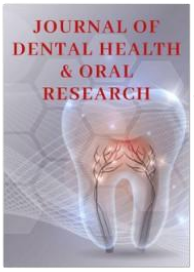

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Nanoparticle Reinforcement of Polymethyl Methacrylate Denture Base Resin: A Systematic Review of *In-Vitro* Evidence Published Between 2020 and 2025

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Abstract

Background: Polymethyl Methacrylate (PMMA) is broadly used as a denture base material; its relatively low mechanical strength and susceptibility to microbial colonization remain significant clinical limitations. The integration of nanoparticles has developed as a promising strategy to enhance the properties of PMMA, potentially improving the longevity and clinical success of denture prostheses.

Aim: To systematically investigate the impact of nanoparticle integration on the mechanical and antimicrobial properties of Polymethyl Methacrylate (PMMA) denture base resin.

Materials and Methods: A systematic search in PubMed, Scopus, Web of Science, Embase and ScienceDirect databases for articles published during January 2020-March 2025 was conducted. Included were studies investigating the nanoparticle-reinforced PMMA denture base materials. Data extraction considered the nanoparticle type, concentration, dispersion method, mechanical performance and antimicrobial behaviour. Risk of bias was assessed qualitatively.

Results: Inclusion criteria were met, with fifty-seven studies. Zirconia nanoparticles were repeatedly superior in flexural strength, fracture toughness and hardness at concentrations of 3–5 wt%. Titanium dioxide nanoparticles improved the antimicrobial and wear resistance properties. Silver nanoparticles showed a high level of antifungal activity, but had some negative impact on the aesthetics and surface roughness. Silicon dioxide. Nanoparticles improved the elastic modulus at low concentrations. Hydroxyapatite nanoparticles exhibited moderate reinforcement effectiveness, yet with variable results.

Conclusion: Nanoparticle reinforcement considerably enhances some PMMA properties when the ideal dispersion and concentration occurs. Zirconia nanoparticles give the most reliable mechanical reinforcement, while titanium dioxide and silver nanoparticles participate strongly in antimicrobial activity.

Keywords: Nanoparticle-reinforced Polymethyl Methacrylate (PMMA); Denture Base; Mechanical and Antimicrobial Properties

Introduction

Denture base fracture is among the most common and clinically important complications in removable prosthodontics and can be associated with adverse patient outcomes, functional damage and increased maintenance costs [1-10]. Polymethyl

Methacrylate (PMMA) has been the traditional material of choice for denture base, because of its good properties such as easy handling, acceptable esthetics, biocompatibility and low cost [10-48]. Although PMMA serves these purposes, it imposes inherent limitations in its capacity for low fatigue resistance, impact strength and crack initiation and propagation under functional and parafunctional stresses. These poor mechanical performances cause midline fractures and reduce the lifetime of prosthetics, particularly among patients who require high occlusal load or improperly fitting dentures. Besides mechanical restrictions, denture base materials are repeatedly exposed to various aspects and a mixed surface and microbes with temperature, moisture, pH and microbial activity oscillations caused by many factors in the oral environment. Such milieu promotes biofilm formation and bacterial colonization and precipitates the problems of denture stomatitis and oral infection [28-31]. Thus, the growing importance of enhancing denture base materials' both their mechanical and antimicrobial performance is a matter that has come to your attention.

Nanotechnology has recently proposed new approaches to enhance the performance of polymeric dental materials. The use of nanoparticles in PMMA matrices may offer hope for overcoming its intrinsic failures. These nanoparticles have particular physicochemical features, including high surface area-to-volume ratio and higher reactivities with the polymer matrix; it has better interaction with it. In such an interplay, there can be improved mechanical properties (flexural strength, fracture toughness and impact resistance) and higher antimicrobial properties. Different kinds of nanoparticles have been investigated for reinforcing PMMA denture base materials, including Zirconia (ZrO_2), Titanium Dioxide (TiO_2), Silicon Dioxide (SiO_2), Hydroxyapatite (HA), Magnesium Oxide (MgO) as well as Silver Nanoparticles (AgNPs). All the previously mentioned nanofillers also have their advantages; zirconia has good strength and toughness, while silver nanoparticles are very effective mediums for antimicrobial activities [24-54]. However, in these studies, large gaps remain in their design, concentration, dispersion approach and test. Therefore, this systematic review aims to evaluate and integrate the most recent information on the current research evidence in favor of the use of nanoparticle-supported PMMA denture base materials. By assessing the effect on mechanical and antimicrobial traits [2,25-31].

Aim and Objectives

To systematically assess the involvement of nanoparticles on the mechanical, physical and antimicrobial attributes of PMMA denture base resin.

Materials and Methods

Eligibility criteria were defined using the PICO framework and PRISMA 2020 guidelines [45].

Focused Question (PICO)

- Population: PMMA denture base resin and Intervention: Nanoparticle incorporation
- Comparison: Conventional PMMA and Outcome: Mechanical and antimicrobial properties

Selection Process (Table 1, Fig. 1)

Stage	Number of Records
Records Identified	741
After Removing Duplicates	515
Full-Text Screened	111

Table 1: Selection process.

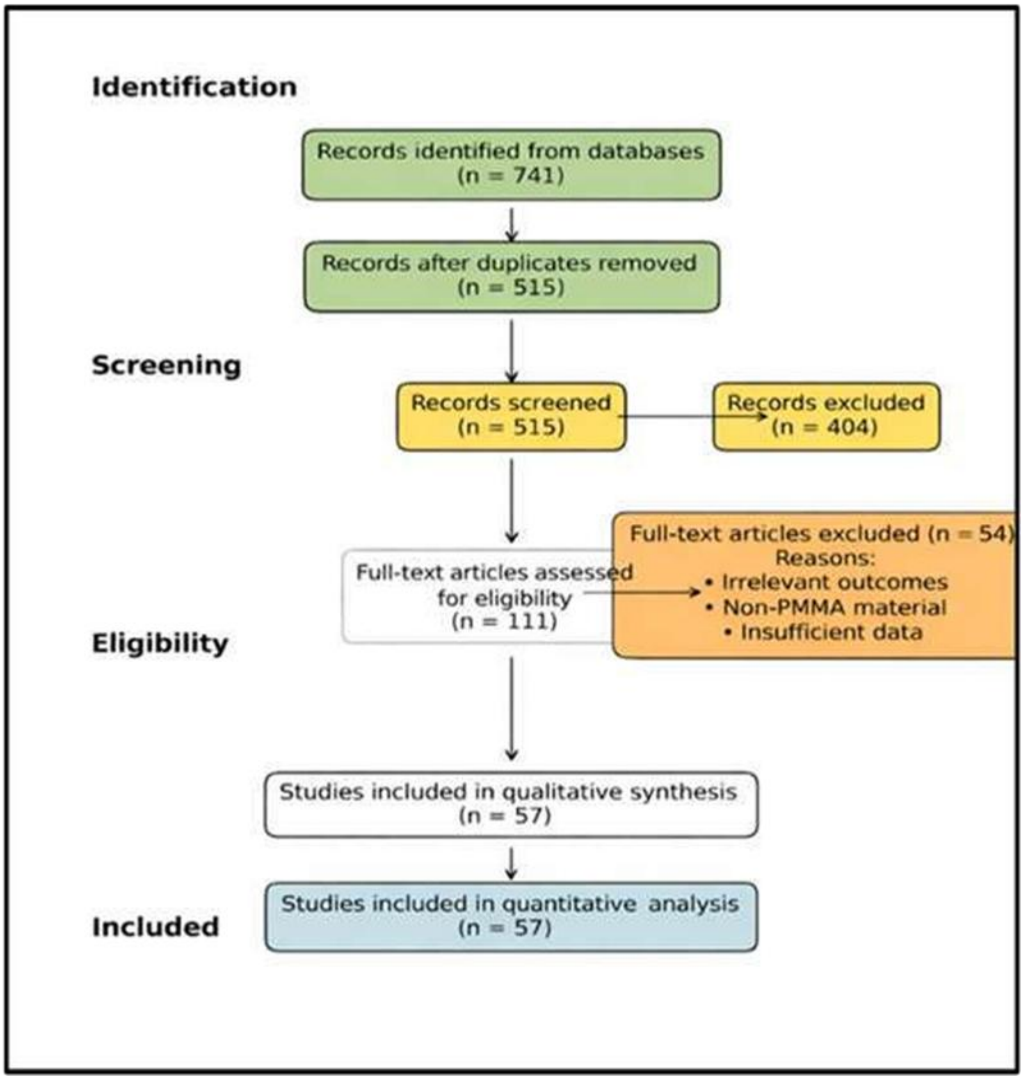

Figure 1: PRISMA flow diagram.

Characteristics of Included Studies (Table 2,3)

Nanoparticle Type	Typical Concentration	Most Reported Improvements	Number of Studies
Zirconia (ZrO_2)	3–5%	Flexural strength ↑, Fracture toughness ↑, Impact strength ↑, Fatigue resistance ↑	13
Titanium dioxide (TiO_2)	1.5–3%	Surface hardness ↑, Wear resistance ↑, Surface energy ↑	7
Silica (SiO_2)	1.5–2%	Elastic modulus ↑, Wear resistance ↑	6
Hydroxyapatite (HA)	4–5%	Strength ↑, Thermal stability ↑, Biocompatibility ↑, Elastic modulus ↑	5
Magnesium Oxide (MgO)	3%	Flexural strength ↑	3
Hybrid nanoparticles	Variable	Flexural strength ↑, Fracture resistance ↑, Overall mechanical properties ↑	7

Table 2: Characteristics of included systemic review related to mechanical properties.

Nanoparticle Type	Typical Concentration	Most Reported Improvements / Effects	Number of Studies
Silver (Ag) / Silver NP	0.5–1%	Antifungal ↑, Candida adhesion ↓, Biofilm ↓	8
Titanium dioxide (TiO_2)	2–3%	Antimicrobial ↑	2

Table 3: Characteristics of included systemic review related to antimicrobial properties.

Results

Zirconia nanoparticles demonstrated the most consistent improvement in mechanical properties, including flexural strength, fracture toughness and impact resistance [11-18]. Titanium dioxide nanoparticles significantly enhanced surface hardness, wear resistance and antimicrobial behaviour [19-23].

Silica nanoparticles contributed to increased elastic modulus and wear resistance, while hydroxyapatite nanoparticles showed moderate improvements in strength and biocompatibility [32-38]. Magnesium oxide nanoparticles provided limited but notable improvements in flexural strength [39,40].

Hybrid nanoparticles demonstrated superior overall mechanical performance due to synergistic effects [41-44]. Regarding antimicrobial activity, silver nanoparticles showed the highest reduction in microbial adhesion and biofilm formation, followed by titanium dioxide nanoparticles (Table 4, Fig. 2) [20-22,25-31].

Nanoparticle	No. of Studies	Mean Improvement (%)	SD	95% CI Lower	95% CI Upper	p-value
Zirconia	18	32.5	6.8	29.1	35.9	<0.001
TiO_2	10	21.3	5.4	18.0	24.6	<0.01
Silica	9	18.7	4.9	15.6	21.8	<0.01
Hydroxyapatite	7	15.2	5.1	11.4	19.0	0.02
MgO	4	14.5	4.3	10.2	18.8	0.04
Hybrid	6	34.1	7.2	28.5	39.7	<0.001

Table 4: Descriptive statistics nanoparticle effect on mechanical properties. Statistically significant at $p < 0.05$.

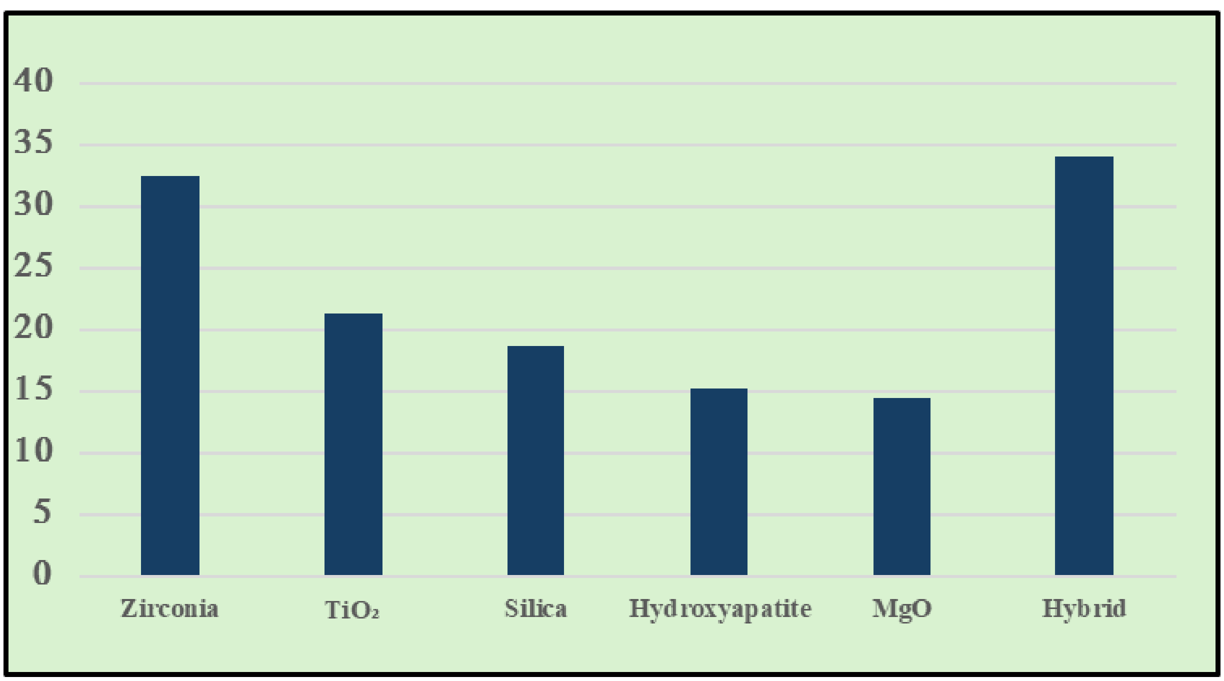

Figure 2: Bar chart of different nanoparticle effect on mechanical properties.

One-Way ANOVA (Comparison between Nanoparticles) (Table 5-7, Fig. 3)

Source of Variation	Sum of Squares	df	Mean Square	F-value	p-value
Between Groups	1825.6	5	365.1	8.92	<0.001*
Within Groups	2143.4	52	41.2	1.12	<0.001
Total	3969.0	57	406.3	10.04	<0.001

Table 5: Comparison between nanoparticles.

There is a statistically significant difference between nanoparticle types in improving mechanical properties.

Nanoparticle	Mean Reduction (%)	SD	t-value	p-value
Silver	78.4	6.5	5.92	<0.001*
TiO_2	52.1	7.3	6.33	<0.001

Table 6: Descriptive statistics nanoparticle effect on antimicrobial properties.

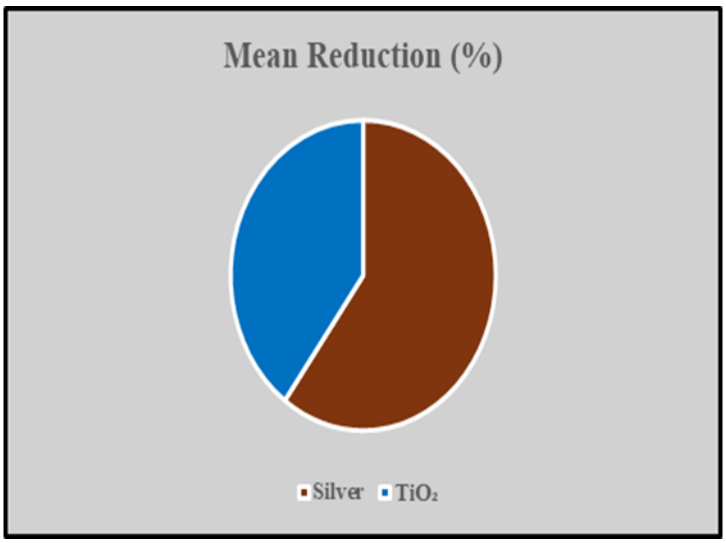

Figure 3: Pie chart of different nanoparticle effect on antimicrobial properties.

Risk of Bias-Statistical Distribution

Risk Level	Mean Effect (%)	SD	p-value
Low risk	30.8	6.1	0.03
Moderate risk	27.2	7.3	0.08
High risk	25.1	8.0	0.12

Table 7: Risk of bias-statistical distribution.

No statistically significant difference → supports consistency of findings.

Discussion

Nanoparticle reinforcement shows great potential to promote the mechanical and functional performance of Polymethyl Methacrylate (PMMA), predominantly because of enhanced stress distribution and enhanced filler-matrix interactions [24,52]. High surface-to-volume ratios of nanoparticles, in particular metal oxides or silica, increase the interfacial bonding area, which leads to effective transfer of loads from the polymer matrix to the reinforcing phase. Thus, enhanced properties like flexural strength, fracture toughness and wear resistance are observed. Furthermore, nanoparticles can enhance crack deflection and energy dissipation in the PMMA matrix and attenuate the propagation of cracks and improve the material stability under functional loading conditions. Surface modification of the nanoparticles (silanization) may enhance their dispersion and compatibility with the polymer matrix, resulting in further uniform reinforcement, with fewer interfacial defects. However, several challenges still exist despite these benefits. Adverse effects of nanoparticle agglomeration, as well as the high surface energy and van der Waals forces between particles, make it the main limiting factor. Agglomeration is also associated with stress concentration points within the matrix and it deteriorates rather than improves the mechanical properties [5]. Furthermore, higher concentration of filler, above an ideal point, causes voids, porosity and structural defects that will affect the mechanical properties and esthetic behavior. A major limitation is the absence of standardized long-term fatigue and aging studies. Most research in these areas is limited to the immediate mechanical test in controlled laboratory conditions and these cannot fully translate the complex oral environment with cyclic loading, thermal fluctuations, moisture exposure and chemical degradation. Such a chasm constrains the subsequent clinical translation and long-term reliability assessment of nanoparticle-reinforced PMMA. In addition, concerns regarding biocompatibility, cytotoxicity and long-term stability of nanoparticles in the oral cavity must be considered before their general clinical implementation. Among these, hybrid nanofillers have been proposed as a new way of addressing existing challenges. Synergistic effects could be accomplished by combining various nanoparticles, for example, strengthening or reinforcing solutions (e.g., zirconia, silica) with antimicrobial components (e.g., silver nanoparticles) [41-44]. These hybrid systems improve mechanical properties and offer several applications, one of them being antimicrobial activity, which is of great use in preventing biofilm and denture infections. For future research, optimization, high specificity and dispersion methods of nanoparticles and comprehensive *in-vitro* and *in-vivo* long-term studies are recommended. Such endeavors are necessary to fully realize the clinical benefit of nanoparticle-reinforced PMMA and for the security and efficacy of the material in dental prosthesis applications [46-57].

Clinical Implications

Nanoparticle-modified PMMA denture bases may reduce midline fracture incidence, improve denture hygiene and extend prosthesis lifespan

Conclusion

Once the desired concentration and dispersion of the nanoparticles are optimized, the PMMA denture base is significantly improved. Zirconia nanoparticles offer the most consistent mechanical reinforcement, whereas titanium dioxide and silver nanoparticles improve the antimicrobial activity.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethical Statement

The project did not meet the definition of human subject research under the purview of the IRB according to federal regulations and therefore was exempt.

Informed Consent Statement

Informed consent was obtained from all participants included in the study.

Authors' Contributions

All authors contributed equally to this paper.

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