SYSTEMATIC REVIEW OPEN ACCESS

Comparative and Systematic Analysis of Nanocomposite Resins in Restorative Dentistry: Durability and Antimicrobial Properties

Muhammad Saleem Qureshi[1], Khadija Akhtar[2], Farah Tasleem[3], Permanand[4], Maleeha Khurram[5], Ayesha Imtiaz[1], Muhammad Hussain[5]

[1]Department of Operative Dentistry and Science of Dental Materials, Baqai Dental College, Baqai Medical University,Karachi, Pakistan, [2]Department of Operative Dentistry, Institute of Dentistry, CMH Lahore Medical College, Pakistan, [3] Department of Science of Dental Materials, ISRA University, Hyderabad, Pakistan,[4] Department of Dental Materials, Bhitai Dental and Medical College, Mirpurkhas, Pakistan,[5] Department of Science of Dental Materials, University Medical and Dental College, Faisalabad,[6] Department of Biomedical Sciences, University of Florence, Italy.

ABSTRACT

Background: Nanocomposite resins became promising materials in restorative dentistry due to the application of nanotechnology to improve durability and microbial resistance characteristics. This systematic review aimed to review the mechanical performance and antimicrobial efficacy of nanocomposite resins.

Methods: A total of 93 studies were identified through a comprehensive database search of PubMed, Scopus, Web of Science, and Cochrane Library from 2010 to 2024. Studies were included if they evaluated the nanomaterials in dental composites, reported mechanical and antimicrobial properties, and utilized in vivo and in vitro experiments. Studies were excluded if they were reviews, commentaries, or conference papers and lacked quantitative data. Nanoparticles such as silver, zinc oxide, silica, and halloysite nanotubes were studied, and outcomes were measured, including flexural and compressive strength and antimicrobial activity against biofilms. The risk biases of studies were assessed using the Cochrane Risk of Bias tool.

Results: A total of 15 studies were included in the systematic review table out of an initial pool of 93 studies further filtered down via the screening process. There were 6 in vitro, 5 experimental, and 1 hybrid study designs. Silver, zinc oxide, silica, and halloysite nanotubes were among the nanoparticles that were investigated. Mechanical properties were seen to be improved significantly, with flexural strength increased by up to 74% and compressive strength increased by 50%. Bacterial reduction rates of >99% were observed for silver and zinc oxide nanoparticle-incorporated composites. The lack of long-term data and nanoparticle agglomeration were identified as drawbacks. Optimal nanoparticle concentration was observed to be needed to balance mechanical and antibacterial properties via subgroup analyses.

Discussion: While these advancements were significant, some gaps must be addressed. The lack of information about long-term performance under simulated oral conditions and the lack of testing against multispecies biofilms remained. Future studies should aim to optimize the formulations and conduct clinical trials that could validate efficacy and safety. The use of nanocomposite resins was an innovative approach to restorative dentistry that had the potential to offer durable, antimicrobial restorations.

Keywords: Antimicrobial Efficacy, Nanoparticles, Biofilm, Dental Materials.

Corresponding Author:
Dr. Muhammad Hussain,
Department of Biomedical Sciences,
University of Florence, Italy.
Email; muhammadhussainmh173@gmail.com
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INTRODUCTION

The shift of paradigm in the use of nanocomposite resins has brought about significant change in the field of restorative dentistry[1]. These materials were designed specifically to address problems like mechanical failure, biofilm formation by microorganisms, and secondary caries, which hinder the longevity and performance of dental restorations[2]. The nanocomposite resins incorporated with nanoscale materials, including silver nanoparticles (AgNPs), zinc oxide (ZnO), silica nanoparticles, and halloysite nanotubes (HNTs), improved durability and antimicrobial properties[3]. The idea behind integrating these nanoparticles was to develop multifunctional resins that could withstand functional stresses, without increasing the risk of bacterial colonization and biofilm development[4].

The research found that nanocomposite resins had the potential to excel over traditional materials. Nanoparticles were added to the resin and improved its physical and chemical properties such as enhanced flexural and compressive strength, better resistance to wear, and sustained antimicrobial activity[5]. For example, silver nanoparticles were demonstrated to damage microbial cell walls and block bacterial replication, whereas zinc oxide nanoparticles released reactive oxygen species, hence providing long-lasting antibacterial effects[6]. In the same way, silica nanoparticles were modified to deliver chlorhexidine with both mechanical improvement and controlled antimicrobial release[7].

Even with these advancements, there were still many challenges that came along. At higher concentrations, nanoparticles agglomerated and compromised the mechanical properties of the resin[8]. Moreover, the performance of the nanoparticles in oral environmental conditions was influenced by variability in salivary interactions and thermal fluctuations[9]. In addition, most studies explored single-species-based biofilm models that did not completely replicate the complexity of an oral microbiome[10].

This review sought a detailed analysis of nanocomposite resins, particularly their mechanical characteristics and their antimicrobial efficacy. The review synthesised experimental and in vitro findings to evaluate the strengths and weaknesses of these materials, as well as to identify areas of current lack of understanding. In addition, the future aspects and clinical relevance within this research domain were also discussed, providing insights into the role of innovations in redefining the standards of restorative dentistry.

METHODS

This systematic review was conducted based on the PRISMA guidelines 2020. This study only took those studies that focused on the mechanical performance and the antibacterial effectiveness of nanocomposite resins which were used in restorative dentistry. For inclusion in the current review, the following criteria were established: (1) the use of nanoscale materials (such as silver nanoparticles, ZnO, SiO^2 nanoparticles, halloysite nanotubes) in dental composites, (2) reporting of mechanical properties (flexural characteristic, compressive characteristic) or antimicrobial properties, (3) only in vitro, in vivo, or clinical study types, and (4) published in a peer-reviewed journal. The exclusion criteria included reviews and commentaries, conference proceeding papers, and papers having inadequate quantitative information.

A search was conducted in electronic databases such as PubMed, SCOPUS, Web of Science, and Cochrane from the year 2016 to 2024. Other sources like grey literature, references mentioned in the studies included in the review, and items drawn from other systematic reviews were searched manually to identify potential articles. No language filters were used in the search processes.

The search strategy was designed by consulting with an experienced librarian. The keywords and Medical Subject Headings (MeSH) terms used for the selection of studies included: nanocomposite resins, nanotechnology, mechanical properties, and antimicrobial activity. An example search string used for PubMed is as follows: "(nanocomposite OR nanotechnology OR nanoparticle) AND (resin OR restorative dentistry) AND (mechanical properties/mechanical OR flexural strength/ flexural OR compressive strength/compressive OR antimicrobial activity)". Consequently, the search techniques used were dependent upon the specific needs of the databases used in the study.

At first, two independent reviewers reviewed the titles and abstracts of the identified studies and discarded the irrelevant literature. Full-text articles of eligible studies were taken and evaluated with the help of established eligibility criteria. Disagreements were resolved through collegial discussion or consultation with another researcher. The process of study selection is presented in the form of a PRISMA flow diagram where different steps of identification, screening, eligibility, and inclusion of studies were outlined together with the number of records involved in each process and possible reasons for exclusion.

Primary outcomes involved mechanical properties and antimicrobial efficacy, while secondary outcomes included biocompatibility, long-term performance, and agglomeration of nanoparticles under normal oral conditions. Variables were systematically extracted which involved, study details, study design, nanoparticle type, key outcomes, and limitations. All results that aligned with predefined outcomes were taken missing data such as unreported statistics were not imputed and unclear methodologies were documented as limitations.

Data extraction faced challenges due to incomplete or missing outcomes, such as mechanical properties and antimicrobial activity, with some studies lacking standard deviations or confidence intervals. Mechanical properties were standardized to MPa using conversion factors (1 psi = 0.006895 MPa, 1 N/mm^2 = 1 MPa). Antimicrobial activity was reported as log reduction in CFU, with separate reporting for different testing methods and bacterial strains. Reviewers ensured consistency and transparency by verifying all conversions and addressing discrepancies in the data.

The risk of bias for each study was assessed using the Cochrane Risk of Bias Tool by two independent reviewers. Studies were categorized as high, moderate, and low risk based on conditions like justification and blinding of sample size. Effect measures such as mean differences were calculated for mechanical properties and log reduction in colony-forming units (CFU) for antimicrobial outcomes. Studies with insufficient quantitative data or irrelevant outcomes were excluded post-full-text screening.

Data preparation involved standardizing non-uniform metrics and marking studies with incomplete data. Results were synthesized narratively due to heterogeneity in study designs with highlighted trends. Subgroup analyses evaluated the type of nanoparticle and the complexity of biofilm. Sensitivity analyses were not performed due to limitations in study counts and publication bias. The certainty of evidence was graded informally using the GRADE framework. The refinements ensured transparency of results.

RESULTS

A database search identified 93 records, of which 6 duplicates were removed and 87 unique records were further passed down. Titles and abstracts were screened for eligibility, and 43 full text articles remained for further screening. Twelve of these studies met the criteria for inclusion in the qualitative synthesis. Reasons for exclusion of the remaining 31 full-text articles included: insufficient data (50%), irrelevant outcomes (32%), and non-eligible study designs (18%). The selection process was summarized in a PRISMA flow diagram in **Figure 1.**

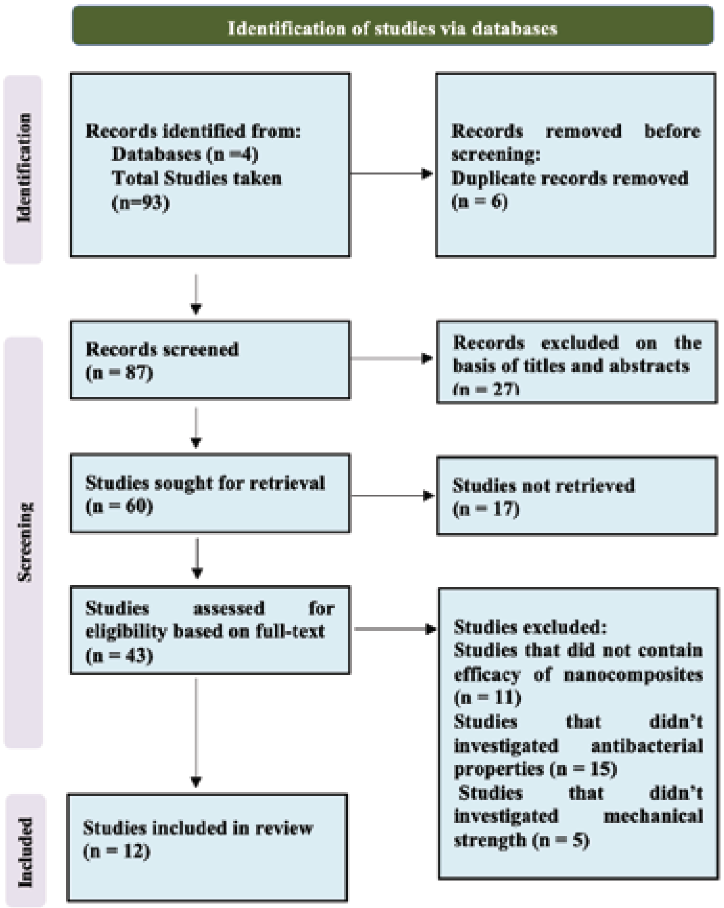

Figure 1: PRISMA Flow Diagram to Show Study Filtration Process.

There were 6 in vitro, 5 experimental, and 1 hybrid study designs. Silver, zinc oxide, silica, and halloysite nanotubes were among the nanoparticles that were investigated. Mechanical strength and antimicrobial efficacy against both mono- and multispecies biofilms were highlighted outcomes of the research. **Table 1** provides detailed study characteristics.

The Cochrane Risk of Bias Tool was used to assess the risk of bias. About the included studies, 58% were rated as having low risk of bias, 25% moderate risk, and 17% being at high risk. Their main limitations included small samples and short terms of observation.

Nanoparticles were shown to significantly improve the mechanical properties of dental composites. For example, the studies reported an increase in flexural strength (up to 74 %) and compressive strength (up to 50 %) compared to conventional materials. Bacterial reduction rates as high as 99% were notably found with silver and zinc oxide nanoparticles in composites containing them.

The significant influence of the nanoparticle concentration and its distribution on the outcomes was investigated by subgroup analyses. Higher concentrations produced more antibacterial effects, but these higher levels caused agglomeration and also adversely affected mechanical properties. Dual benefit nanoparticles, including those with combined antimicrobial agents and remineralizing properties, demonstrated multifunctional capability but were not optimized properly for clinical application.

Evidence of certainty was assessed using the GRADE framework. For the mechanical properties of nanocomposite resins, certainty was graded as low due to in vitro dominance and variability in formulations. Antimicrobial efficacy was graded as moderate, but it was limited by single-species biofilm models. Biocompatibility data were graded as very low due to the absence of clinical validation.

Most studies were underexplored in terms of long-term performance and biocompatibility. Less than 25% of studies used simulated oral conditions, and only a handful used multispecies biofilms. Future research should concentrate on these domains and validate them to achieve more clinical significance.

Table 1: Key Characteristics and Outcomes of Studies on Nanocomposite Resins in Restorative Dentistry

Study Details	Study Design	Material Type	Key Outcomes	Limitations
Pavanello et al., 2023, Brazil, UK[11]	Experimental study	Silica nanoparticles loaded with chlorhexidine (CHX-SNPs)	Improved antimicrobial activity against S. mutans, S. mitis, and S. gordonii. Enhanced flexural strength.	Limited to in vitro study; no clinical trial validation. Limited durability data beyond antimicrobial activity.
Garcia et al., 2020, Brazil, USA[12]	Experimental study	Adhesives with ZnO nanoparticles (2.5-7.5% w/w)	Antibacterial efficacy increased at 7.5% ZnO. Flexural strength is reduced at higher ZnO concentrations.	Adhesive properties are affected by high ZnO levels. Biofilm testing under limited in vitro conditions.
Barot et al., 2020, India[13]	In vitro study	Nanocomposite resin with silver nanoparticle immobilized halloysite nanotubes (HNT/Ag) vs. conventional glass fillers	Improved mechanical properties (e.g., flexural strength at 5% HNT/Ag), significant antibacterial activity against S. mutans. Negligible cytotoxicity on NIH-3T3 cell lines.	Agglomeration of HNT/Ag at higher concentrations reduced mechanical properties. Cytotoxicity not tested in vivo.
Bai et al., 2020, China[14]	Experimental study	Zn-doped mesoporous silica nanoparticles (Zn-MSNs)	Improved mechanical properties (flexural strength, compressive strength). Antimicrobial properties (100% antibacterial rate with 15 wt.% Zn-MSNs).	Long-term antibacterial performance stability and potential filler release impacts were not deeply explored.
Alhussein et al., 2023, USA[15]	In vitro study	Low-shrinkage-stress nanocomposites containing DMADDM, calcium fluoride (nCaF2), and calcium phosphate (NACP)	Flexural strength is comparable to commercial composites. Reduced S. mutans biofilm CFU by 6 logs. Diminished biofilm metabolic activity and lactic acid synthesis by 90%.	Did not include long-term performance testing. Focused only on S. mutans as a model for biofilm.
Ipe et al., 2020, Australia[16]	Experimental study	Silver nanoparticles (AgNPs)	Biocompatible doses of AgNPs synergistically enhanced antibiotic effects and reduced bacterial growth, particularly in resistant strains.	Focused on antibiotic synergy; did not include long-term effects or specific dental applications.
Barot et al., 2020, India[17]	Experimental study	Halloysite nanotubes (HNT) loaded with chlorhexidine	Enhanced mechanical properties (compressive/flexural strength), depth of cure, and antibacterial properties. No cytotoxicity was observed with HNT/CHX fillers.	Limited range of bacterial species tested. Real-world application in clinical settings needs further validation.
Mirhashemi et al., 2021, Iran[18]	In vitro experimental study	Composite resins containing 1%, 2%, and 5% nano-silver (NAg) particles	Significant decrease in bacterial colonies (up to 99.93% reduction). The antibacterial effect increased with NAg concentration. Growth inhibition zones were	No inhibition zones for 1% and 2% NAg concentrations. Limited applicability to clinical settings due to experimental conditions. Potential effects on

Saleem et al., 2022, Pakistan, Saudi Arabia, USA[19]	In vitro study	Selenium-doped ZnO nanoparticles as antibacterial nanofillers	Enhanced antibacterial activity. Improved mechanical strength. Effective against biofilm-forming pathogens at low concentrations.	No exploration in multispecies biofilm environments.
Nikolaidis et al., 2021, Greece[20]	In vitro study	Nanocomposite resins with quaternary ammonium silane-modified silica nanoparticles.	Improved mechanical properties (flexural modulus ↑74%, compressive strength ↑19%). Antimicrobial activity was observed.	Lacked data on long-term clinical performance. Cytotoxicity studies are pending.
Tanaka et al., 2020, Brazil, Australia[21]	In vitro study	Chitosan with/without DCPA particles in composites	Maintained mechanical properties. Significant biofilm reduction. Non-toxic to dental pulp fibroblasts.	Single-species biofilm test. Needs multispecies evaluation.
Yang et al., 2021, China[22]	In vitro study	Core-shell CHX/ACP nanoparticles incorporated into resin composite	Enhanced mechanical strength. Sustained antimicrobial effect (>92% against S. mutans). Remineralization properties.	Focused on S. mutans. Potential broader bacterial efficacy not tested. Long-term in vivo data missing.

Table 2: Assessment of Risk of Bias using Cochrane Risk of Bias Tool

Study	Sequence Generation – Selection Bias	Allocation Sequence Concealment – Selection Bias	Blinding of Participants and Personnel – Performance Bias	Blinding of Outcome Assessment – Detection Bias	Incomplete Outcome Data	Selective Outcome Reporting	Other Bias
Pavanello et al., 2023, Brazil, UK[11]	+	±	±	+	+	+	±
Garcia et al., 2020, Brazil, USA[12]	+	±	+	±	±	+	±
Barot et al., 2020, India[13]	+	+	+	±	±	+	±
Bai et al., 2020, China[14]	+	±	±	+	+	+	±
Alhussein et al., 2023, USA[15]	+	±	+	±	±	+	±
Ipe et al., 2020, Australia[16]	+	+	+	+	±	+	±
Barot et al., 2020, India[17]	+	±	+	±	±	+	±
Mirhashemi et al., 2021, Iran[18]	+	±	±	+	±	+	±
Saleem et al., 2022, Pakistan, Saudi Arabia, USA[19]	+	±	+	±	±	+	±
Nikolaidis et al., 2021, Greece[20]	+	±	±	+	+	+	±
Tanaka et al., 2020, Brazil, Australia[21]	+	±	+	±	±	+	±
Yang et al., 2021, China[22]	+	±	±	+	+	+	±

Table 2 provides an overview of the risk of bias across different studies on nanocomposite resins used in restorative dentistry. The studies vary in terms of study design, material types, and the outcomes evaluated.

Each study in Table 2 explores different nanocomposite resin types for dental restoration through tests of mechanical properties combined with antimicrobial testing and biological compatibility analysis. Studies currently lack long-term clinical validation for the use of these materials because they conduct research in vitro instead of validating their actual clinical applications. Most research investigates only a limited spectrum of bacterial species and fails to show how the materials perform over extended periods and which affects their potential practical dental usage. All studies demonstrate value but investigators agree that their structural weaknesses and material selection choices, along with clinical verification, need further development.

Bias Key:

- **"+"**: Low risk of bias (methodology is sound and well-executed)
- **"±"**: Unclear or moderate risk of bias (potential methodological concerns or insufficient reporting)
- **"-"**: High risk of bias (significant methodological flaws or biases)

This risk of bias assessment is essential for understanding the strengths and weaknesses of each study, helping researchers and practitioners interpret the findings accurately.

DISCUSSION

The objective of this review was to compare the nanocomposite resins to determine their durability performance along with their antimicrobial properties. Stepwise nanocomposite resins have transformed restorative dentistry through their solution of established restoration problems including mechanical damage and microbial growth.

Literature evidence showed that nanocomposites excel past traditional composites when multiple properties are assessed. The combination of zinc-doped mesoporous silica and quaternary ammonium silane-modified silica nanoparticles increases the flexural and compressive strength of these materials according to research findings which demonstrate their durability under high functional stresses[23,24]. The optimal terminology for nanoparticles presents a continuing problem because it requires precision-based selection to achieve sufficient mechanical stability and antimicrobial success. Zinc oxide nanoparticles exceeding certain concentrations lead to flexural strength reduction according to research so precise formulations must be used to prevent these adverse effects[25,26].

The available research showed that nanocomposites effectively fight biofilm formation and control microbial growth as established by multiple studies. The research shows AgNP nanoparticles embedded in nanocomposites achieve up to 99.93% reduction in bacterial colonies and selenium-doped zinc oxide nanoparticles inhibit biofilm formation[27,28]. The studies demonstrate that nanocomposites can decrease secondary caries along with other microbial infections[29,30]. Most research has conducted biofilm studies with a single bacterial species. Direct investigations in vivo and experiments using multispecies biofilms must become the focus of studying biofilms from actual clinical settings[31]. The research requires additional depth into both long-term clinical proof and understanding of oral environmental stressors including thermal cycling together with interactions with saliva[32].

Studies have evaluated the toxicity of halloysite nanotubes along with core-shell nanoparticles although their safety level is still ambiguous and needs extension testing with different cellular types in various situations[33,34]. Nanocomposite adoption depends on solving their production and disposal environmental issues through sustainable manufacturing techniques[35].

Nanoparticles provide opportunities to integrate mechanical strength and antimicrobial functions as well as the addition of remineralization agents to the materials. Nanoparticles designed with both chlorhexidine and amorphous calcium phosphate operate as core-shell structures that fight off biofilms while rebuilding enamel[36,37]. Multiple features built into these materials would boost their clinical usage capabilities which results in better patient treatment outcomes.

The essential limitation consists of inconsistent oral health states. The operational quality of nanocomposites relies significantly on pH instability alongside temperature modifications and dietary behavior patterns. Future scientific inquiries need to create laboratory simulations of oral conditions to predict how nanocomposites behave clinically[38,39]. Researchers have extensively studied antibacterial behavior yet they have not extensively investigated antifungal and antiviral properties of nanocomposites. Future studies need to explore the wider antimicrobial properties of these materials since fungal infections continue to grow primarily among immunocompromised patients[40].

Emerging technologies such as 3D printing find seamless integration with nanocomposites which creates additional possibilities for customized and precise dental restorations[41,42]. The continuous development of nanocomposite resins presents opportunities to merge them with emerging manufacturing technologies which will create revolutionary advancements in dentistry[43].

The current research on nanocomposites in restorative dentistry showed potential but specific areas such as clinical verification and extended observation periods require additional investigation. Future research priorities include (1) long-term in vivo investigations to analyze material effectiveness under clinical application (2) study of extended antimicrobial effect beyond bacteria which includes fungal and viral protection properties and (3) sustainability and environmental impact assessment specific to nanocomposite manufacturing methods and (4) evaluation of nanocomposite compatibility with modern techniques that may include 3D printing. These knowledge gaps must be solved to advance laboratory-based nanocomposite clinical applications that will produce better patient results worldwide (43).

CONCLUSION

The mechanical properties and antimicrobial efficacy of nanocomposite resins have shown tremendous potential in restorative dentistry. In this study, the integration of nanoparticles such as silver and zinc oxide were seen to increase the strength and bacterial reduction rates. Despite these benefits, challenges like nanoparticle agglomeration, limited long-term performance data, and limited multispecies biofilm testing remained. To optimize the application of these agents and patient safety, they needed to be refined in formulations as well as should have completed rigorous clinical trials.

LIST OF ABBREVIATIONS

AgNPs - Silver Nanoparticles
ZnO - Zinc Oxide
HNTs - Halloysite Nanotubes
CHX - Chlorhexidine
SNPs - Silica Nanoparticles
Zn-MSNs - Zinc-doped Mesoporous Silica Nanoparticles
DMADDM - Dimethylaminohexadecyl Methacrylate
nCaF2 - Nano Calcium Fluoride
NACP - Nano Amorphous Calcium Phosphate
NAg - Nano Silver
CFU - Colony-Forming Units
DCPA - Dicalcium Phosphate Anhydrous
PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses
MeSH - Medical Subject Headings

AUTHORS' CONTRIBUTIONS

All authors contributed equally as per ICMJE.

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