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Systematic Review

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The Role of Nanomaterials in Preventive Dentistry: Antimicrobial Coatings for Dental Restorations

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ABSTRACT

The applicability of antimicrobial nanomaterial coatings in preventive dentistry such as dental restoration practice in combating dental caries while embracing biocompatibility, and long-lasting and low bacterial adhesion properties has been the main area of research for many decades. **Objective:** To review the role of different types of nanomaterials in the field of preventive dentistry by focussing on anti-microbial coatings for dental restorations. **Methods:** The articles were taken from PubMed, Science Direct, and Google Scholar within the years 2018-2024 following PISMA 2020 guidelines. The effectiveness of nanomaterials included in dental coatings in terms of antimicrobial properties, biocompatibility, and durability in clinical applications was observed. Bacterial adhesion, caries prevention, material nanotechnology, and patient satisfaction were assessed. The antimicrobial efficiency and restorative outcomes of different nanomaterials: via silver, zinc oxide and titanium dioxide; were evaluated. Initially, 109 articles were retrieved, which were then screened based on predefined inclusion and exclusion, resulting in 16 studies for detailed analysis. The regions of study conduction were North America, Europe and Asia. **Results:** The antimicrobial efficacy of nano-coatings in dental restorations was seen via reduced bacterial adhesion and biofilm. The link between nanomaterials like silver nanoparticles and titanium dioxide enhanced secondary caries prevention and improved the long-term stability of restorative materials. Biocompatibility studies demonstrated that these coatings are biocompatible; however, more work is required. The application of antimicrobial nano-coatings gives adaptive and therapeutic characteristics. **Conclusions:** It was concluded that nanotechnology should lead to better durability and performance of dental restorations thus better oral health and less caries.

INTRODUCTION

Both direct and indirect restorative techniques rely heavily on the use of adhesive procedures with resin fill materials preferred commonly [1]. Despite good adhesion and appearance, the formation of biofilm is higher when using resin-based composite materials compared to amalgam and natural enamel [2]. Biofilm development discolours restorations and fosters bacterial proliferation chiefly of S. mutans which synthesise acid that decalcifies tooth tissues thereby causing secondary caries [3, 4]. Recent studies suggest that after 10 years 48.3% of the dental restorations are considered unsatisfactory mainly attributable to poor marginal seal [5], and redoing contributes 50-70% of the overall re-treatment output [6]. This challenge is not unique to restorative procedures only. In orthodontic treatments, bonded embrace devices, including braces, present extra surfaces where oral bacterium with cariogenic potential can thrive, thereby causing the emergence of a white spot lesion (WSL) on the enamel [7, 8]. White spot lesions are the first sign of enamel demineralization, and all patients wearing braces are at risk of developing them [9, 10]. All carious lesions that are not cavitation are avoidable and if diagnosed early curable, but

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if not well managed the lesion may worsen and put the life of the particular tooth at risk [10]. In addition, non-pharmacological interventions where patients' adherence to processes is less critical, including materials which inherently do not promote bacterial colonization, are highly preferred [11]. The primary cause of both secondary caries in restorations and WSLs in orthodontic treatments is the same i.e. carrio-pathogenic bacteria, and their acid by-products [12]. One such area of research, which may help in enhancing the durability of restorations and decreasing the rate of WSLs is the fabrication of dental materials that inhibit bacterial attachment as well as counteract bacterial metabolism on the tooth/ material interface [13]. It must be noted, however, that conventional restorative materials are sometimes unable to eradicate bacteria while maintaining strength and toughness to other available materials [14]. Several authors have highlighted that nanotechnology offers possibilities for restorative and preventive dentistry to work on existing problems. Due to their small size and big surface, nanoparticles can be used with better antibacterial properties as compared to the previous research, without losing the restoration strength. Literature reveals that particles such as silver, zinc oxide, and titanium dioxide prevent bacterial adhesion and biofilm formation which causes secondary caries [15, 16]. Furthermore, these materials show good mechanical properties like superior abrasive attributes and enhanced adhesive capability, clearly making them appropriate for long-term use in clinics [17, 18].
This study aims to focus on the goal of identifying and critically discussing the studies of incorporating nanoparticles into dental restorative materials and their antimicrobial characteristics. In this review, antibacterial properties, mechanical properties, and overall performance of nanoparticle-containing dental materials used to enhance the performance and longevity of restoration as well as prevention of secondary caries and WSLs will be discussed.

METHODS

The selection process of this systematic review was rigorous and consistent with PRISMA guidelines commenced from March 2024 to July 2024. Two independent reviewers performed literature searches on studies published between 2018 and 2024 in multiple databases such as PubMed, Science Direct; Springer; Google Scholar etc. The focus of the search strategy was on nanomaterials that were used in dental restorative applications, especially the antimicrobial effects of these types of materials. We first searched with the following search keywords: 'nanoparticles', 'antimicrobial coatings', 'dental restoration', 'zinc oxide', 'titanium dioxide' and 'silver nanoparticles,' which initially yielded 109 articles. 8 of articles were fetched from sources other than scientific libraries and databases. Predefined inclusion and exclusion criteria were used to perform the systematic screening of articles. Inclusion criteria include studies that use nanoparticles for dental restorative applications for evaluating their anti-microbial properties, ranging within the years 2018 to 2024 and have enough data which is relevant for analysis. Excluded studies were: a) did not have enough data, b) did not focus on dental restoration or c) were duplicates. 95 articles remained after removing 14 duplicate articles for screening. A total of 93 articles were excluded because they were of no relevance or contained insufficient data, and 16 studies met the inclusion criteria that were reviewed in detail. Efficacy, biocompatibility and mechanical properties of selected nanomaterials (Ag, ZnO and TiO2) in dental applications were analyzed about the related literature. These studies were mainly geographically based in the Middle East, USA and Europe. One clinical study was included, while the majority of them were in vitro experiments. The article selection process was illustrated in a PRISMA flowchart, excluding studies which did not meet the inclusion criteria (Figure 1).

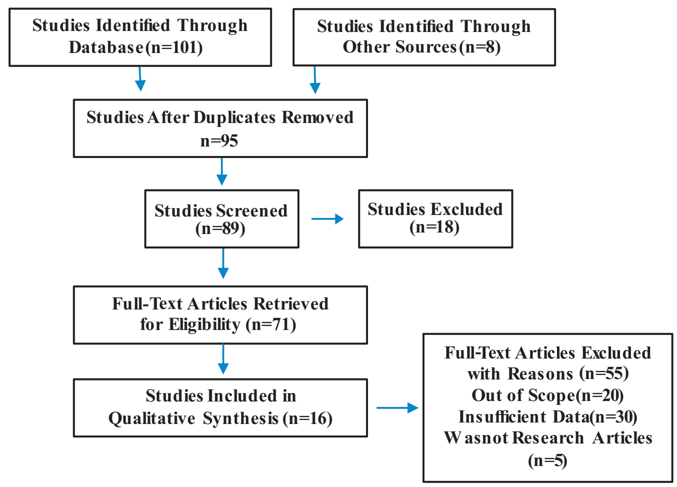

Figure 1: Selection of Studies for Review Process Showing Elimination of Studies That Were Not Lying Under the Inclusion Criteria

RESULTS

The majority of the papers were found to be written according to experimental in vitro data. All the papers included some sort of nanoparticle infused with other materials for their antimicrobial and restoration effects according to dental conditions. 16/17 of the studies were longitudinal, correlation but in vitro studies and 1/16 was a longitudinal clinical study. The majority of the studies were taken from the USA and the Middle East few were taken from the European region. Research studies were taken from the last five years i.e. 2020_2024. The study reviewed papers that were conducted in the Middle East (50%), USA (40%) and Europe (10%) respectively. The studies were taken from Google Scholar (80%), Science Direct (10%), Frontiers (7%) and others (3%) from Research Gate and PubMed. Results of these studies [19-34] are shown (Table 1).

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Table 1: Schematic Review of Studies That Were Most Appropriate According to the PRISMA Defined Rules

Reference	Study Design (Nanomaterial Used),	Methodology	Outcomes Measured (efficacy),	Key Findings (regarding effects of nanoparticle used)	Conclusions	Limitations
[19]	Experimental study (quaternary ammonium monomer and amorphous calcium phosphate nanoparticles)	Nanoparticles assessment of antibacterial and mechanical properties in vitro.	Reduction of biofilm viability, metabolic activity of microorganisms,lactic acid production and colony making units.	Increase in ammonium monomer increased antibacterial efficacy. Combination of 5% DMAHDM and 20% NACP led to significant biofilm reduction.	DMAHDM and NACP composite is effective in reducing dental biofilms.	Evaluation of long-term bioactivity, mechanical stability and fatigue is required under clinical conditions.
[20]	Experimental in vitro study (Amorphous calcium phosphate, dimethylaminohexadecyl methacrylate)	In vitro observation of interaction between biofilm and adhesive material	Alternation in colony-forming units (CFU), lactic acid production, biofilm thickness, and pH change.	NACP+ DMAHDM adhesive showed significant acid neutralization, reduced lactic acid production, decreased CFU counts, and improved enamel remineralization.	The adhesive combining NACP and DMAHDM showed great promise for preventing secondary caries.	In vitro may not fully replicate clinical conditions
[21]	Experimental study (Titanium dioxide (TiO2) coatings doped with Silver (Ag) and Gallium (Ga))	Coatings were prepared using sol gel techniques in vitro, their efficacy was measured	Efficacy in Antibacterial Activity, Cytotoxicity, and Osteodifferentiation Potential	TiO2 coatings doped with Ag and Ga displayed significant antibacterial effects against S.aureus and E. coli, especially with Ag, without cytotoxicity.	TiO2 coatings doped with Ag and Ga exhibited excellent antibacterial properties without cytotoxicity.	Further in-depth biological evaluations needed to assess anti-biofilm properties and mechanical stability of the coatings on CoCrMo alloys
[22]	Experimental lab-based study (Silver nanoparticles (AgNPs), synthesized in situ.)	Long-term study of antibacterial activity and adhesive durability tests conducted over a period of 1 year.	Antibacterial activity of the adhesive. Durability of bonding, assessed by μTBS and NL tests.	Adhesive containing AgNPs exhibited long-term antibacterial properties over one year,effectively reducing biofilm formation.	Silver nanoparticles (0.10%) synthesized in situ are appropriate for imparting long-term antibacterial properties	The study tested a limited concentration range (0.05%, 0.10%, and 0.20%) of AgNPs
[23]	Experimental study (Silver nanoparticles (AgNPs) deposited on Ti-18Zr-15Nb alloys.)	The antibacterial activity was assessed through colony-forming unit (CFU) counts against E. coli.	Antibacterial activity, Ag+ ion release, Surface characterization	The porous surface with AgNPs exhibited strong antibacterial activity.	The surface-modified Ti-18Zr-15Nb alloy with AgNPs showed effective antibacterial action.	The study was conducted in vitro, which may not fully reflect real clinical outcomes.
[24]	Experimental study (Nanoparticles of amorphous calcium phosphate combined with dimethylaminododecyl methacrylate.)	Testing of ion recharge and re-release over 12 cycles (lasting 6 months) in vitro.	Long-term antibacterial properties,Ion recharge and re-release for remineralization were effective.	The NACP-DMAHDM composite showed significant antibacterial properties, reducing CFU counts by 3-4 logs compared to controls.	The rechargeable NACP-DMAHDM composite effectively suppresses biofilm and lactic acid production, and provides long-term ion release for remineralization.	The study was conducted in vitro, so real-world clinical efficacy remains to be validated.
[25]	Experimental study (Nano silver (NAg) combined with N-acetylcysteine (NAC))	Enamel shear bond strength (SBS), antibacterial capability, and cytotoxicity were evaluated using in vitro assays	Bond strength (SBS), antibacterial activity (biofilm metabolic activity, lactic acid production, CFU counts), and cytotoxicity (cell viability).	Incorporating 0.15% NAg and 20% NAC enhanced antibacterial efficacy	The combination of NAg and NAC in orthodontic cement shows promise for improving antibacterial performance and biocompatibility	Further clinical studies are needed to validate in vitro findings and improve bonding strength for long-term orthodontic use.
[26]	Experimental study (Calcium fluoride nanoparticles combined with DMAHDM and 2-methacryloyloxyethyl phosphorylcholine)	Mechanical properties, ion release, biofilm colony-forming units (CFU), metabolic activity, and lactic acid production were evaluated using in vitro assays on dental biofilm models.	Flexural strength, fluoride and calcium ion release, biofilm CFU, lactic acid production, and biofilm metabolic activity.	The combination of nCaF2 and DMAHDM achieved strong antibacterial effects, reducing biofilm CFU by 4 logs and decreasing lactic acid production.	The novel nanocomposite with nCaF2 and DMAHDM shows promise for preventing recurrent caries by reducing biofilm formation and supporting tooth remineralization.	Further studies are needed to investigate long-term wear and ion release behavior in clinical conditions.

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[27]	Experimental study (Silvernanoparticles (nano-Ag) and Zinc oxide nanoparticles (nano-ZnO).)	The antimicrobial effectiveness against Streptococcus mutans, Lactobacillus acidophilus, and Candida albicans was evaluated, along with cell viability using the MTT assay.	Antimicrobial activity (biofilm inhibition) and biocompatibility (cell viability of human gingival fibroblasts)	Nano-Ag showed superior antimicrobial activity compared to nano-ZnO,	Coating orthodontic bands with nano-Ag and nano-ZnO induced antimicrobial effects against oral pathogens.	Multispecies biofilms and long-term durability were not assessed
[28]	Experimental (zinc oxide nanoparticles)	Tested antibacterial activity against Streptococcus mutans biofilm.	Number of colony forming units (CFU/mL), biofilm morphology (SEM)	Zinc oxide nanoparticles did not significantly improve the antibacterial activity of the glass ionomer cement.	Low concentrations (1% and 2%) of zinc oxide nanoparticles do not promote additional antimicrobial activity against S. mutans.	Higher concentrations and their effects on antibacterial activity and material properties were not explored.
[29]	Prospective in-vitro study (Graphene Oxide (GO) Nanoparticles, Silver-doped Titanium Dioxide (AgTiO2), Zinc Oxide (ZnO))	Evaluated antibacterial efficacy against Streptococcus mutans.	Number of CFUs, biofilm morphology (SEM), cytotoxicity	GO+AgTiO2 exhibited the highest antibacterial activity, followed by GO 1wt%, GO+ZnO. GO 1wt% significantly reduced bacterial growth compared to control.	Coating metal brackets with GO and its combinationscan enhance antibacterial properties, potentially reducing white spot lesions.	As an in-vitro study,it doesn't replicate the oral environment.
[30]	Experimental, In-vitro study (Polymerizable Quaternary Ammonium Silane-Modified Silica Nanoparticles)	Evaluated mechanical properties, polymerization shrinkage, curing kinetics, and degree of conversion of nanoparticles.	Mechanical properties (flexural modulus, compressive strength), polymerization shrinkage,curing kinetics,degree of conversion	The nanocomposites exhibited superior mechanical properties and curing behaviour, indicating potential stability and effectiveness for dental applications	Quaternary ammonium silane-modified silica nanoparticles showed antibacterial effects.	Limited to in-vitro conditions, not replicating complex oral environment.
[31]	Experimental study (Zirconia/Silver Phosphate Nanoparticles)	Evaluated nanoparticle -based adhesives for mechanical properties, biofilm inhibition, bond strength, and color stability.	Antibacterial activity, mechanical strength, bond strength, colour stability	Increased micro-hardness, enhanced antibacterial properties, better bond strength and colour stability at higher nanoparticle concentrations (0.5 wt.%).	Adhesives with zirconia/silver phosphate nanoparticles showed improved antibacterial and physical properties	Further studies are required to assess antibacterial and cytocompatibility efficacy in more detail.
[32]	Experimental study (Amorphous Calcium Phosphate (NACP), Dimethylaminododecyl Methacrylate (DMAHDM))	Tested bond strength, antibacterial efficacy, and Ca/P ion recharge capabilities. 3 adhesive groups were evaluated.	Bond strength, antibacterial efficacy, Ca/P ion release/recharge	DMAHDM addition significantly improved antibacterial properties.NACP maintained ion release.	The novel adhesive formulation demonstrated strong antibacterial activity and ion recharge	Long-term clinical performance and effects of ageing were not fully assessed.
[33]	Experimental study (Silver (Ag), Zinc oxide (ZnO), and combination of Ag/ZnO nanoparticles)	Tested antibacterial activity of coated orthodontic brackets on S .mutans and L. acidophilus. Coatings applied by physical vapor deposition.	Antibacterial efficacy measured by CFU reduction and inhibition percentage against S.mutans and L. acidophilus.	Ag/ZnO combination provided the highest antibacterial effect, with long-term persistence of efficacy.	Ag/ZnO nanoparticles showed superior antibacterial effects, suggesting their potential for preventing decalcification in orthodontic brackets.	Friction effects on coatings and potential cytotoxicity were not evaluated.
[34]	Clinical study (Calcium fluoride nanoparticles (nCaF2))	The study involved 31 orthodontic patients who were evaluated for enamel demineralization and bacterial load.	Degree of enamel demineralization (measured by DIAGNOdent pen) Streptococcus mutans bacterial count (real-time PCR) Incidence of WSLs (photographic assessment)	nCaF2-primer significantly reduced demineralization scores within 6 months of bracket bonding, particularly in the first month.	nCaF2-primer was effective in reducing early demineralization and bacterial colonization	The study was conducted in a single center,and its generalizability might be limited

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DISCUSSION

Nanoparticles play a significant role in enhancing the dental materials utilized in restorative dentistry, making this an emerging field of research. Numerous in vitro studies have explored various nanoparticles, their optimal concentrations, and methods for their incorporation to inhibit bacterial attachment. In this systematic review, the authors analyzed 109 experimental studies to highlight the variability in experimental methodologies. Unlike other literature reviews that focus on a single type of nanoparticle, this review encompasses multiple nanoparticles in the context of preventive dentistry. The application of nanotechnology in preventive and adhesive dental materials is discussed, including how nanoparticles can effectively control oral bacterial infections and the antibacterial and biological effects of silver nanoparticles (Ag-NPs) used in dental materials [35, 36]. Only one clinical study was included among all the studies incorporated into this review. However, clinical and in vivo experiments typically yield more accurate outcomes, and certain ethical and practical issues may arise during the initial assessment. The presence of various experimental conditions, including differences in control groups, can introduce potential biases in comparisons. For example, Yin *et al.,* reviewed both in vivo and in vitro experiments, but their discussion was based solely on the in vitro findings [37]. Although it is impossible to fully replicate the oral cavity in vitro, these experiments are valuable during preliminary assessments. Out of these, silver nanoparticles are the most extensively studied and widely used, either as standalone agents or in combination with others, including zinc oxide [38], silver nanoparticle-loaded hydroxyapatite nanowires [39], quaternary ammonium di-methacrylate [40], and silica nanoparticles [41]. One significant drawback is that the use of commercially available nanoparticles may involve undefined additives. Notably, a distinct study utilized laser synthesis to create nano-metric fibres from ZnO and Ca-O powders using a CO2 laser [42]. However, no research has yet applied in situ synthesized nanoparticles in dental materials. It may be beneficial to compare the properties of laser-synthesized nanoparticles with those of commercial variants. Nano-diamonds (NDs) have recently garnered attention in the medical and dental fields, particularly in drug delivery and tissue engineering [43, 44]. However, to the author's surprise, there have been no specific studies investigating the incorporation of NDs into dental restorative materials, despite earlier research highlighting their potential as an antibacterial layer for implants [45, 46]. The primary rationale for incorporating nanoparticles into dental materials is to provide protection against bacterial invasions and to minimize the formation of secondary caries. In addition to Streptococcus mutans and Lactobacillus acidophilus, other microorganisms have been tested, including Escherichia coli [47, 48], Staphylococcus aureus [49, 50], and Candida albicans [51]. Expanding the scope of testing to include various categories of nanoparticles and a broader range of related microorganisms could yield more comprehensive data on their antibacterial efficacy. The disc diffusion method and direct contact test are the most commonly used techniques to assess the antibacterial properties of dental materials. The disc diffusion test utilizes water-soluble constituents released from the material [52], while the direct contact test is essential for assessing insoluble nanoparticles, such as zinc oxide [53], to determine their antibacterial efficacy. For instance, Kim *et al.,* employed the disc diffusion method to evaluate chlorhexidine nanoparticles in resin, with chlorhexidine being solubilized in distilled water before activity assessment [18]. Most studies have focused on modified materials, including resin-based products, dental adhesives, and glass ionomer cement, particularly orthodontic adhesives like Trans-bond XT (3M) and Neo-Bond (Dentsply). In several studies, the omission of manufacturer specifications has negatively affected the methodological quality. Overall, the majority of studies included in this systematic review demonstrate that incorporating nanoparticles into dental restorative materials enhances the antibacterial activity of the base materials. Improvements were noted in various dental materials, such as glass ionomer cement (GIC), resin-modified (RM) materials, dental adhesives, and orthodontic appliances (OA). However, some researchers found that the antibacterial activity of the films was comparable to that of the control groups. For example, Magalhães *et al,.* reported that while silver nanoparticles (Ag-NP) in resin-based cement increased colour and sorption, they did not enhance antibacterial activity against Streptococcus mutans [54, 55]. Similarly, Garcia-Contreras *et al.* indicated that the antibacterial effect was only slightly increased in FX-II Enhanced restorations containing zinc oxide and titanium dioxide nanoparticles [56]. Additionally, Garcia *et al.* observed that zinc oxide nanoparticles in glass ionomer cement exhibited no antibacterial properties against S. mutans [57]. However, the varying concentrations of nanoparticles required for antibacterial agents demonstrate significant variability, despite nanotechnology being one of the most rapidly developing and actively researched fields today. Low concentrations may lack efficacy, and clumping can occur if the pH of the medium is not optimal [58]. Additionally, differences in sample storage and transport can also contribute to variability in results. This clearly indicates the need to introduce new dental restorative materials that

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possess enhanced antibacterial activity and incorporate nanoparticles. The variation in nanoparticles and their concentrations suggests the possibility of creating new dental materials that are more finely tuned. Future studies should establish protocols to minimize variability and enhance clinical relevance. Consequently, there is significant potential for the application of nanotechnology in dentistry, both in restorative and preventive procedures.

CONCLUSIONS

It was concluded that the utilization of nanoparticles in dental restorative materials promises increased antibacterial efficiency and working length of prevention in preventive dentistry. It became clear that silver, zinc oxide and titanium dioxide nanoparticles are primary preventatives of the bacterial adhesion and biofilm formation factors that contribute to secondary caries and restoration failures. However, more in vivo studies are required to corroborate these observations. Though lab studies have demonstrated the antibacterial prowess of these materials, application in oral environments needs further study. This subject requires proper control of the experimental procedures and nanoparticle synthesis, which in turn, may offer materials that resist bacterial attachment and caries formation.

Authors Contribution

Conceptualization: SS, RS, FT
Methodology: SS, RS, FT
Formal analysis: SS, RS, FT
Writing review and editing: NK, AI, MZ, FA

All authors have read and agreed to the published version of the manuscript

Conflicts of Interest

All the authors declare no conflict of interest.

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