26). The nanoparticles disrupt bacterial adhesion and biofilm formation on the restoration surface, significantly reducing the risk of recurrent decay (27). Furthermore, zirconia's chemical stability prevents ion leaching, ensuring long-term biocompatibility and minimizing adverse immune responses (28). This dual functionality—mechanical resilience combined with bioactive and antimicrobial action—positions HANBG as a groundbreaking solution for durable, infection-resistant dental fillings and crowns (29). By addressing both structural failure and microbial infiltration, this material aligns with the growing demand for restorations that enhance clinical outcomes while extending the lifespan of dental treatments (30).

Precision Additive Manufacturing for Prosthetics

Nanoparticle jetting (NPJ) technology represents a breakthrough in dental prosthetics manufacturing, utilizing zirconia nanoparticles to 3D-print crowns, bridges, and other restorations with exceptional accuracy (31). This additive manufacturing process involves depositing layers of zirconia nanoparticle suspensions, which are then sintered to achieve dense, high-strength structures (32). By optimizing build angles during fabrication, clinicians can control the orientation of each layer, reducing marginal discrepancies to as low as 21.8 µm—significantly below the 50 µm threshold deemed clinically acceptable (33). Studies indicate that orientations of 0° and 180° yield the highest precision for molar crowns, minimizing errors at critical interfaces between the prosthetic and natural tooth (34). This level of accuracy ensures passive fit, reducing stress concentrations at the implant-restoration junction and enhancing long-term stability (35).

The adoption of NPJ streamlines workflows by integrating digital scans, CAD/CAM design, and automated printing, drastically cutting production time compared to conventional casting or milling methods (36). The precise fit achieved through this technology reduces the need for chairside adjustments, enhancing patient comfort and satisfaction (37). Furthermore, zirconia's inherent biocompatibility and wear resistance contribute to prosthetics that are both durable and aesthetically seamless (28). As digital dentistry evolves, NPJ is poised to expand beyond crowns to frameworks for full-arch restorations, offering scalable solutions for complex cases (38). This shift not only elevates clinical outcomes but also underscores the role of nanotechnology in advancing personalized, patient-centric dental care (39).

Implant Surface Modifications for Bone Integration

The application of plasma-sprayed zirconia nanoparticles as coatings on titanium dental implants significantly improves osseointegration by creating a nano-porous surface topography (40). This nanostructured layer mimics the natural roughness of bone, promoting cellular adhesion and mechanical interlocking between the implant and surrounding tissue (41). Animal studies demonstrate that zirconia-coated implants achieve a 54.7% bone-implant contact (BIC) rate within 12 weeks, compared to 41.5% for uncoated titanium (42). The enhanced performance is attributed to increased surface hydrophilicity, with contact angles reduced from 74.4° to 54.6°, which facilitates the adsorption of proteins like fibronectin and collagen (43). These proteins act as biochemical signals, accelerating osteoblast migration, proliferation, and differentiation, thereby fostering rapid bone matrix deposition around the implant (44).

Such surface modifications are particularly advantageous for patients with osteoporosis, diabetes, or age-related bone loss, where traditional implants may struggle to integrate (45). The accelerated bone formation reduces healing times and enhances primary stability, lowering the risk of implant failure (46). Additionally, zirconia's chemical inertness prevents corrosion and inflammatory responses, ensuring long-term biocompatibility (47). Future research aims to optimize coating thickness and porosity gradients to further tailor implants for specific patient needs, while clinical trials are underway to validate these benefits in humans (48). This innovation underscores the potential of nanotechnology to address critical challenges in implant dentistry, offering safer and more reliable solutions for at-risk populations.

High-Performance Prosthetic Frameworks

Zirconia has emerged as a premier material for implant-supported prosthetic frameworks, particularly in high-stress regions such as molars, due to its remarkable fracture resistance, which can withstand forces up to 3200 N in connector designs (49). This exceptional durability stems from zirconia's crystalline structure and transformation toughening mechanism, which prevents crack propagation under mechanical stress (50, 51). To address the dual demands of strength and aesthetics, advanced multilayered systems like KATANA™ HTML utilize gradient yttria stabilization (52). In these systems, the outer layers contain lower yttria concentrations (e.g., 3-4 mol%), enhancing translucency to mimic natural enamel, while the core is fortified with higher yttria levels (e.g., 5-6 mol%), achieving flexural strengths exceeding 800 MPa (53, 54). This stratified design ensures that restorations resist occlusal forces without compromising visual harmony, making it ideal for multi-unit bridges and full-arch prostheses (55, 56).

The innovation of gradient yttria stabilization bridges a critical gap in prosthetic dentistry, where traditional materials often force a trade-off between durability and aesthetics (20, 57). By strategically layering zirconia, frameworks maintain a lifelike appearance in visible areas while ensuring structural integrity in load-bearing zones (54). For instance, posterior bridges benefit from the core's high strength, whereas anterior restorations leverage the outer layers' light transmission properties. Clinical studies highlight reduced chipping and fracture rates compared to monolithic porcelain-fused-to-metal alternatives, enhancing long-term patient outcomes (58). Furthermore, CAD/CAM manufacturing precision allows customization of yttria gradients to match patient-specific biomechanical and aesthetic needs (59). As dental practices increasingly prioritize minimally invasive and patient-centric solutions, zirconia's versatility positions it as a cornerstone of modern prosthodontics, revolutionizing restorative outcomes in both function and form (60).

Antimicrobial and Bioactive Innovations

Zirconia nanocomposites are engineered to combat microbial colonization through multifaceted mechanisms, including electrostatic repulsion and nanoscale surface topography (61). The negatively charged surfaces of zirconia nanoparticles repel bacteria, which typically carry a negative charge, thereby reducing adhesion (62-65). Simultaneously, surface roughness at the nano-level disrupts biofilm formation by limiting the physical attachment of pathogens like Staphylococcus aureus and Streptococcus mutans (66). For instance, HANBG (hydroxyapatite - alumina / zirconia - nanobioactive glass) cement demonstrates a 60–70% reduction in biofilm accumulation compared to conventional materials, as shown in in-vitro studies (67). This antimicrobial efficacy is critical for preventing periimplantitis and secondary caries, common complications that compromise dental restorations (68). Furthermore, the bioactive components in these composites, such as nanobioactive glass, release ions that neutralize acidic environments, further inhibiting bacterial growth and promoting a healthier oral microbiome (69-71)(figure.1).

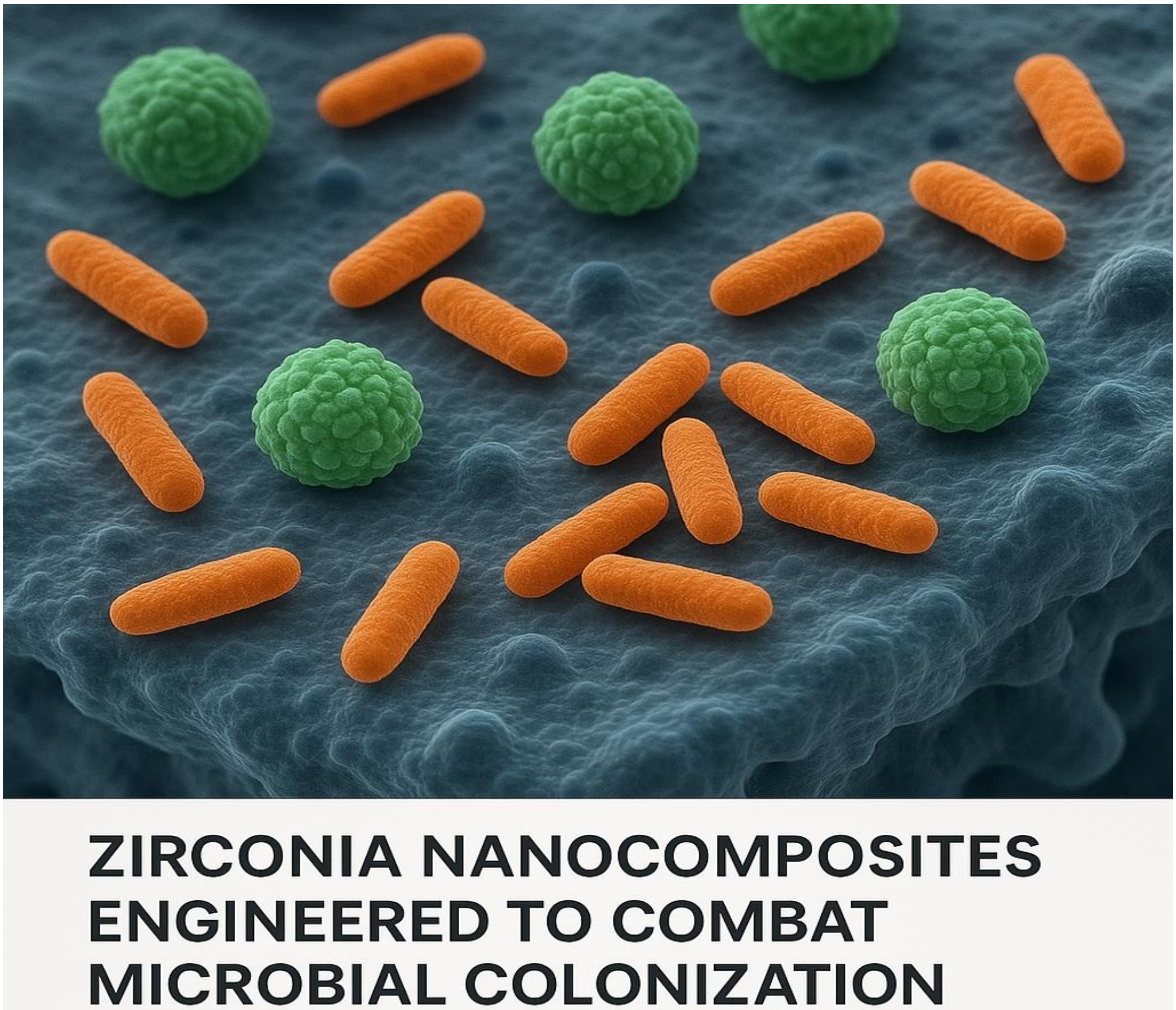

Figure.1: Antimicrobial Mechanisms of Zirconia Nanocomposites

This schematic illustrates how zirconia nanocomposites inhibit bacterial colonization through dual-action mechanisms. Negatively charged surfaces repel Staphylococcus via electrostatic forces, while nano-scale surface roughness disrupts Streptococcus mutans adhesion and biofilm formation. These features enhance the longevity and hygiene of dental restorations.

Beyond antimicrobial action, zirconia's chemical stability plays a pivotal role in ensuring biocompatibility (72). Unlike metal alloys, zirconia does not release ions into surrounding tissues, eliminating risks of allergic reactions or chronic inflammation, particularly in patients with sensitivities to nickel or cobalt (73). This inertness, combined with its resistance to corrosion in saliva, ensures long-term performance without degradation (74). Studies indicate that zirconia-based materials evoke minimal immune response, fostering soft tissue integration around implants and reducing postoperative complications (75). These properties make zirconia nanocomposites a safer, more reliable option for patients requiring durable restorations, while aligning with the growing emphasis on bioactive materials that actively support oral health rather than passively resisting failure (20, 76).

Aesthetic Customization Through Material Science

Modern advancements in zirconia formulations have redefined aesthetic outcomes in dental restorations, particularly for visible anterior teeth where mimicking natural dentition is critical (77). By engineering translucency gradients and polychromatic layering, zirconia restorations replicate the nuanced optical properties of enamel and dentin (78). Multilayer systems, such as those produced via CAD/CAM-driven gradient shading, strategically vary composition and density across layers. The incisal edge of a crown, for example, may incorporate highly translucent zirconia to emulate youthful enamel, while deeper layers use more opaque formulations to simulate the underlying dentin's light-scattering effects (79). This stratification enables seamless color matching with adjacent teeth, even under varying lighting conditions, ensuring restorations blend naturally with the patient's smile (80).

Central to these innovations is the precise dispersion of nanoparticles within the zirconia matrix (81). Traditional zirconia's opacity stemmed from light scattering at larger grain boundaries, but reducing particle size to the nanoscale (≤100 nm) minimizes this effect, enhancing translucency without sacrificing strength (82). Advanced processing techniques, such as high-pressure sintering and dopant integration (e.g., yttria), further refine light transmission to match natural enamel's refractive index (83). Additionally, surface texturing at the microscale replicates the subtle grooves and ridges of tooth anatomy, enhancing realism (84). These breakthroughs address longstanding aesthetic limitations of ceramic restorations, offering patients lifelike results that are virtually indistinguishable from natural teeth while maintaining zirconia's renowned durability—a balance once deemed unattainable in prosthetic dentistry (18, 85).

Challenges and Future Directions

- Brittleness Limitations: While zirconia excels in strength, its inherent brittleness necessitates cautious application in large-span prostheses (20). Hybrid materials, such as zirconia-polymer composites, are under investigation to enhance toughness (86).
- Manufacturing Precision: Techniques like NPJ require stringent calibration to avoid micro-cracks or marginal gaps (87). Ongoing research focuses on optimizing printing parameters and post-sintering protocols (88).
- Long-Term Clinical Data: Despite promising short-term results, long-term performance under cyclic loading, salivary exposure, and pH fluctuations remains understudied (89). Longitudinal clinical trials are essential to validate durability (90-93).

Conclusion

Zirconia nanoparticles represent a paradigm shift in dental material science, addressing critical needs in restoration durability, implant integration, and aesthetic personalization. Their antimicrobial and bioactive properties further align with preventive oral care trends. Future advancements should prioritize multifunctional composites, improved manufacturing scalability, and rigorous clinical validation to solidify their role in mainstream dentistry. Collaborative efforts between material scientists and clinicians will be pivotal in harnessing zirconia's full potential, ensuring patient-specific solutions that marry form, function, and longevity.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

Not applicable.

Authors' Contributions

All authors equally contributed to this study.

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Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

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