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Biogenic Nanomaterials: A New Frontier in Oral Healthcare

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ABSTRACT
Eco-friendly synthesis techniques have enabled the production of biocompatible nanomaterials through natural sources such as microorganisms, algae, and agricultural byproducts. These biologically derived nanoparticles exhibit excellent antimicrobial, anti-inflammatory, and regenerative properties, making them highly suitable for dental and oral health interventions. Metallic nanostructures, including silver, gold, and zinc oxide, show significant efficacy against common oral pathogens and can be incorporated into composites, coatings, and therapeutic systems. Their ability to enhance targeted drug delivery and reduce toxicity supports their application in diagnostics, restorations, and soft tissue healing. This sustainable approach offers a safer, more responsible alternative to conventional fabrication methods in dental care.
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Introduction

Nanomaterials are revolutionizing science and technology with their unique properties and vast potential. These materials, typically ranging from 1 to 100 nanometers in size, exhibit exceptional strength, conductivity, and reactivity due to their high surface-area-to-volume ratio (1). They are already being used in medicine for targeted drug delivery, in electronics for faster and smaller devices, and in energy storage for more efficient batteries and solar cells (2). Their versatility allows for innovative applications across industries, improving performance and sustainability while enabling breakthroughs that were once thought impossible (3-5).

Beyond their current uses, nanomaterials hold promise for future advancements that could transform everyday life. Researchers are exploring their potential in environmental remediation, such as cleaning pollutants from water and air (6, 7), as well as in lightweight (8), ultra-strong materials for aerospace and construction (9-11). With precise engineering, nanomaterials can be tailored for specific functions, opening doors to smarter textiles, self-healing materials, and even next-generation computing. Their ability to enhance existing technologies while enabling entirely new solutions makes nanomaterials a cornerstone of modern scientific progress (12, 13).

Green-Synthesized Nanomaterials:

Green-synthesized nanomaterials are nanoparticles produced using environmentally friendly, sustainable methods that avoid toxic chemicals and high energy consumption (14). Unlike conventional synthesis techniques, which often involve hazardous reducing agents (e.g., sodium borohydride) and generate harmful byproducts (15), green synthesis utilizes natural sources such as plant extracts, fungi, bacteria, algae, or even food waste (16, 17). These biological agents contain phytochemicals (e.g., flavonoids, terpenoids, and polyphenols) that act as reducing and stabilizing agents, facilitating the formation of nanoparticles with controlled size, shape, and enhanced biocompatibility. This approach aligns with the principles of green chemistry by minimizing waste, reducing energy use, and promoting safer alternatives for medical and industrial applications (18, 19).

In dentistry and oral healthcare, green-synthesized nanomaterials, particularly those made of silver, gold, zinc oxide, and hydroxyapatite, offer significant advantages due to their antimicrobial, anti-inflammatory, and bioactive properties. Since they are derived from natural sources, they exhibit lower cytotoxicity compared to chemically synthesized counterparts, making them ideal for applications such as antibacterial coatings(20), dental composites, drug delivery systems, and tissue regeneration. The eco-friendly nature of their production also makes them a sustainable choice for future dental innovations, addressing both clinical efficacy and environmental concerns (21, 22).

Advantages of Green-Synthesized Nanomaterials:

Green-synthesized nanomaterials offer significant advantages over conventionally produced nanoparticles, making them highly attractive for biomedical and dental applications. One of the most critical benefits is their enhanced biocompatibility and reduced toxicity (23). Traditional chemical synthesis methods often employ harsh reducing agents such as sodium borohydride or toxic solvents, which can leave harmful residues on nanoparticles, posing risks to human tissues. In contrast, green synthesis utilizes natural reducing and stabilizing agents derived from plant extracts, microorganisms, or biowaste, resulting in nanoparticles with superior biocompatibility (24, 25). Studies have demonstrated that green-synthesized silver (26), gold (27), and zinc oxide nanoparticles exhibit minimal cytotoxicity while maintaining potent antimicrobial effects, making them safer for use in oral care products, dental implants, and drug delivery systems (28)(figure.1).

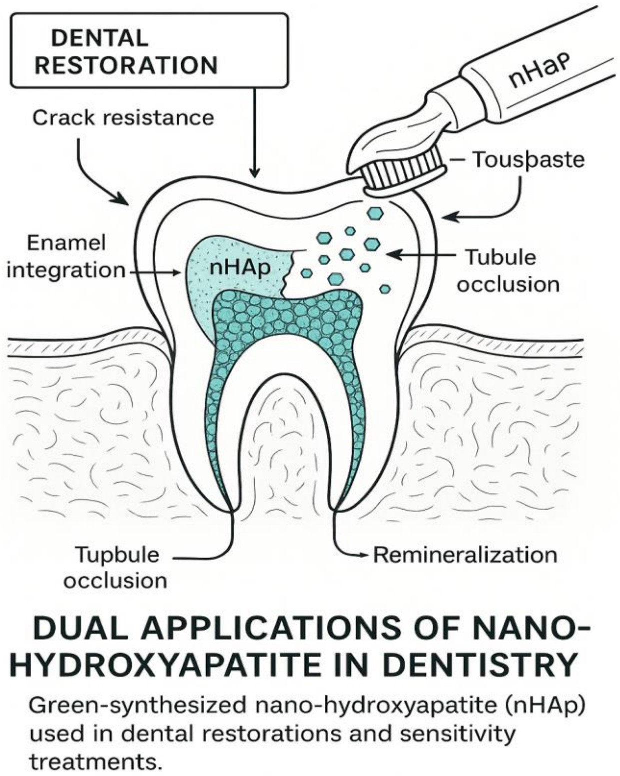

Figure.1: Dual Role of Nano-Hydroxyapatite in Modern Dentistry

This diagram illustrates the dual function of green-synthesized nano-hydroxyapatite (nHAp) in dental care. On the left, nHAp reinforces composite restorations by integrating with enamel and enhancing crack resistance. On the right, nHAp in toothpaste occludes dentinal tubules and promotes enamel remineralization, reducing tooth sensitivity(29).

Another key advantage is the eco-friendly nature of their production. Conventional nanoparticle synthesis generates substantial chemical waste and consumes high energy, contributing to environmental pollution (30). Green synthesis, however, relies on renewable biological sources, reducing reliance on hazardous chemicals and lowering carbon footprints. For instance, plant-mediated synthesis eliminates the need for extreme temperatures or pressures, aligning with sustainable manufacturing principles (31). Additionally, the use of agricultural byproducts such as fruit peels and algae in nanoparticle synthesis promotes waste valorization, further enhancing environmental sustainability (32, 33).

From an economic perspective, green synthesis is often more cost-effective than traditional methods. Chemical precursors and specialized equipment used in conventional synthesis can be expensive, whereas green synthesis leverages abundant natural resources as reducing agents, significantly cutting production costs (34). For example, turmeric (35), neem (36), and aloe vera extracts (37) have been successfully used to synthesize nanoparticles at a fraction of the cost of chemical methods, without compromising quality or functionality. This affordability facilitates large-scale production, making green nanomaterials more accessible for clinical and industrial applications (38).

Beyond safety and sustainability, green-synthesized nanomaterials demonstrate superior bioactivity compared to their chemically synthesized counterparts. The presence of bioactive phytochemicals on nanoparticle surfaces enhances their antimicrobial, antioxidant, and regenerative properties (39, 40). Research indicates that green-synthesized nanoparticles exhibit stronger antibacterial effects against oral pathogens like Streptococcus mutans (41) and Porphyromonas gingivalis (42), crucial for preventing dental caries and periodontal diseases. Furthermore, their improved bioactivity promotes faster tissue regeneration, benefiting applications such as bone grafting and wound healing in dentistry (43, 44).

Green-synthesized nanomaterials present a compelling alternative to conventional nanoparticles, combining biocompatibility, environmental sustainability, cost efficiency, and enhanced functional performance. These advantages position them as a promising solution for advancing dental therapeutics, oral hygiene products, and regenerative medicine while adhering to global sustainability goals. Further research into optimizing synthesis protocols and long-term biosafety assessments will solidify their role in modern dentistry (45, 46).

Synthesis methods:

Green-synthesized nanomaterials are fabricated using eco-conscious methods that leverage biological systems to reduce metal ions into nanoparticles, avoiding toxic chemicals (47). Plant-mediated synthesis is a widely adopted technique where plant extracts serve as reducing and stabilizing agents (48). For instance, silver nanoparticles can be synthesized using neem leaf extract or turmeric rhizome extract (49). These plants contain phytochemicals such as polyphenols, flavonoids, and terpenoids, which donate electrons to metal ions like Ag^+, converting them into metallic nanoparticles (Ag^0). The process typically involves mixing aqueous plant extracts with metal salt solutions under ambient conditions, resulting in nanoparticles with controlled size and morphology. This method is favored for its simplicity, scalability, and minimal environmental footprint, as it eliminates the need for synthetic stabilizers and harsh reaction conditions (50, 51).

Microbial synthesis employs bacteria, fungi, or yeast as biofactories to produce nanoparticles through enzymatic or metabolic activity (52). Certain bacterial species, such as Pseudomonas aeruginosa and Lactobacillus strains, secrete reductases or electron-shuttling compounds that reduce metal ions into nanoparticles (53). For example, silver nanoparticles synthesized by Fusarium oxysporum fungi exhibit uniform size distribution due to extracellular proteins that stabilize the particles (54). Similarly, yeast cells like Saccharomyces cerevisiae internalize metal ions and enzymatically convert them into nanoparticles within their cellular matrix (55). Microbial methods allow precise control over nanoparticle properties by adjusting parameters such as pH, temperature, and incubation time, though they often require longer reaction periods compared to plant-based approaches (56, 57).

Algae-based synthesis utilizes marine or freshwater algae to fabricate nanoparticles, capitalizing on their rich content of polysaccharides, pigments, and antioxidants (58). Macroalgae (seaweed) and microalgae like Chlorella vulgaris have been used to synthesize gold, zinc oxide, and iron oxide nanoparticles (59). Algal biomolecules act as both reducing and capping agents, enabling single-step synthesis under mild conditions (60). Bio-waste-derived synthesis further enhances sustainability by repurposing agricultural or industrial byproducts (61). For instance, fruit peels (citrus, banana), rice husks, or sugarcane bagasse contain bioactive compounds that reduce metal precursors into nanoparticles (62). These waste materials are cost-effective and abundant, reducing reliance on virgin resources while addressing waste management challenges (63).

Both algae and bio-waste methods align with circular economy principles, as they transform low-value biomass into high-value nanomaterials (64, 65). For example, silica nanoparticles derived from rice husk ash exhibit potential in dental composites due to their reinforcing properties. These approaches minimize energy consumption and chemical waste, offering scalable solutions for industrial applications (66). However, challenges such as variability in raw material composition and the need for process optimization persist, requiring further research to standardize synthesis protocols and enhance reproducibility across batches (50, 67).

Applications:

Antimicrobial and Anticaries Agents:

Electropositive metal nanoparticles (MNPs) are attracted to the negatively charged surfaces of bacterial cell walls via electrostatic interactions. This interaction leads to a strong binding with the cell membrane, disrupting the cell wall's integrity and increasing its permeability. Additionally, MNPs can transport metal ions into the cell from the outside environment, interfering with normal cell functions. Both metal ions and nanoparticles can then generate reactive oxygen species (ROS) within the cell (21, 68).

Green-synthesized nanoparticles, particularly those composed of silver (Ag), zinc oxide (ZnO), and copper oxide (CuO), have demonstrated significant potential as antimicrobial and anticaries agents in dentistry (44, 69). These nanoparticles exhibit potent activity against common oral pathogens such as Streptococcus mutans (41) and Porphyromonas gingivalis (21), which are major contributors to dental caries and periodontal diseases (70). Their small size and high surface area enhance interactions with bacterial cell membranes, leading to membrane disruption, oxidative stress, and eventual cell death (71). Studies have shown that incorporating these nanoparticles into dental composites, coatings, or mouth rinses effectively reduces biofilm formation and plaque accumulation (72). For example, silver nanoparticles embedded in dental adhesives have been found to inhibit bacterial colonization without compromising material strength, offering a dual function of restoration and infection control (73, 74).

Dental restorations, whitening and desensitizing:

Green-synthesized nanocomposites are reshaping dental restorations by combining strength with natural aesthetics (21). Materials like nano-hydroxyapatite reinforce fillings while mimicking tooth structure, preventing cracks and secondary decay. These biocompatible composites blend seamlessly with natural teeth, avoiding the metallic appearance of traditional options (75). The same nano-hydroxyapatite appears in desensitizing toothpaste, where it repairs microscopic enamel defects and seals exposed dentin tubules to reduce sensitivity. This dual application demonstrates how one nanomaterial can serve both structural and therapeutic purposes in oral care (76, 77).

For cosmetic improvements, nanomaterials offer safer whitening alternatives to harsh chemical bleaches. Nano-sized metal oxides gently remove surface stains through light-activated reactions rather than abrasive scrubbing, preserving enamel integrity. Unlike conventional whiteners that may cause sensitivity, these nanoparticles simultaneously brighten teeth while depositing protective mineral layers (48, 78). The crossover between restorative and cosmetic uses shows how green nanomaterials provide comprehensive dental solutions and fixing damage while enhancing appearance, all through eco-friendly production methods (44, 79).

Drug delivery:

Green-synthesized nanomaterials, particularly those fabricated using plant phytochemicals or microbial systems, demonstrate exceptional potential as drug carriers due to their inherent biocompatibility and modifiable surface properties. In periodontal applications, curcumin-loaded silver nanoparticles synthesized using turmeric extract have shown pH-responsive release kinetics, with significantly enhanced antibacterial efficacy against Porphyromonas gingivalis biofilms compared to conventional delivery systems (80, 81). Similarly, chitosan nanoparticles produced through fungal-mediated synthesis exhibit improved mucoadhesive properties, enabling prolonged retention and controlled release of anti-inflammatory agents at gingival sites (82, 83). The natural reducing and capping agents present in these green-synthesized systems not only stabilize the nanostructures but also contribute synergistic therapeutic effects, as seen in propolis-functionalized nanoparticles that combine inherent antimicrobial activity with payload delivery (84, 85). Importantly, these delivery platforms address key challenges in oral therapeutics by protecting bioactive compounds from degradation in the harsh oral environment while maintaining favorable safety profiles, as demonstrated in recent cytotoxicity studies using human gingival fibroblasts. Their ability to penetrate dental biofilms and target specific pathogenic niches offers promising solutions for managing complex oral diseases while minimizing disruption to the commensal microbiome (80).

Oral cancer detection and treatment:

Green-synthesized gold nanoparticles (AuNPs) show exceptional promise for oral cancer detection and treatment(86) due to their unique optical properties and biocompatibility. In diagnostics, plant-derived AuNPs functionalized with cancer-specific antibodies or biomarkers enable highly sensitive detection of early-stage oral squamous cell carcinoma through surface-enhanced Raman spectroscopy (SERS) and colorimetric assays, outperforming conventional biopsy methods in recent clinical studies (87-89). For therapeutic applications, biosynthesized AuNPs serve as effective carriers for targeted drug delivery, with studies demonstrating pH-responsive release of chemotherapeutic agents like doxorubicin specifically in tumor microenvironments while sparing healthy tissues (90). Particularly noteworthy is the dual functionality exhibited by green AuNPs, where the natural phytochemical capping agents from plants like pomegranate or green tea not only stabilize the nanoparticles but also provide synergistic anticancer effects through antioxidant and pro-apoptotic activity (88, 91).

Bone regeneration and implant coating:

Green-synthesized nanomaterials are proving valuable for bone regeneration and implant coatings in dentistry. Hydroxyapatite nanoparticles derived from natural sources like eggshells or algae closely mimic natural bone mineral, promoting osteoblast activity and accelerating jawbone healing (92, 93). These bioactive nanomaterials are incorporated into scaffolds that guide new bone growth while resisting bacterial colonization (94).

For dental implants, plant-synthesized titanium dioxide and silver nanoparticle coatings create antibacterial surfaces that prevent peri-implantitis while enhancing osseointegration (95-97). Recent studies show these green coatings improve bone-to-implant contact compared to conventional surfaces, with the added benefit of reduced inflammatory response (98-101).

Conclusion

Green synthesis methods produce eco-friendly nanoparticles with dual therapeutic and environmental benefits. Their proven efficacy against oral pathogens, dental restoration and enhancing tooth aesthetic demonstrates remarkable clinical potential. These sustainable nanomaterials represent the future of medical innovation, combining therapeutic performance with ecological responsibility.

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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