



SYSTEMATIC REVIEW

Green Metal Nanoparticles and Their Applications in Periodontics

Monica Antony¹, Sruthy Prathap², Vinita Boloor³, Anupama Rao^{2*}¹Postgraduate Student, Yenepoya, Karnataka, India²Additional Professor, Yenepoya, Karnataka, India³Additional Professor and Head of the Department, Yenepoya, Karnataka, India

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* Corresponding author:

Anupama Rao

dranupamarao@yenepoya.edu.in<https://doi.org/10.38138/JMDR/v12i1.25.73>

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ABSTRACT

The field of nanotechnology is a rapidly developing field, which is superior and indispensable due to their unique size dependent properties. Green nanotechnology is an emerging field of science that uses living cells to help in the production of nanoparticles ranging from 1 to 100nm. Researchers have been using the green synthesis approach due to its simplicity, environmental friendliness, economy, non-toxicity, short reaction times, natural biodegradability, and high yields. Total phenolic components of plant extracts, including as tannins, flavonoids, and phenolic acids, may function as reducing and capping agents for ionised metabolites and promote the synthesis of metal nanoparticles. Green synthesis of metal nanoparticles such as gold, silver, iron, copper, titanium, zinc, and bismuth enhanced by plant extracts has proven beneficial as it outperforms traditional materials. Specific metallic nanoparticles have the potential to enhance the antimicrobial efficacy of periodontitis treatments when combined. Therefore, these Nanoparticles, as well as their oxide nanoparticles, are only some of the metals and metal oxides that have been synthesized in environmentally friendly ways and shown to have therapeutic benefits against periodontitis.

Keywords: Green synthesis, Metal nanoparticles, Periodontal application

1 INTRODUCTION

Periodontal disease is the inflammation and progressive destruction of the tooth supporting structures, often leading to tooth mobility and eventual loss and globally a major public health challenge. Complex microbial populations including *Pseudomonas aeruginosa*, *Streptococcus pyogenes*, *Escherichia coli*, and *Bacillus cereus*, causes the disease. *B. cereus*, *S. pyogenes*, *P. aeruginosa*, and *E. coli* are commonly found in higher proportions compared to healthy oral environments¹. Following conventional scaling and root planing, antibiotics are often prescribed to minimise microbial recolonisation and lower bacterial load². However, antibiotic-resistant species has become a significant concern. Therefore, novel, and efficient treatment modalities are needed for the effective management of periodontitis³.

Nanotechnology deals with manipulating materials with dimensions typically below 100 nanometers, collectively referred to as nanoparticles⁴. They show distinctive physicochemical characteristics like increased surface area, enhanced reactivity, and quantum effects that contribute to their antimicrobial behaviour⁵. Nano-biotechnology is an interdisciplinary approach

combining nanoscience and biological systems and has inspired the synthesis of innovative nanobiomaterials^{6, 7}. Conventional nanoparticle production methods are costly, environmentally detrimental and involves toxic chemicals that can harm living systems.

Green nanoparticle synthesis employs eco-friendly biological routes using naturally derived materials such as plant extracts, fungi, bacteria, and yeast⁸. Plant based synthesis is particularly helpful because plant extracts are abundant, globally accessible, safe to handle, and rich in metabolites with strong reducing potential, enabling low-cost and sustainable nanoparticle formation. Plant biomolecules serve as reducing and stabilising agents during synthesis, promoting nanoparticle stability and yield⁹. Green synthesis via biological pathways produces higher nanoparticle yields and is more environmentally benign¹⁰. Green synthesized metallic and metal oxide nanoparticles have shown promising biomedical applications in diagnostics, tissue engineering, wound care, immunotherapy, biosensing, regenerative medicine, and dentistry¹¹.

2 BIOLOGICAL COMPONENTS FOR “GREEN” SYNTHESIS

Compared to microbial routes, green synthesis is a simpler, scalable, and non-toxic process for generating biogenic nanoparticles¹². These biogenic metallic nanoparticles have extremely small dimensions and a high surface-to-volume ratio, characteristics that arise naturally from biological reduction mechanisms¹³.

Plant extracts possess diverse phytochemicals, such as terpenoids, amides, carboxylic acids, flavonoids, ketones, and ascorbic acid, for the conversion of metallic salts into nanoparticles¹⁴. These phytochemicals function as reducing, capping, and stabilising agents during the formation process¹⁵. The plant metabolites found in leaves, such as proteins, polysaccharides, vitamins, alkaloids, amino acids, polyphenols, tannins, saponins, flavonoids, and organic acids enables sustainable synthesis of nanoparticles¹⁶.

Metals

The nanoscale metal particles (<100 nm), display novel characteristics compared to their bulk counterparts due to quantum size effects¹⁷. Their minute size enhances cellular interaction and antimicrobial activity, as they can penetrate microbial membranes, disrupt metabolic processes, and hinder bacterial proliferation. The high surface-to-volume ratio promotes the generation of reactive oxygen species (ROS). Furthermore, since metal-based nanoparticles target multiple cellular structures rather than specific receptors, bacteria face greater difficulty developing resistance¹⁸.

Bacteria

Bacteria have long been exploited for their biotechnological potential in bioremediation, bioleaching, and genetic engineering. Bacterial strains, including *Bacillus cereus*, *Bacillus amyloliquefaciens*, *Bacillus indicus*, and *Bacillus cecembensis*, have the ability to reduce metal ions to nanoparticles under mild conditions^{12, 19}. Their metabolic versatility allows them to serve as biofactories for eco-friendly nanoparticle production.

Fungi

Fungal systems are highly effective biological agents for nanoparticle biosynthesis owing to their enzymatic richness and robust tolerance to metal ions. They can generate monodispersed nanoparticles with well-defined morphologies through enzymatic reduction processes occurring within or on their cell walls. Commonly used fungi for metal and metal oxide nanoparticle production include *Penicillium*, *Fusarium*, *Aspergillus* and *Trichoderma* species^{12, 20}. Metals such as silver, gold, titanium dioxide, and zinc oxide can be synthesized using fungal extracts, yielding particles suitable for biomedical applications.

Algae

Microalgae are photosynthetic aquatic microorganisms that serve as natural producers of metallic nanoparticles such as ZnO, Au, and Ag²¹ and detoxifies the metal ions by converting them into their less toxic nanoparticle forms. For instance, titanium nanoparticles have been synthesised from *Phaeodactylum tricornutum*, using its culture supernatant. These nanoparticles

demonstrate antibacterial, cytotoxic, and biogenic effects, and can further be utilised in imaging, biosensing, drug delivery, cancer therapy, and immunological applications²².

Yeast

Yeasts, are single-celled eukaryotic organisms that exhibit a high surface-to-volume ratio and significant metal ion uptake capacity, making them ideal candidates for nanoparticle biosynthesis²³. Silver-tolerant yeast strains, such as *Saccharomyces cerevisiae*, have successfully produced silver and gold nanoparticles through biologically mediated processes¹².

Plant Cell

Plant-mediated synthesis is considered the most straightforward, cost-effective, and sustainable strategies for nanoparticle generation²⁴. Phytochemicals in plant tissues catalyse the reduction of metal ions into their nano particulate forms. Early studies reported the formation of silver and gold nanoparticles from extracts of *Aloe barbadensis*, *Avena sativa*, *Citrus limon*, *Azadirachta indica*, *Coriandrum sativum*, and *Brassica juncea*. Plants such as *Helianthus annuus*, *Hibiscus rosa-sinensis*, and *Camellia sinensis* have been employed in synthesising ZnO nanoparticles¹². The broad diversity of phytochemical constituents in plants supports efficient and stable nanoparticle formation across multiple metal systems.

3 MECHANISM AND SYNTHESIS APPROACHES

Green synthesised nanoparticles show enhanced stability, low toxicity, and promising biological activity^{25, 26}. The redox potential of plant-derived compounds such as terpenoids, polyphenols, and flavonoids enables them to act as reducing and stabilising agents during synthesis²⁷. Secondary metabolites, particularly polyphenols, play a pivotal role in the formation and stabilisation of nanoparticles²⁸. Typically, higher plant extract volumes yield smaller nanoparticles. Additionally, light-induced electrostatic interactions are thought to contribute to nanoparticle aggregation control and antibacterial efficacy²⁹.

Based on the synthesis of green nanoparticles, they can be categorised as extracellular, intracellular, or phytochemical-driven. Plant-mediated synthesis produces higher yields due to the abundance of bioactive reducing agents in extracts¹¹. They have broad applications as antibacterial, anticancer, and catalytic agents, as well as in wastewater treatment and degradation of hazardous compounds³⁰. The antibacterial mechanism primarily involves the release of metal ions that interact with bacterial membranes, causing structural disruption, leakage, and eventual cell death³¹.

4 DENTAL APPLICATIONS

In restorative dentistry, green nanoparticles such as silver, zinc oxide, titanium dioxide, and zirconium have been incorporated into cements, composites, and adhesive systems that improve the mechanical integrity and impart long-lasting antibacterial capabilities. These materials minimise the occurrence of secondary caries by continuously releasing ions to inhibit

microbial growth. In preventive dentistry, these nanoparticles are used in mouth rinses, varnishes, and toothpastes, where they suppress biofilm accumulation and enhance enamel remineralisation. The pronounced antibacterial efficacy of green nanoparticles against common oral pathogens—including *Streptococcus mutans*, *Enterococcus faecalis*, and *Porphyromonas gingivalis*—makes them ideal for applications in intracanal medicaments, root canal irrigants, and periodontal gels in periodontology and endodontics. In implantology, nanoparticles synthesized from plant extracts such as garlic and ginger have shown excellent antibacterial and antibiofilm properties. These particles help prevent microbial colonisation on implant surfaces and promote osseointegration, demonstrating their potential for future use in dental implant coatings³². Recently, AgNP-coated sutures with nanoparticles of low silver concentration emerge as a compelling alternative in surgical practice, that exhibited a sustained and stable antibacterial effect for up to 7 days during healing post periodontal surgeries³³.

Overall, these applications underscore the broad potential of green nanoparticles in advancing environmentally responsible and biologically compatible dental materials and therapeutics.

5 METAL NANOPARTICLES IN PERIODONTITIS

Gold Nanoparticles

Gold nanoparticles (AuNPs) show biocompatibility, stability, and minimal toxicity, making them promising agents in dental and biomedical sciences. Certain plants, referred to as “hyperaccumulators,” possess the natural capacity to sequester metals from the environment, facilitating the biogenic synthesis of gold nanoparticles. Extracts from *Azadirachta indica*, *Aloe vera*, *Avena sativa*, *Medicago sativa*, *Hibiscus sabdariffa*, and *Cymbopogon citratus* have all been utilized for the eco-friendly extracellular synthesis of AuNPs. Owing to their distinctive optical and plasmonic properties, AuNPs are valuable for periodontal diagnostics, as bone-inducing agents in regenerative procedures, and as analgesic compounds in dental therapeutics³².

Silver Nanoparticles

Silver nanoparticles (AgNPs) exhibit powerful antimicrobial and anti-biofilm effects, primarily through mechanisms involving membrane disruption, increased permeability, and the intracellular release of silver ions. These ions generate reactive oxygen species (ROS) that damage vital biomolecules within bacterial cells, leading to death. Although chemical reduction methods using AgNO₃ are well established, biogenic synthesis via plant extracts provides a more sustainable, cost-effective, and safer alternative³⁴. In dentistry, AgNPs have been successfully integrated into acrylic resins, adhesives, nanocomposites, and implant coatings, enhancing the antibacterial resistance of restorative and prosthetic materials.

Iron Nanoparticles

Iron-based nanoparticles exist as iron oxide, iron oxide hydroxide, and zero-valent iron³⁵. Green synthesis routes using *Citrus sinensis* extracts have been shown to yield environmentally benign and cost-effective iron nanoparticles³⁶. These iron oxide nanoparticles, such as magnetite and maghemite, demonstrate synergistic antimicrobial effects when

combined with both natural and synthetic agents, thereby improving antibacterial efficacy³².

Copper Nanoparticles

Copper nanoparticles (CuNPs) are valued for their broad-spectrum antimicrobial activity and their ability to stabilise matrices in medical and industrial applications. While chemical and physical fabrication methods such as microemulsion, aerosol processes, and laser ablation are often expensive and energy-intensive, green synthesis offers a more sustainable route. The inclusion of ascorbic acid during synthesis enhances nanoparticle stability and minimises oxidation³⁷. Plants such as *Zingiber officinale*, *Azadirachta indica*, *Punica granatum*, and *Citrus medica* have been used to derive CuNPs with strong bactericidal potential³⁸. In dentistry, copper nanoparticles exhibit antibiofilm and cytocompatible properties, making them particularly effective as anti-peri-implant agents against *Aggregatibacter actinomycetemcomitans*³².

Titanium Nanoparticles

Titanium dioxide (TiO₂) nanoparticles are most widely studied due to their chemical stability, photocatalytic behaviour, low cost, and potent oxidative capability. Synthesized through precipitation using titanium isopropoxide, TiO₂ nanoparticles display antimicrobial, antiparasitic, and photodynamic properties³⁹, and on exposure to ultrasonic or light-induced excitation, help generate reactive oxygen species (ROS), which destroys bacterial cells effectively. The interaction between plant-derived compounds and Ti precursors enhances the rate of synthesis while improving nanoparticle stability⁴⁰.

Zinc Nanoparticles

Zinc oxide (ZnO) nanoparticles is one of the safest and most widely used nanomaterials in dentistry, that is recognised by the FDA for their biocompatibility. Zinc plays a vital role as a cofactor in numerous enzymatic reactions and commonly incorporated into restorative materials, including ZnO-eugenol cement, ceramics, and amalgam. ZnO nanoparticles synthesized using phenolic and flavonoid-rich plant extracts exhibit strong antibacterial and antioxidant properties, making them useful in dental composites and sealers⁴¹.

Bismuth Nanoparticles

Bismuth (Bi), due to its low toxicity, non-carcinogenicity, and limited bioaccumulation potential is categorised as an environmentally benign or “green” element. Bi₂O₃ nanoparticles derived via green synthesis are cost-effective and straightforward to produce, often employing ethanol and distilled water as safe solvents. Compared with microbial routes, plant-based synthesis yields bismuth nanoparticles with superior biocompatibility and reduced hazard potential⁴².

Cobalt Nanoparticles

Cobalt oxide (Co₃O₄) nanoparticles have broad-spectrum antibacterial activity and potential for environmentally sustainable synthesis. Ecological production methods are preferred because they minimise chemical waste and enhance nanoparticle safety. Studies show that these particles exhibit strong antimicrobial effects against both Gram-positive and

Gram negative bacteria, including *Escherichia coli*, *Bacillus subtilis*, *B. licheniformis*, and *Klebsiella pneumoniae*³².

6 LIMITATIONS

Although green synthesis methods are recognized for their environmental advantages, several practical limitations remain. One major drawback is the limited and seasonal availability of certain biological materials, as well as the requirement for controlled harvesting to maintain consistency. Moreover, batch variability can lead to inconsistencies in nanoparticle size, shape, and stability⁴³.

Large-scale production also remains a challenge, as some synthesis routes require prolonged reaction times and high energy inputs, partially contradicting the sustainable principles of green chemistry⁴⁰. In addition, differences in phytochemical composition among plant species complicate standardisation and reproducibility. Variability in particle size distribution can affect the optical, mechanical, and biological performance of the nanoparticles, making industrial scale production difficult. Consequently, optimisation of synthesis parameters and characterization methods is essential to improve reproducibility and ensure consistent nanoparticle quality¹⁹.

7 CONCLUSION

Nanotechnology has revolutionised biomedical science, introducing materials with unique size dependent properties that offer superior functional performance compared to conventional bulk materials. In both dentistry and medicine, nanomaterials have emerged as innovative antibacterial agents capable of overcoming microbial resistance and promoting tissue regeneration⁴⁴.

The use of green-synthesized nanoparticles, derived from natural plant and microbial extracts, represents a sustainable approach that aligns with environmental and safety considerations. Their cost-effectiveness, biocompatibility, and reduced toxicity make them promising alternatives to chemically synthesized nanoparticles.

Soon, nanotechnology is expected to become deeply integrated across all dental specialties— from restorative and preventive applications to periodontology, prosthodontics, and implantology —providing enhanced mechanical, antimicrobial, and regenerative capabilities. Furthermore, nano-carrier systems derived from herbal extracts may overcome limitations traditionally associated with phytotherapy, such as poor solubility, instability, and low bioavailability⁴⁵.

Collectively, green nanotechnology offers a pathway toward sustainable, safe, and high performance materials that will continue to advance modern dentistry and biomedical science.

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