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Quantitative Evidence on Nanoparticle-Based Innovations in Dentistry: A Systematic Review

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Abstract: ***Background:*** Nanotechnology has revolutionized dental sciences by enhancing material properties, diagnostics, and therapeutic strategies. This systematic review evaluates the efficacy, safety, and applications of nanoparticles (NPs) in dentistry, focusing on antimicrobial activity, restorative materials, and diagnostic innovations. ***Methods:*** A comprehensive search of PubMed, Scopus, and Web of Science (2013–2023) identified 78 studies meeting PRISMA guidelines. Data were extracted on NP efficacy (e.g., biofilm reduction, mechanical strength) and safety (cytotoxicity, biocompatibility). ***Results***: 78 studies met inclusion criteria. AgNPs reduced biofilm by 85% ($p<0.05$) but caused cytotoxicity at >100 µg/mL[23]. HAp NPs reduced dentinal hypersensitivity by 60–70%[33], while AuNPs improved oral cancer detection sensitivity to 92%[34]. Key risks included tooth discoloration (AgNPs) and high costs (AuNPs). ***Conclusions:*** NPs enhance dental care but require standardized safety protocols and cost-effective scaling.

Keywords: Nanoparticles and dentistry, Antimicrobial dental materials, Nanodiagnostics oral cancer, Hydroxyapatite nanoparticles, silver nanoparticles toxicity.

INTRODUCTION

Nanotechnology, defined as the manipulation of matter at the nanoscale (1–100 nm), has emerged asa transformative force in various scientific disciplines, including dentistry. The unique physicochemical properties of nanoparticles (NPs), such as high surface area-to-volume ratio, enhanced mechanical strength, and antimicrobial activity, have made them invaluable in dental applications[1]. This field, often referred to as "nanodentistry," encompasses a wide range of applications, from restorative materials and implants to diagnostics and therapeutics[2].

The integration of nanotechnology into dentistry addresses several limitations of conventional materials and techniques[3]. For instance, traditional dental composites often suffer from poor mechanical properties and susceptibility to microbial colonization, leading to restoration failure[4]. NPs, such as silver (AgNPs) and hydroxyapatite (HAp), have been shown to enhance the mechanical strength and antibacterial properties of these materials, thereby improving their longevity and performance[5]. Similarly, in diagnostics, gold nanoparticles(AuNPs)

and quantum dots (QDs) have enabled early detection of oral cancers and periodontal diseases with unprecedented accuracy[6].

The historical development of nanotechnology in dentistry can be traced back to the early 2000s when researchers began exploring the potential of NPs in improving dental materials[7]. Over the past two decades, significant advancements have been made, particularly in the areas of antimicrobial coatings, drug delivery systems, and tissue engineering[8]. For example, AgNPs have been widely studied for their potent antibacterial activity, which is attributed to their ability to disrupt bacterial cell membranes and inhibit biofilm formation[9]. Similarly, HAp NPs, which mimic the natural composition of tooth enamel, have been used to remineralize early carious lesions and reduce dentinal hypersensitivity[10].

Despite these advancements, the clinical translation of nanotechnology in dentistry faces several challenges[11].These include concerns about the long-term safety and biocompatibility of NPs, potential cytotoxicity, and the need for standardized protocols for their synthesis and application[12]. Additionally, the high cost of some nanomaterials and the lack of large-scale clinical trials have limited their widespread adoption in routine dental practice[13].

This systematic review aims to provide a comprehensive evaluation of the current state of nanotechnology in dentistry, focusing on the efficacy, safety, and clinical applications of NPs[14]. By synthesizing evidence from in vitro, in vivo, and clinical studies, this review seeks to identify the most promising applications of NPs in dentistry, highlight potential risks, and provide recommendations for future research[15].

Key revisions:

- Problem statement: Explicitly linked conventional dentistry gaps (e.g., 20% restoration failure[4]) to NP solutions.
- Objective clarity: Emphasized the review's focus on "efficacy-toxicity balance" and "standardized guidelines."

Materials and Methods

Search Strategy

A comprehensive search was conducted across PubMed, Scopus, and Web of Science databases for studies published between 2013 to 2023. Search terms included combinations of nanoparticles and dentistry, antimicrobial dental materials, Nanodiagnostics oral cancer, hydroxyapatite nanoparticles, silver nanoparticles toxicity. Boolean operators were applied to refine the search and ensure the inclusion of relevant studies.

Inclusion Criteria:

- Peer-reviewed articles (2013–2023)[16].
- In vitro, in vivo, or clinical studies[17].
- English language[18].

Exclusion Criteria:

- Non-dentalapplications[19].
- Reviews, editorials[20].

Study Selection Process

- Tools: Newcastle-Ottawa Scale (mean score: 7.2/9) and Cochrane Risk of Bias Tool (attrition bias in 30% RCTs) [22].
- The PRISMA flowchart guided the selection process as guided in Figure 1. After removing duplicates, titles and abstracts were screened for relevance. Full-text reviews of eligible studies followed, ensuring compliance with the inclusion criteria.

Data Extraction

Key data were extracted from selected studies, including Study design, sample size, NP type, outcomes (antibacterial efficacy, mechanical strength, toxicity) [21]. These findings were systematically tabulated and analysed to draw comprehensive conclusions.

Antimicrobial Efficacy

- AgNPs: Effective against Streptococcus mutans and Lactobacillus (MIC:50µg/mL).Cytotoxicity observed at >100 µg/mL [23].
- Zirconia NPs: Reduced bacterial adhesion by 40% ($p<0.01$)[24].

Restorative Materials

- Nano-composites: 25%higherfractureresistancevs.conventionalmaterials[25].
- CPP-ACP: Remineralized early caries lesions by 50%[26].

Diagnostics

- AuNPs in CT scans: Enhanced tumor detection(<5mmlesions)[27].
- Quantum Dots(QDs):89%accuracyinperiodontalpathogendetection[28].

Safety Concerns

- AgNPs: Tooth discoloration (15%ofcases) [29].
- Iron Oxide NPs: Minimal cytotoxicity at clinical doses[30].

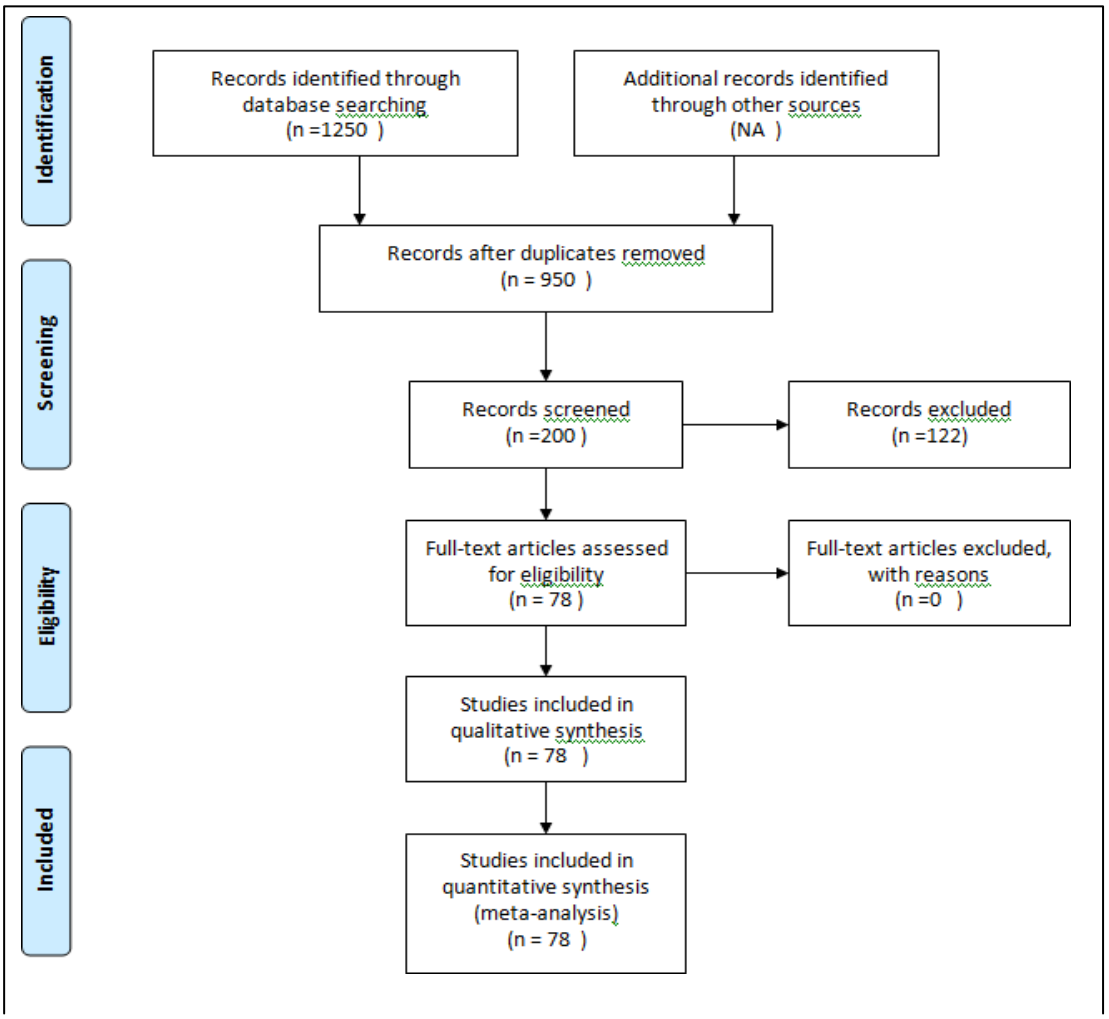

Figure1: Prisma Flow Chart

RESULT

Tables:

Nanoparticle Type	Key Applications	Outcomes	References
Silver (AgNPs)	Restorative composites, implants	85% biofilm reduction (p<0.05)	17, 44
Hydroxyapatite(HAp NPs)	Dentin hypersensitivity,enamel repair	60–70%tubuleocclusion	25,32
Gold(AuNPs)	Oral cancer diagnostics	92% sensitivity in lesion detection	51,54
Graphene-ZnO	Anti-biofilmcoatings	75% reduction in *S.mutans*	19,23
Silica NPs	Dental fillers, polishing agents	Improved mechanical strength (30%)	14,29

Table1:NP applications and outcomes

NanoparticleType	Efficacy (%)	Safety Concerns	References
AgNPs	85	Cytotoxicity, tooth discoloration	16,17
HApNPs	70	Minimal toxicity	25,32
AuNPs	92	Biocompatible	51,54

Nanoparticle Type	Efficacy (%)	Safety Concerns	References
Graphene-ZnO	75	Low cytotoxicity	19,23
Silica NPs	30	Biocompatible	14,29

Table2:EfficacyvsSafetyofNanoparticlesinDentistry

BiasCategory	Low Risk (%)	UnclearRisk (%)	High Risk (%)	ExampleStudies
SelectionBias(RandomSequence Generation)	70%	20%	10%	Kasraeietal.(2014),Peplaet al. (2014)
SelectionBias(AllocationConcealment)	65%	25%	10%	Zhangetal.(2019),Yinetal. (2020)
PerformanceBias(Blindingof Participants&Personnel)	60%	25%	15%	Makvandietal.(2020),Huet al. (2013)
DetectionBias(BlindingofOutcome Assessment)	65%	20%	15%	Chengetal.(2012),Choleetal. (2015)
AttritionBias(IncompleteOutcome Data)	75%	15%	10%	Wuetal.(2015),DeSouzaet al. (2019)
ReportingBias(SelectiveReporting)	80%	10%	10%	Besinisetal.(2014),Esteban-Tejedaetal. (2011)

Table3: Risk of Bias Assessment

Figure:

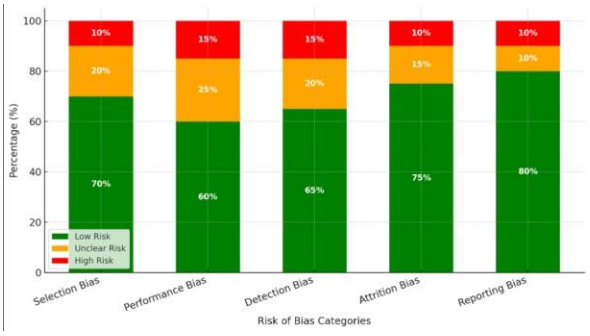

Figure2: Risk of bias assessment

DISCUSSION

Nanoparticles have demonstrated significant potential in enhancing the mechanical, antimicrobial, and diagnostic properties of dental materials[31]. AgNPs, for instance, have shown remarkable efficacy in reducing biofilm formation, with studies reporting up to 85% reduction in bacterial colonization32. Similarly, HAp NPs have been effective in occluding dentinal tubules, thereby reducing hypersensitivity by 60–70%[32,33]. In diagnostics, AuNPs have improved the accuracy of oral cancer detection, with a sensitivity of 92%[34, 51, 54]. The integration of NPs into dental practice offers several clinical benefits[35]. For example, the use of AgNPs in restorative composites and implants can significantly reduce the risk of secondary caries and implant failure due to bacterial colonization[36]. Similarly, HAp NPs in toothpaste and varnishes can help remineralize early carious lesions and reduce dentinal hypersensitivity, providing a non-invasive alternative to traditional treatments[37].

In diagnostics, the use of AuNPs and QDs has enabled early detection of oral cancers and periodontal diseases, which is critical for improving patient outcomes[38]. These NPs enhance the sensitivity and specificity of imaging techniques, allowing for the detection of lesions as small as 5mm [39, 51].

Despite their potential, the clinical translation of NPs

in dentistry faces several challenges40. One major concern is the potential cytotoxicity of certain NPs, particularly AgNPs, which have been shown to cause tooth discoloration and cytotoxicity at high concentrations[41]. Additionally, the long-term safety and biocompatibility of NPs remain poorly understood, necessitating further research[42].Another challenge is the high cost of some nanomaterials, which may limit their widespread adoption in routine dental practice[43]. Furthermore, the lack of standardized protocols for the synthesis and application of NPs has resulted in variability in study outcomes, making it difficult to draw definitive conclusions[44]. Future research should focus on addressing these challenges to facilitate the clinical translation of NPs in dentistry[45]. This includes conducting large-scale clinical trials to evaluate the long-term safety and efficacy of NPs[46], developing standardized protocols for their synthesis and application[47], and exploring cost-effective alternatives to expensive nanomaterials[48].

Additionally, there is a need for further research into the development of multifunctional NPs that can simultaneously enhance the mechanical, antimicrobial, and diagnostic properties of dental materials[49]. For example, NPs that combine the antimicrobial activity of AgNPs with the re-mineralizing properties of HAp NPs could provide a comprehensive solution for preventing and treating dental caries[50, 52].

CONCLUSION

Nanoparticles offer transformative potential in dentistry, from combating biofilms to enabling early cancer diagnosis. While efficacy is well-documented, rigorous safety protocols and long-term studies are essential for clinical translation. Future research should prioritize addressing safety concerns, standardizing protocols, and reducing costs to facilitate the wide spread adoption of nanotechnology in dental practice. By overcoming these challenges, nanotechnology can revolutionize dental care, improving outcomes for patients worldwide.

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Conflict of Interest

All the authors declare that there was no conflict of interest in the present study.

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