IOSR Journal of Dental and Medical Sciences (IOSR-JDMS)
e-ISSN: 2279-0853, p-ISSN: 2279-0861.Volume 25, Issue 1 Ser. 3 (January. 2026), PP 50-52
www.iosrjournals.org

Antibacterial Nanoparticles In Conservative Dentistry And Endodontics: Current Evidence And Future Perspectives

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Abstract

Microbial persistence remains one of the most important causes of failure in conservative dentistry and endodontics. Despite advances in restorative materials and endodontic techniques, complete elimination of microorganisms from the tooth structure and root canal system continues to be challenging. Conventional antimicrobial agents and materials often show limited penetration into dentinal tubules, reduced effectiveness against organized biofilms, and short duration of antibacterial action. Antibacterial nanoparticles have emerged as a promising strategy to overcome these limitations due to their nanoscale size, large surface area, enhanced reactivity, and ability to interact closely with microbial cells.

Antibacterial nanoparticles exhibit broad-spectrum antimicrobial activity, disrupt biofilms, penetrate dentinal tubules, and reduce the likelihood of microbial resistance through multimodal mechanisms of action. Various nanoparticles such as silver, zinc oxide, chitosan, titanium dioxide, and nano-calcium hydroxide have been incorporated into restorative materials, adhesives, irrigants, intracanal medicaments, and root canal sealers. This review provides a comprehensive overview of antibacterial nanoparticles used in conservative dentistry and endodontics, focusing on their mechanisms of action, types, applications, advantages, limitations, biocompatibility concerns, and future prospects. Current evidence supports their potential to enhance clinical outcomes; however, further long-term clinical studies are required to establish safety, standardization, and cost-effectiveness.

Keywords: *Antibacterial nanoparticles; Nanotechnology; Conservative dentistry; Endodontics; Biofilms; Root canal disinfection*

Date of Submission: 12-01-2026 Date of Acceptance: 22-01-2026

I. Introduction

The primary objective of conservative dentistry and endodontics is the preservation of natural tooth structure while restoring function, esthetics, and eliminating infection. Microorganisms play a central role in the initiation and progression of dental caries, pulpal inflammation, periapical pathology, and secondary caries. Persistent bacterial infection is a major cause of failure of restorative and endodontic treatments.

In restorative dentistry, residual bacteria left beneath restorations and bacterial microleakage at restoration margins can lead to secondary caries and restoration failure. In endodontics, the complex anatomy of the root canal system, including lateral canals, isthmuses, and dentinal tubules, makes complete elimination of microorganisms difficult. Enterococcus faecalis is frequently associated with persistent endodontic infections and exhibits resistance to many conventional antimicrobial agents.

Conventional antibacterial agents such as calcium hydroxide, chlorhexidine, and sodium hypochlorite have limitations, including cytotoxicity at higher concentrations, limited penetration, and reduced effectiveness against biofilms. Nanotechnology offers a novel approach by enabling the development of antibacterial agents at the nanoscale, which exhibit enhanced antimicrobial activity and improved interaction with biological tissues.

Nanotechnology refers to the manipulation of materials at a scale of 1–100 nanometers. At this scale, materials exhibit unique physical, chemical, and biological properties, including increased surface area-to-volume ratio, enhanced surface reactivity, and altered optical and electrical properties. These characteristics make nanoparticles particularly suitable for antimicrobial applications in dentistry.

This review focuses exclusively on antibacterial nanoparticles in conservative dentistry and endodontics, discussing their mechanisms of action, commonly used nanoparticles, applications, advantages, limitations, and future directions.

II. Mechanisms Of Antibacterial Action Of Nanoparticles

Antibacterial nanoparticles exhibit their effects through multiple mechanisms, which contributes to their superior antimicrobial efficacy and reduced risk of bacterial resistance.

Disruption of Bacterial Cell Membranes

Nanoparticles can adhere to bacterial cell walls due to electrostatic interactions. This leads to increased membrane permeability, leakage of intracellular contents, and eventual cell death. The small size of nanoparticles allows close contact with microbial cells, enhancing their antibacterial effect.

Generation of Reactive Oxygen Species

Many metal and metal oxide nanoparticles generate reactive oxygen species such as hydroxyl radicals and superoxide ions. These reactive species cause oxidative damage to bacterial cell membranes, proteins, and nucleic acids, leading to bacterial death.

Interaction with DNA and Proteins

Nanoparticles can penetrate bacterial cells and interact with DNA and ribosomes, interfering with DNA replication, transcription, and protein synthesis. This inhibits bacterial growth and reproduction.

Biofilm Disruption

Biofilms are structured microbial communities embedded in an extracellular matrix that protects bacteria from antimicrobial agents. Nanoparticles can penetrate biofilms, disrupt their structure, and enhance the susceptibility of bacteria to antimicrobial agents.

III. Types Of Antibacterial Nanoparticles Used In Dentistry

Silver Nanoparticles

Silver nanoparticles are among the most extensively studied antibacterial nanoparticles. They exhibit broad-spectrum antimicrobial activity against Gram-positive and Gram-negative bacteria, fungi, and viruses. Silver nanoparticles act by disrupting bacterial cell membranes, generating reactive oxygen species, and interfering with DNA replication. In dentistry, silver nanoparticles have been incorporated into resin composites, adhesives, root canal sealers, and irrigants. Studies have demonstrated their effectiveness against Streptococcus mutans and Enterococcus faecalis.

Zinc Oxide Nanoparticles

Zinc oxide nanoparticles possess antibacterial and antifungal properties. They generate reactive oxygen species and release zinc ions, which disrupt bacterial metabolism and cell membrane integrity. Zinc oxide nanoparticles are commonly incorporated into root canal sealers, temporary restorative materials, and liners. They also exhibit acceptable biocompatibility at controlled concentrations.

Chitosan Nanoparticles

Chitosan is a natural polysaccharide derived from chitin and exhibits inherent antibacterial properties. Chitosan nanoparticles are biocompatible, biodegradable, and exhibit strong antibacterial and antibiofilm activity. They are particularly effective against Enterococcus faecalis and have been studied as nano-irrigants and intracanal medicaments in endodontics.

Titanium Dioxide Nanoparticles

Titanium dioxide nanoparticles exhibit photocatalytic antibacterial activity when exposed to light. They generate reactive oxygen species that damage bacterial cells. Titanium dioxide nanoparticles are incorporated into restorative materials and surface coatings to reduce bacterial colonization.

Nano-Calcium Hydroxide

Nano-calcium hydroxide consists of calcium hydroxide particles in the nanometer range. These nanoparticles exhibit improved penetration into dentinal tubules and sustained release of hydroxyl ions, resulting in enhanced antibacterial activity compared to conventional calcium hydroxide.

IV. Applications In Conservative Dentistry

In conservative dentistry, antibacterial nanoparticles are primarily used to prevent secondary caries and improve the longevity of restorations. Incorporation of nanoparticles into resin composites reduces bacterial adhesion and biofilm formation at restoration margins. Antibacterial adhesives containing nanoparticles reduce microleakage and residual bacterial activity.

Nanoparticle-based liners and bases provide antibacterial protection in deep cavities and reduce the risk of postoperative sensitivity and pulpal inflammation. These materials contribute to minimally invasive dentistry by allowing preservation of affected dentin while controlling bacterial activity.

V. Applications In Endodontics

Endodontic success depends on effective disinfection of the root canal system and prevention of reinfection. Antibacterial nanoparticles have been incorporated into irrigants, intracanal medicaments, and root canal sealers.

Nano-irrigants demonstrate superior penetration into dentinal tubules and enhanced biofilm disruption compared to conventional irrigants. Nanoparticle-based intracanal medicaments provide sustained antimicrobial activity and improved effectiveness against resistant microorganisms such as Enterococcus faecalis. Root canal sealers containing antibacterial nanoparticles exhibit improved sealing ability and antimicrobial properties.

VI. Advantages Of Antibacterial Nanoparticles

Antibacterial nanoparticles offer several advantages, including broad-spectrum antimicrobial activity, enhanced penetration into dentinal tubules, sustained release of antibacterial agents, effective biofilm disruption, and reduced likelihood of bacterial resistance.

VII. Limitations And Safety Concerns

Despite their advantages, concerns remain regarding potential cytotoxicity, long-term tissue response, environmental impact, and lack of standardized formulations. The biological behavior of nanoparticles depends on their size, shape, concentration, and surface characteristics. Controlled concentrations are essential to ensure biocompatibility.

VIII. Future Prospects

Future research in antibacterial nanoparticles is focused on the development of smart nanoparticles with controlled drug release, multifunctional nanoparticles combining antibacterial and bioactive properties, and nanoparticles for regenerative endodontic applications. Long-term clinical trials are required to establish safety and clinical effectiveness.

IX. Conclusion

Antibacterial nanoparticles represent a significant advancement in conservative dentistry and endodontics. Their ability to enhance antimicrobial efficacy, disrupt biofilms, and improve material properties has the potential to improve treatment outcomes. While current evidence is promising, further research is necessary to translate these technologies into routine clinical practice.

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