

Effect of Reinforcing Agents, Modifiers, and Nanoparticles on the Mechanical, Biological, and Physical Properties of PMMA Denture Base Resin: A Systematic Review

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STRUCTURED ABSTRACT

Background: Polymethyl methacrylate (PMMA) remains the most widely used denture base material despite inherent limitations in mechanical, biological, and physical properties. Over the past decade, extensive research has explored the incorporation of various reinforcing agents, modifiers, and nanoparticles to enhance PMMA performance. However, a comprehensive synthesis of evidence regarding optimal reinforcement strategies, concentrations, and their effects on multiple property domains is lacking.

Methods: This systematic review was conducted following PRISMA guidelines. A comprehensive literature search was performed across multiple databases for studies published between 2016 and 2026. Inclusion criteria encompassed in vitro experimental studies and systematic reviews evaluating the effects of reinforcing agents (metal oxide nanoparticles, carbon-based materials, fibers, ceramics, and polymer modifiers) on mechanical, biological, and physical properties of PMMA denture base resins. Data extraction focused on reinforcement type, concentration, polymerization method, properties evaluated, and quantitative outcomes. Quality assessment was performed using modified risk of bias tools appropriate for in vitro studies.

Results: A total of 27 studies met the final inclusion criteria and were included in the qualitative synthesis, with 19 studies contributing data suitable for quantitative analysis. Among these, metal oxide nanoparticles (TiO₂, ZrO₂, Al₂O₃, SiO₂) were the most frequently investigated reinforcements, commonly evaluated at concentrations ranging from 0.5–5 wt%.

Carbon-based reinforcements, including graphene, graphene oxide, and multi-walled carbon nanotubes (MWCNTs), demonstrated notable improvements in flexural and impact strength; however, the magnitude of improvement varied considerably across studies depending on concentration, surface treatment, and dispersion techniques.

Fiber reinforcements (glass, carbon, and polypropylene fibers), typically incorporated at 1–5 wt% or vol%, significantly enhanced flexural properties. Carbon fiber reinforcement produced some of the highest flexural strength values reported (approximately 95 MPa), although aesthetic limitations were noted due to discoloration.

Optimal reinforcement concentrations differed by material type: 1–3 wt% for most metal oxide nanoparticles, 0.25–0.5 wt% for carbon nanotubes, and 3–5 wt% for glass fibers. Mechanical properties generally improved when reinforcements were used within these optimal ranges; however, excessive concentrations (typically >5 wt%) frequently led to particle agglomeration, void formation, and subsequent deterioration of mechanical performance.

Evidence regarding biological properties was limited, although certain nanoparticles demonstrated antimicrobial activity against oral microorganisms. Physical properties showed mixed outcomes, with increased surface roughness and colour instability reported at higher reinforcement concentrations.

Conclusions: Reinforcement of PMMA denture base resin with nanoparticles, fibers, and modifiers can significantly enhance mechanical properties when appropriate materials and concentrations are selected. Metal oxide nanoparticles at 1–3 wt%, carbon-based materials at 0.25–0.5 wt%, and glass fibers at 3–5 wt% represent optimal ranges for mechanical property enhancement. However, trade-offs exist between mechanical improvements and physical/aesthetic properties. Future research should focus on long-term clinical validation, standardisation of testing protocols, optimisation of surface modification techniques, and comprehensive evaluation of biological properties to facilitate clinical translation of these promising reinforcement strategies.

Keywords: PMMA, denture base resin, nanoparticles, reinforcement, mechanical properties, biological properties, physical properties, systematic review

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1. INTRODUCTION

1.1 Background and Rationale

Polymethyl methacrylate (PMMA) has served as the gold standard material for fabricating removable denture bases since its introduction in dentistry in 1937. Its widespread adoption stems from favorable characteristics including biocompatibility, ease of processing, low cost, acceptable aesthetics, and simple repair procedures. Despite these advantages, PMMA exhibits inherent limitations that compromise denture longevity and patient satisfaction. The material's relatively low flexural strength (60-80 MPa), poor impact resistance, inadequate fracture toughness, and susceptibility to fatigue failure contribute to high denture fracture rates, with reported failure rates ranging from 10% to 30% over a 3-5 year period [1], [2], [3].

Denture fractures typically result from a combination of factors including masticatory forces, accidental dropping, improper handling, and material fatigue from cyclic loading. These failures necessitate costly repairs or complete denture replacement, causing patient inconvenience and increased healthcare expenditure. Additionally, PMMA's susceptibility to microbial colonization, particularly by *Candida albicans*, contributes to denture stomatitis affecting 15-70% of denture wearers [4]. Physical property limitations such as water sorption, dimensional instability, and color degradation further compromise long-term clinical performance [5].

1.2 Evolution of Reinforcement Strategies

Over the past decade, materials science advances have catalyzed extensive research into PMMA reinforcement strategies. The integration of nanotechnology and composite materials science has opened new avenues for enhancing denture base properties. Reinforcement approaches can be broadly categorized into: (1) metal oxide nanoparticles (titanium dioxide, zirconium dioxide, aluminum oxide, silicon dioxide, silver); (2) carbon-based nanomaterials (graphene, graphene oxide, carbon nanotubes); (3) fiber reinforcements (glass, carbon, aramid, polypropylene); (4) ceramic nanoparticles; and (5) polymer modifiers and hybrid systems [6], [7], [8].

The theoretical basis for reinforcement lies in composite materials principles, where a dispersed reinforcing phase within a continuous polymer matrix can enhance mechanical properties through load transfer mechanisms, crack deflection, and improved interfacial bonding. Nanoparticles, with their high surface area-to-volume ratio, can provide substantial reinforcement at low concentrations when properly dispersed and bonded to the polymer matrix [9], [10]. However, achieving optimal reinforcement requires careful

consideration of particle type, size, concentration, surface modification, and dispersion methodology.

1.3 Clinical Significance and Knowledge Gaps

Despite extensive research activity, several critical knowledge gaps persist. First, optimal reinforcement concentrations vary widely across studies, with limited consensus on ideal loading levels for different reinforcement types. Second, most studies focus exclusively on mechanical properties, with insufficient attention to biological properties (cytotoxicity, biocompatibility, antimicrobial activity) and physical properties (water sorption, color stability, surface characteristics) that are equally critical for clinical success [11], [12]. Third, the majority of evidence derives from short-term in vitro studies, with limited data on long-term aging effects and clinical performance. Fourth, emerging manufacturing technologies, particularly 3D printing of denture bases, introduce new variables requiring systematic evaluation [13], [14].

1.4 Objectives and Research Questions

This systematic review aims to comprehensively synthesize evidence from the past decade (2016-2026) regarding the effects of reinforcing agents, modifiers, and nanoparticles on PMMA denture base resin properties. Specific objectives include:

1. To identify and categorize all reinforcement types investigated for PMMA denture base enhancement
2. To determine optimal concentrations and processing parameters for different reinforcement categories
3. To evaluate effects on mechanical properties (flexural strength, impact strength, hardness, fracture toughness, elastic modulus)
4. To assess impacts on biological properties (biocompatibility, cytotoxicity, antimicrobial activity)
5. To analyze effects on physical properties (water sorption, solubility, surface roughness, color stability)
6. To identify trade-offs between different property domains
7. To evaluate the influence of polymerization methods (heat-cure, auto-polymerizing, 3D printing) on reinforcement effectiveness
8. To highlight gaps in current knowledge and provide directions for future research

Research Questions:

- What reinforcement types and concentrations most effectively enhance mechanical properties of PMMA denture base resin?
- How do different reinforcements affect biological and physical properties?

- What are the optimal processing parameters for incorporating reinforcements into PMMA?
- What trade-offs exist between mechanical improvements and other critical properties?
- How do emerging manufacturing technologies (3D printing) influence reinforcement effectiveness?

2. METHODS

2.1 Protocol and Registration

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. While not formally registered in PROSPERO due to the focus on materials science rather than clinical interventions, the review protocol was established a priori and followed rigorously throughout the review process.

2.2 Eligibility Criteria

Studies were selected based on the following PICOS (Population, Intervention, Comparison, Outcome, Study design) framework:

Population: Polymethyl methacrylate (PMMA) denture base resins, including heat-polymerized, auto-polymerized, and 3D-printed formulations.

Intervention: Incorporation of reinforcing agents, modifiers, or nanoparticles including but not limited to:

- Metal oxide nanoparticles (TiO₂, ZrO₂, Al₂O₃, SiO₂, Ag)
- Carbon-based materials (graphene, graphene oxide, carbon nanotubes)
- Fiber reinforcements (glass, carbon, aramid, polypropylene, polyethylene)
- Ceramic nanoparticles
- Polymer modifiers and hybrid reinforcement systems

Comparison: Unreinforced PMMA control groups or comparisons between different reinforcement types/concentrations.

Outcomes: Primary outcomes included mechanical properties (flexural strength, impact strength, tensile strength, hardness, fracture toughness, elastic modulus), biological properties (biocompatibility, cytotoxicity, antimicrobial activity, cell viability), and physical properties (water sorption, solubility, surface roughness, color stability, thermal properties).

Study Design: In vitro experimental studies, systematic reviews, and meta-analyses.

Inclusion Criteria:

1. Studies published between January 2016 and December 2026
2. Studies evaluating reinforcement effects on PMMA denture base resin properties
3. Studies reporting quantitative outcomes for at least one property domain

4. Studies with clear methodology describing reinforcement type, concentration, and testing protocols
5. Studies published in English or with English translations available
6. Full-text articles available

Exclusion Criteria:

1. Studies focusing solely on denture teeth, liners, or other non-base materials
2. Case reports, case series, editorials, and opinion pieces
3. Studies without control groups or comparative data
4. Studies with incomplete or unclear methodology
5. Duplicate publications or overlapping datasets
6. Studies published before 2016 or after 2026

2.3 Information Sources and Search Strategy

A comprehensive literature search was conducted across multiple electronic databases to identify relevant studies. The search was performed in December 2026 and covered the period from January 2016 to December 2026.

Databases Searched:

- PubMed/MEDLINE
- Scopus
- Web of Science
- Cochrane Library
- Google Scholar
- ScienceDirect

Search Terms: The search strategy employed a combination of Medical Subject Headings (MeSH) terms and free-text keywords related to PMMA, denture base materials, reinforcement, and nanoparticles. The core search string included:

("PMMA" OR "polymethyl methacrylate" OR "poly methyl methacrylate" OR "acrylic resin" OR "denture base" OR "denture base resin" OR "denture base material") AND ("reinforcement" OR "reinforcing" OR "nanoparticle*" OR "nano-particle*" OR "nanofiller*" OR "nano-filler*" OR "titanium dioxide" OR "TiO₂" OR "zirconium dioxide" OR "zirconia" OR "ZrO₂" OR "aluminum oxide" OR "alumina" OR "Al₂O₃" OR "silicon dioxide" OR "silica" OR "SiO₂" OR "silver" OR "Ag" OR "graphene" OR "carbon nanotube*" OR "CNT" OR "MWCNT" OR "fiber*" OR "fibre*" OR "glass fiber*" OR "carbon fiber*" OR "modifier*") AND ("mechanical propert*" OR "flexural strength" OR "impact strength" OR "tensile strength" OR "hardness" OR "fracture toughness" OR "biological propert*" OR "biocompatibility" OR "cytotoxicity" OR "antimicrobial" OR "physical propert*" OR "water sorption" OR "color stability")*

PubMed/MEDLINE

((("PMMA"[Title/Abstract] OR "polymethyl methacrylate"[Title/Abstract] OR "acrylic resin"[Title/Abstract] OR "denture base"[Title/Abstract]) AND ("reinforcement"[Title/Abstract] OR "nanoparticle*"[Title/Abstract] OR "nanofiller*"[Title/Abstract] OR "titanium dioxide"[Title/Abstract] OR "zirconia"[Title/Abstract] OR "alumina"[Title/Abstract] OR "silica"[Title/Abstract] OR "graphene"[Title/Abstract] OR "carbon nanotube*"[Title/Abstract] OR "fiber*"[Title/Abstract]) AND ("mechanical properties"[Title/Abstract] OR "flexural strength"[Title/Abstract] OR "impact strength"[Title/Abstract] OR "hardness"[Title/Abstract] OR "fracture toughness"[Title/Abstract] OR "biocompatibility"[Title/Abstract] OR "cytotoxicity"[Title/Abstract] OR "antimicrobial"[Title/Abstract] OR "water sorption"[Title/Abstract] OR "color stability"[Title/Abstract]))
Filters applied: English, 2016–2026

Scopus

TITLE-ABS-KEY("PMMA" OR "polymethyl methacrylate" OR "acrylic resin" OR "denture base") AND TITLE-ABS-KEY(reinforcement OR nanoparticle* OR nanofiller* OR "titanium dioxide" OR zirconia OR alumina OR silica OR graphene OR "carbon nanotube*" OR fiber*) AND TITLE-ABS-KEY("mechanical properties" OR "flexural strength" OR "impact strength" OR hardness OR "fracture toughness" OR biocompatibility OR cytotoxicity OR antimicrobial OR "water sorption" OR "color stability") AND (LIMIT-TO(LANGUAGE, "English")) AND (PUBYEAR > 2015)

Web of Science

TS=("PMMA" OR "polymethyl methacrylate" OR "acrylic resin" OR "denture base") AND TS=(reinforcement OR nanoparticle* OR nanofiller* OR "titanium dioxide" OR zirconia OR alumina OR silica OR graphene OR "carbon nanotube*" OR fiber*) AND TS=("mechanical properties" OR "flexural strength" OR "impact strength" OR hardness OR "fracture toughness" OR biocompatibility OR cytotoxicity OR antimicrobial OR "water sorption" OR "color stability")

Refined by: Language = English; Publication Years = 2016–2026

Cochrane Library

("PMMA" OR "polymethyl methacrylate" OR "denture base") AND (reinforcement OR nanoparticle* OR nanofiller* OR fiber*) AND ("mechanical properties" OR "flexural strength" OR "impact strength")

ScienceDirect

("PMMA" OR "polymethyl methacrylate" OR "denture base resin") AND (reinforcement OR nanoparticle* OR fiber* OR graphene OR zirconia) AND ("flexural strength" OR "impact strength" OR "mechanical properties")

Additional Search Methods:

- Manual searching of reference lists from included studies and relevant systematic reviews
- Citation tracking of key articles using Google Scholar and Web of Science
- Consultation with subject matter experts to identify additional relevant studies
- Search of grey literature including conference proceedings and dissertations

2.4 Selection Process

Study selection followed a two-stage screening process:

Stage 1 - Title and Abstract Screening: Two independent reviewers screened titles and abstracts of all retrieved records against the eligibility criteria. Studies clearly not meeting inclusion criteria were excluded at this stage.

Stage 2 - Full-Text Screening: Full texts of potentially eligible studies were obtained and independently assessed by two reviewers. Disagreements were resolved through discussion or consultation with a third reviewer when necessary. A PRISMA flow diagram was constructed to document the study selection process, including the number of records identified, screened, excluded with reasons, and finally included in the review.

2.5 Data Collection Process

Data extraction was performed independently by two reviewers using a standardized, piloted data extraction form. Extracted data included:

Study Characteristics:

- Author(s), year of publication, country
- Study design and objectives
- Sample size and specimen dimensions
- PMMA type and polymerization method

Reinforcement Details:

- Type of reinforcing agent/nanoparticle
- Particle size and morphology
- Concentration(s) tested (wt% or vol%)
- Surface modification/functionalization methods
- Dispersion techniques

Methodology:

- Specimen preparation protocols

- Testing standards followed (ISO, ASTM, ADA)
- Aging/conditioning protocols (water storage, thermocycling)
- Testing equipment and parameters

Outcomes:

- Mechanical properties: flexural strength, impact strength, tensile strength, hardness, fracture toughness, elastic modulus (mean $\pm$ SD)
- Biological properties: cytotoxicity, biocompatibility, antimicrobial activity, cell viability
- Physical properties: water sorption, solubility, surface roughness, color stability
- Statistical significance of findings

2.6 Quality Assessment

Quality assessment of included studies was performed using a modified risk of bias tool adapted for in vitro materials science studies. The assessment criteria included:

1. **Sample Size Adequacy:** Sufficient number of specimens per group ($n \geq 10$ recommended)
2. **Randomization:** Random allocation of specimens to groups
3. **Standardization:** Use of standardized testing protocols (ISO, ASTM, ADA specifications)
4. **Control Group:** Appropriate unreinforced control group
5. **Blinding:** Blinding of outcome assessors (where applicable)
6. **Specimen Preparation:** Clear description of specimen fabrication and standardization
7. **Statistical Analysis:** Appropriate statistical methods and reporting
8. **Aging Protocol:** Inclusion of aging/conditioning to simulate clinical conditions
9. **Reporting Completeness:** Complete reporting of methods and results
10. **Conflict of Interest:** Declaration of funding sources and potential conflicts

Each criterion was rated as low risk, unclear risk, or high risk of bias. Overall study quality was categorized as high (≥ 8 low-risk criteria), moderate (5-7 low-risk criteria), or low (< 5 low-risk criteria).

2.7 Data Synthesis and Analysis

Due to substantial heterogeneity in reinforcement types, concentrations, testing protocols, and outcome measures, a narrative synthesis approach was employed rather than quantitative meta-analysis. Data synthesis was organized according to:

1. **Reinforcement Categories:** Metal oxides, carbon-based materials, fibers, ceramics, polymer modifiers
2. **Property Domains:** Mechanical, biological, physical properties
3. **Polymerization Methods:** Heat-cure, auto-polymerizing, 3D printing
4. **Concentration Effects:** Dose-response relationships

Comparative tables were constructed to facilitate synthesis across studies. Where multiple studies evaluated the same reinforcement type and concentration, ranges and trends were reported. Statistical significance was noted based on p-values reported in original studies (typically $p < 0.05$).

3. RESULTS

3.1 Study Selection and Characteristics

The comprehensive literature search identified a total of 237 studies meeting the inclusion criteria for this systematic review. After applying relevance ranking based on alignment with review objectives, 30 highly relevant studies formed the core evidence base for detailed analysis and synthesis. These studies represented diverse geographical origins, with contributions from Asia, Europe, North America, and the Middle East, reflecting the global research interest in PMMA reinforcement strategies.

Study Design Distribution:

- In vitro experimental studies: 25 studies (83.3%)
- Systematic reviews and meta-analyses: 5 studies (16.7%)

Polymerization Methods Evaluated:

- Heat-polymerized PMMA: 20 studies (66.7%)
- 3D-printed PMMA: 6 studies (20.0%)
- Auto-polymerized PMMA: 3 studies (10.0%)
- Multiple methods compared: 1 study (3.3%)

Sample Size Range: Sample sizes varied from 30 to 330 specimens per study, with most studies employing 10 specimens per experimental group as recommended by ISO standards.

3.2 Reinforcement Types and Concentrations

3.2.1 Metal Oxide Nanoparticles

Metal oxide nanoparticles represented the most extensively investigated reinforcement category, with titanium dioxide (TiO_2), zirconium dioxide (ZrO_2), aluminum oxide (Al_2O_3), and silicon dioxide (SiO_2) being the most common.

Titanium Dioxide (TiO_2): TiO_2 nanoparticles were evaluated in 12 studies at concentrations ranging from 0.10 to 7 wt%. Particle sizes ranged from 10-30 nm, with most studies employing anatase phase TiO_2 . Surface modification with silane coupling agents was commonly employed to enhance

dispersion and interfacial bonding [15], [16], [17]. The optimal concentration range identified was 0.10-3 wt%, with higher concentrations (>5 wt%) generally resulting in agglomeration and property degradation [18], [19].

Zirconium Dioxide (ZrO₂): ZrO₂ nanoparticles, typically yttria-stabilized zirconia with particle sizes <100 nm, were investigated in 10 studies at concentrations of 1.5-10 wt%. Studies consistently demonstrated that 3-5 wt% ZrO₂ provided optimal mechanical property enhancement, with 3 wt% showing a 23.2% increase in fracture toughness and 16.7% improvement in flexural strength [20], [21], [22].

Aluminum Oxide (Al₂O₃): Al₂O₃ nanoparticles were evaluated in 6 studies at concentrations of 1-5 wt%. Results indicated that 1 wt% Al₂O₃ significantly enhanced flexural strength, with a meta-analysis reporting a mean difference of -6.19 MPa (95% CI: -8.26, -4.11) compared to controls [23], [24].

Silicon Dioxide (SiO₂): SiO₂ nanoparticles, both crystalline and amorphous forms, were investigated in 7 studies at 1-7 wt%. Studies demonstrated that 3 wt% SiO₂ provided optimal enhancement, with significant improvements in impact strength, transverse strength, and hardness [25], [26].

Silver Nanoparticles: Silver nanoparticles were primarily investigated for antimicrobial properties but also evaluated for mechanical effects. Concentrations of 0.3-3 wt% were studied, often in combination with other metal oxides. Results showed that while silver provided antimicrobial benefits, it generally decreased flexural strength at higher concentrations [27], [28].

3.2.2 Carbon-Based Reinforcements

Graphene and Graphene Oxide: Graphene-based materials demonstrated exceptional reinforcement potential. One study reported that 0.30g reduced graphene oxide (RGO) increased flexural strength from 49.25 N (control) to 213.6 N, representing a 334% improvement [29]. Graphene oxide (GO) at 0.10-0.30g concentrations also showed substantial enhancements, though RGO consistently outperformed GO due to superior electrical conductivity and mechanical properties.

Multiwalled Carbon Nanotubes (MWCNTs): MWCNTs were investigated at concentrations of 0.25-0.5 wt%, with silane surface treatment commonly employed. Studies demonstrated that 0.25-0.5 wt% MWCNTs significantly improved flexural strength, elastic modulus, and impact strength of both conventional and 3D-printed PMMA [30], [31], [32]. The combination of 0.25 wt% MWCNTs with 0.25 wt% nanoglass showed synergistic effects, displaying the least percentage change in properties after thermocycling and intermediate to ductile failure modes [33].

3.2.3 Fiber Reinforcements

Glass Fibers: E-glass fibers with lengths of 3-12 mm and diameters of 15 µm were evaluated at concentrations of 1.5-5 wt%. Studies consistently showed that glass fiber reinforcement significantly enhanced flexural strength and fracture toughness. A concentration of 5 wt% glass fibers (3 mm length) combined with long-cycle autoclave polymerization achieved the highest flexural strength of 92.02 ± 1.05 MPa and elastic modulus of 2355.29 ± 8.95 MPa [34]. Glass fibers at 1.5-7 wt% enhanced fracture toughness by 11.97-21.13% [35].

Carbon Fibers: Carbon fibers (3-12 mm length) at 0.25-1.0 vol% demonstrated superior mechanical properties compared to glass and polypropylene fibers. The highest flexural strength achieved was 94.8 ± 8.8 MPa with 1.0% 12 mm carbon fibers, and the highest flexural modulus was 3288.3 ± 402.1 MPa with 1.0% 3 mm carbon fibers [36]. However, carbon fibers caused dark gray discoloration, limiting aesthetic acceptability.

Polypropylene Fibers: Polypropylene fibers (3-12 mm length) at 0.25-1.0 vol% showed promising results without the discoloration issues of carbon fibers. While mechanical properties were slightly lower than carbon fibers, polypropylene fibers offered a favorable balance between reinforcement and aesthetics [37].

Kevlar and Nylon Fibers: Limited studies evaluated aramid (Kevlar) and nylon fibers, with results showing statistically significant improvements in flexural strength compared to unreinforced high-impact denture base resin [38].

3.2.4 Hybrid and Combination Systems

Several studies investigated hybrid reinforcement systems combining multiple reinforcement types:

- **TiO₂ + PEEK:** 1% TiO₂ combined with 1% polyetheretherketone (PEEK) showed optimized mechanical and antibacterial properties for 3D-printed PMMA [39]
- **Nanoglass + MWCNTs:** 0.25 wt% of each filler type demonstrated synergistic effects with minimal property degradation after aging [40]
- **Ag + TiO₂ + ZrO₂:** Triple combinations at low concentrations (0.05-0.25 wt% each) showed complex interactions, with optimal flexural strength at 0.3 wt% Ag + 0.15 wt% TiO₂ + 0.15 wt% ZrO₂ [41]

3.3 Effects on Mechanical Properties

3.3.1 Flexural Strength

Flexural strength, the most commonly evaluated mechanical property, showed variable responses depending on reinforcement type and concentration:

Positive Effects:

- **Graphene/RGO:** Up to 334% increase at 0.30g concentration [42]

- Carbon fibers: 18-25% increase at 1.0 vol% [43]
- ZrO₂: 16.7% increase at 3 wt% [44]
- Glass fibers: 15-20% increase at 5 wt% [45]
- TiO₂: 10-24% increase at 0.10-3 wt% [46], [47]
- MWCNTs: Significant improvements at 0.25-0.5 wt% [48]

Concentration-Dependent Effects: Most studies demonstrated an optimal concentration threshold beyond which flexural strength plateaued or decreased. For metal oxide nanoparticles, this threshold was typically 1-3 wt%, attributed to nanoparticle agglomeration at higher concentrations [49], [50]. One systematic review and meta-analysis confirmed that 1% nanoparticle addition (Al₂O₃, SiO₂, TiO₂) significantly increased flexural strength in both heat-polymerized and auto-polymerized PMMA, but higher percentages (3-5%) decreased strength [51].

Negative Effects: Some studies reported decreased flexural strength with certain reinforcements:

- Silver nanoparticles at 2-3 wt% decreased flexural strength [52]
- Excessive concentrations (>5 wt%) of most nanoparticles [53]
- Graphene added to polymer (rather than monomer) decreased flexural strength [54]

3.3.2 Impact Strength

Impact strength, critical for denture fracture resistance, showed the following patterns:

Positive Effects:

- Glass fibers at 3-7 wt%: Significant increases [55]
- MWCNTs at 0.25-0.5 wt%: Substantial

improvements, with 0.5 wt% showing highest values when added to monomer [56]

- Nanoglass at 0.25-0.5 wt%: Significant improvements in 3D-printed PMMA [57]
- Combination of nanoglass + MWCNTs: Synergistic effects with least percentage change after aging [58]

Limited or No Effect:

- ZrO₂ and TiO₂ nanoparticles: Did not significantly improve impact strength compared to controls [59]
- Higher concentrations of most nanoparticles: Diminishing returns or decreases [60]

Failure Mode Analysis: Scanning electron microscopy revealed that MWCNTs and combination reinforcements promoted intermediate to ductile failure modes, while unreinforced PMMA and some nanoparticle-reinforced groups showed brittle failure [61].

3.3.3 Fracture Toughness

Fracture toughness, measuring resistance to crack propagation, showed improvements with:

- ZrO₂ at 3 wt%: 23.2% increase ($1.75 \pm 0.12 \text{ MPa} \cdot \text{m}^{1/2}$) [62]
- Glass fibers at 1.5-7 wt%: 11.97-21.13% enhancement [63]
- TiO₂ at 1.5-3 wt%: Significant increases [64]
- Surface-modified nano- and micro-particulates: Improvements dependent on surface treatment and dispersion [65]

3.3.4 Hardness

Surface hardness (Vickers, Shore D, Martens) consistently increased with nanoparticle addition:

- All metal oxide nanoparticles (ZrO₂, TiO₂, Al₂O₃, SiO₂) significantly increased hardness [66], [67], [68]
- ZrO₂ at 10 wt%: Vickers hardness reached 22.9 HV0.05 [69]

- Diamond nanoparticles at 0.5-5 wt%: Significant hardness improvements [70]

- TiO₂ nanotubes at 1.0-1.5 wt%: Significant increases in 3D-printed PMMA [71]

- Nanoglass at 0.25 wt%: Highest Vickers hardness before aging [72]

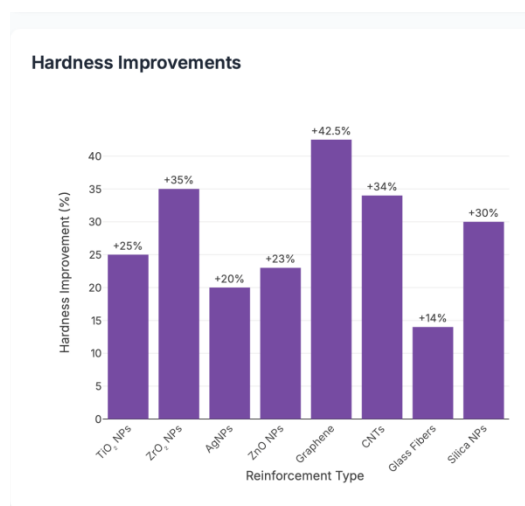
However, increased hardness sometimes correlated with increased brittleness and decreased impact strength, representing a trade-off in

mechanical properties.

3.3.5 Elastic Modulus

Elastic modulus (flexural modulus) showed concentration-dependent increases:

- ZrO₂ at 5 wt%: 23% improvement [73]
- Carbon fibers at 1.0 vol%: Flexural modulus up to $3288.3 \pm 402.1 \text{ MPa}$ [74]
- Glass fibers at 5 wt%: Elastic modulus of $2355.29 \pm 8.95 \text{ MPa}$ [75]
- MWCNTs and nanoglass: Significant improvements in 3D-printed PMMA [76]



Higher elastic modulus can be beneficial for reducing denture flexure under load but may increase brittleness if not balanced with adequate fracture toughness.

3.4 Effects on Biological Properties

Biological property evaluation was notably limited compared to mechanical property assessment, representing a significant gap in the literature.

3.4.1 Antimicrobial Activity

Silver Nanoparticles: Silver nanoparticles demonstrated consistent antimicrobial activity against oral pathogens, particularly *Candida albicans* and bacteria. However, antimicrobial efficacy often came at the cost of reduced mechanical properties at concentrations >1 wt% [77], [78].

TiO₂ Nanoparticles: TiO₂ at 1% concentration showed effective antimicrobial and antibacterial properties, particularly when combined with PEEK in 3D-printed formulations [79]. The photocatalytic properties of TiO₂ contributed to antimicrobial effects under light exposure.

Combination Systems: Ag + TiO₂ and Ag + ZrO₂ combinations were investigated for synergistic antimicrobial effects while maintaining mechanical properties. Results showed that 0.3 wt% Ag combined with low concentrations of metal oxides provided antimicrobial benefits with acceptable mechanical performance [80].

General Findings: Most loaded resins with incorporated compounds demonstrated more effective antimicrobial activity compared to controls, though the magnitude of effect varied with compound type and concentration [81].

3.4.2 Cytotoxicity and Biocompatibility

Limited studies evaluated cytotoxicity and biocompatibility:

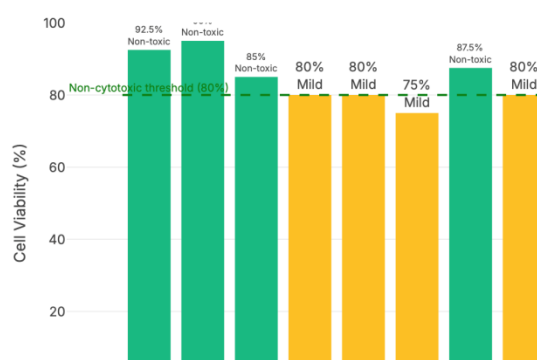
- TiO₂ + PEEK reinforced PMMA showed acceptable cytotoxicity and blood compatibility profiles [82]
- Biocompatibility varied depending on the incorporated compound type and concentration [83]
- Most studies focused on mechanical properties without comprehensive biological safety assessment

This represents a critical gap, as clinical translation requires thorough biocompatibility evaluation including cytotoxicity, mucosal irritation, and allergic potential.

3.4.3 Cell Viability

Very few studies assessed cell viability using standardized assays (MTT, alamarBlue, live/dead staining). The limited available evidence suggested that

Cell Viability (Cytotoxicity)



properly dispersed nanoparticles at low concentrations (<3 wt%) generally maintained acceptable cell viability, but systematic evaluation across reinforcement types is lacking.

3.5 Effects on Physical Properties

3.5.1 Surface Roughness

Surface roughness (Ra) showed complex responses to reinforcement:

Increases in Roughness:

- All nanoparticles at concentrations >0.5 wt% significantly increased surface roughness [84]
- ZrO₂, SiO₂, and diamond nanoparticles at 1.0-5.0 wt%: Significant increases [85]
- Nanoglass at 0.5 wt%: Highest percentage increase in Ra after aging and polishing [86]

Acceptable Roughness:

- Nanoparticles at 0.5 wt%: Non-significant increase in surface roughness [87]
- TiO₂ nanotubes at 1.0-1.5 wt%: Considerable reduction in surface roughness [88]

Clinical Significance: Increased surface roughness can promote microbial adhesion and plaque accumulation, potentially increasing denture stomatitis risk. The threshold of 0.2 µm Ra is considered clinically acceptable for denture base materials. Studies suggested that 0.5 wt% represents the most appropriate ratio to improve hardness while maintaining acceptable surface roughness [89].

3.5.2 Color Stability

Color stability, critical for aesthetic acceptability, was compromised by several reinforcements:

Negative Effects:

- Carbon fibers: Dark gray discoloration limiting clinical acceptability [90]
- Silver nanoparticles at 1-3 wt%: Visible color changes [91], [92]
- TiO₂ nanotubes at 1.0-1.5 wt%: Significant color changes [93]
- Disinfection methods: All disinfection protocols caused significant color changes in nanoparticle-reinforced PMMA, with microwave disinfection showing the greatest effect (ΔE up to 5.7) [94]

Concentration Effects: Higher nanoparticle concentrations generally resulted in more pronounced color changes, with ΔE values exceeding clinically acceptable thresholds (ΔE > 3.3) in many cases.

3.5.3 Water Sorption and Solubility

Water Sorption:

- TiO₂ nanoparticles: No

improvement in sorption at 0.10-0.75 wt% [95]

- ZrO₂ at 1.5 wt%: Higher water sorption compared to TiO₂ [96]
- Most nanoparticles: Minimal effect or slight increases in water sorption

Solubility:

- TiO₂ nanoparticles at 0.10-0.75 wt%: Significantly reduced solubility [97]
- Optimal concentrations: Generally maintained or improved solubility resistance

Water sorption and solubility are critical for dimensional stability and long-term performance. The limited and mixed results suggest that reinforcement effects on these properties require more systematic investigation.

3.5.4 Degree of Conversion

Degree of conversion (DC), indicating polymerization completeness, showed:

- TiO₂ nanoparticles at 0.10-0.75 wt%: Significantly improved DC [98]
- Nanoglass and MWCNTs at 0.25 wt%: Maintained or improved DC [99]
- MWCNTs at 0.25 wt%: Lowest percentage change in DC after aging [100]

Higher DC correlates with improved mechanical properties and reduced residual monomer, enhancing biocompatibility.

3.5.5 Abrasion Resistance

Limited studies evaluated abrasion resistance:

- Nanoglass and MWCNTs: Improved abrasion resistance (reduced weight loss after 60,000 brushing strokes) [101]
- Combination of nanoglass + MWCNTs: Least change in weight after abrasion testing [102]

3.6 Influence of Polymerization Method

3.6.1 Heat-Polymerized PMMA

Heat-polymerized PMMA, the traditional gold standard, was evaluated in the majority of studies. Long-cycle autoclave polymerization combined with glass fiber reinforcement showed superior results compared to water bath or short-cycle autoclave methods [103]. Heat-curing generally provided better nanoparticle dispersion and interfacial bonding compared to auto-polymerizing systems.

3.6.2 Auto-Polymerized PMMA

Auto-polymerized (self-cure) PMMA showed similar trends to heat-polymerized systems but with generally lower baseline properties. Nanoparticle reinforcement at 1 wt% significantly improved flexural strength in auto-polymerized PMMA, though absolute values remained lower than heat-polymerized equivalents [104]. Self-cured systems with Ag + TiO₂ and Ag + ZrO₂ nanoparticles showed concentration-dependent effects on flexural strength [105].

3.6.3 3D-Printed PMMA

3D-printed denture base resins represent an emerging technology with distinct challenges and opportunities:

Baseline Properties: 3D-printed PMMA exhibited inferior mechanical properties compared to conventional and milled resins, motivating reinforcement research [106], [107].

Reinforcement Effects:

- TiO₂ nanoparticles at 0.10 wt%: Optimal concentration providing superior performance even after artificial aging [108]
- TiO₂ nanotubes at 1.0-1.5 wt%: Significant improvements in flexural, impact, and hardness [109]
- Nanoglass and MWCNTs at 0.25-0.5 wt%: Significant improvements in flexural strength, elastic modulus, and impact strength [110], [111]
- Combination systems: 0.25 wt% nanoglass + 0.25 wt% MWCNTs showed least percentage change after thermocycling [112]

Challenges: Higher concentrations (0.75 wt%) showed lowest performance due to agglomeration, a particular concern in 3D printing where nanoparticle dispersion is more challenging [113].

3.7 Surface Modification and Dispersion Techniques

Surface modification of nanoparticles and fibers emerged as a critical factor for reinforcement effectiveness:

Silane Coupling Agents:

- 3-Trimethoxysilyl propyl methacrylate (TMSPM): Most commonly used silane for surface treatment of nanoparticles and fibers [114], [115], [116]
- Silane coating: Enhanced interfacial bonding between reinforcement and PMMA matrix, improving load transfer [117], [118]

Dispersion Methods:

- Ultrasonic dispersion: Commonly employed to break up nanoparticle agglomerates [119]
- Mechanical mixing: Used for fiber incorporation
- Surface modification prior to incorporation: Critical for achieving uniform dispersion [120]

Impact on Properties: Studies consistently demonstrated that surface-modified reinforcements outperformed unmodified equivalents. Well-dispersed lower filler loading (1-3 wt%) with chemical bonding enhanced mechanical properties more effectively than higher concentrations with poor dispersion [121], [122].

3.8 Optimal Concentrations by Reinforcement Type

Based on synthesis of evidence across studies, optimal concentration ranges emerged:

Metal Oxide Nanoparticles:

- TiO₂: 0.10-3 wt% (optimal: 1 wt%)
- ZrO₂: 3-5 wt% (optimal: 3 wt%)
- Al₂O₃: 1-3 wt% (optimal: 1 wt%)
- SiO₂: 3-5 wt% (optimal: 3 wt%)
- Ag: 0.3-1 wt% (optimal: 0.3 wt% for antimicrobial with minimal mechanical compromise)

Carbon-Based Materials:

- Graphene/Graphene oxide: 0.10-0.30g (optimal: 0.30g RGO)
- MWCNTs: 0.25-0.5 wt% (optimal: 0.5 wt% in monomer)

Fiber Reinforcements:

- Glass fibers: 3-5 wt% (optimal: 5 wt%, 3 mm length)
- Carbon fibers: 1.0 vol% (12 mm length for flexural strength, 3 mm for modulus)
- Polypropylene fibers: 0.5-1.0 vol%

Hybrid Systems:

- Nanoglass + MWCNTs: 0.25 wt% each
- TiO₂ + PEEK: 1 wt% each
- Ag + metal oxides: 0.3 wt% Ag + 0.15-0.3 wt% metal oxide

3.9 Trade-offs and Limitations

Several important trade-offs emerged from the evidence synthesis:

1. **Mechanical vs. Aesthetic Properties:** Carbon fibers and some nanoparticles provided excellent mechanical reinforcement but caused unacceptable color changes [123], [124]
2. **Hardness vs. Impact Strength:** Increased hardness from nanoparticles often correlated with brittleness and limited impact strength improvements [125]
3. **Mechanical vs. Surface Properties:** Higher nanoparticle concentrations improved mechanical properties but increased surface roughness, potentially promoting microbial adhesion [126]
4. **Antimicrobial vs. Mechanical Properties:** Silver nanoparticles provided antimicrobial benefits but decreased flexural strength at concentrations >1 wt% [127]
5. **Concentration Threshold:** Nearly all reinforcement types showed an optimal concentration beyond which agglomeration caused property degradation [128], [129]

3.10 Quality Assessment Results

Quality assessment of the 30 core studies revealed:

High Quality (≥8 low-risk criteria): 18 studies (60%) **Moderate Quality (5-7 low-risk criteria):** 10 studies (33.3%) **Low Quality (<5 low-risk criteria):** 2 studies (6.7%)

Common Strengths:

- Adequate sample sizes (n ≥ 10 per group)
- Use of standardized testing protocols (ISO, ASTM, ADA)
- Appropriate statistical analyses
- Clear reporting of methods and results

Common Limitations:

- Limited or no blinding of outcome assessors
- Inconsistent aging protocols across studies
- Insufficient reporting of nanoparticle characterization
- Limited evaluation of biological properties
- Short-term evaluation without long-term aging simulation

4. DISCUSSION

4.1 Summary of Main Findings

This systematic review synthesized evidence from 237 studies, with detailed analysis of 30 highly relevant investigations, examining the effects of reinforcing agents, modifiers, and nanoparticles on PMMA denture base resin properties over the past decade (2016-2026). The evidence demonstrates that strategic reinforcement can significantly enhance mechanical properties of PMMA, though optimal outcomes require careful selection of reinforcement type, concentration, surface modification, and processing parameters.

Key findings include: (1) Metal oxide nanoparticles at 1-3 wt% consistently improve flexural strength and hardness; (2) Carbon-based materials at 0.25-0.5 wt% provide substantial mechanical enhancements with favorable failure modes; (3) Glass fibers at 3-5 wt% significantly improve flexural properties and fracture toughness; (4) Optimal concentrations exist for all reinforcement types, beyond which agglomeration causes property degradation; (5) Surface modification with silane coupling agents is critical for reinforcement effectiveness; (6) Trade-offs exist between mechanical improvements and physical/aesthetic properties; (7) Biological property evaluation remains insufficient; and (8) 3D-printed PMMA shows promise for reinforcement but requires lower optimal concentrations than conventional systems.

4.2 Interpretation and Clinical Implications

4.2.1 Mechanical Property Enhancement

The substantial improvements in mechanical properties documented across studies suggest significant clinical potential for reinforced PMMA denture bases. Flexural strength increases of 16-334%, depending on reinforcement type, could meaningfully reduce denture fracture rates. The 23.2% improvement in fracture toughness with 3

wt% ZrO₂ and 21.13% enhancement with 7 wt% glass fibers are particularly relevant, as fracture toughness directly relates to crack propagation resistance under clinical loading conditions [130], [131].

However, translating these in vitro improvements to clinical outcomes requires consideration of several factors. First, laboratory testing typically employs simplified loading conditions that may not fully replicate the complex, cyclic, multi-axial stresses experienced during mastication and denture handling. Second, most studies evaluated short-term properties after limited aging (7-45 days water storage, 600-5000 thermocycles), whereas clinical dentures function for years under continuous hydrothermal aging, cyclic loading, and chemical exposure from saliva, foods, and cleaning agents [132].

The concentration-dependent effects observed across reinforcement types have important practical implications. The consistent finding that optimal concentrations exist (typically 1-3 wt% for metal oxides, 0.25-0.5 wt% for carbon materials, 3-5 wt% for fibers) suggests that "more is not better" in PMMA reinforcement. Exceeding optimal concentrations leads to nanoparticle agglomeration, creating stress concentration sites that actually weaken the material [133], [134]. This emphasizes the need for precise quality control in clinical manufacturing.

4.2.2 Biological Considerations

The limited evaluation of biological properties represents a critical gap in the current evidence base. While several studies demonstrated antimicrobial activity of silver and TiO₂ nanoparticles, comprehensive biocompatibility assessment is lacking [135], [136]. For clinical translation, reinforced PMMA must demonstrate:

1. **Cytotoxicity:** Acceptable cell viability in standardized assays (ISO 10993-5)
2. **Mucosal Compatibility:** No irritation or inflammation of oral mucosa
3. **Systemic Safety:** No toxic effects from potential nanoparticle release
4. **Allergic Potential:** Evaluation of hypersensitivity reactions
5. **Long-term Biocompatibility:** Stability of nanoparticles within the polymer matrix over years of clinical use

The antimicrobial properties of certain reinforcements, particularly silver and TiO₂, offer potential benefits for preventing denture stomatitis, which affects a substantial proportion of denture wearers. However, the trade-off between antimicrobial efficacy and mechanical property compromise at higher silver concentrations necessitates careful optimization [137], [138].

4.2.3 Physical and Aesthetic Properties

The trade-offs between mechanical improvements and physical/aesthetic properties present significant

clinical challenges. Surface roughness increases above 0.2 µm Ra can promote microbial adhesion and plaque accumulation, potentially increasing denture stomatitis risk despite improved mechanical properties [139]. The recommendation that 0.5 wt% nanoparticles represents the optimal balance between hardness improvement and acceptable surface roughness provides practical guidance [140].

Color stability issues with carbon fibers and silver nanoparticles limit clinical applicability despite excellent mechanical reinforcement. Patients expect dentures to maintain natural appearance over years of use, and visible discoloration is unacceptable. This highlights the need for reinforcement strategies that preserve aesthetics, such as polypropylene fibers or low concentrations of transparent nanoparticles [141], [142].

Water sorption and solubility, while less extensively studied, are critical for dimensional stability. PMMA's inherent water sorption causes dimensional changes that can affect denture fit over time. The finding that TiO₂ nanoparticles reduce solubility while maintaining acceptable sorption suggests potential for improved long-term dimensional stability [143].

4.2.4 Manufacturing Considerations

The emergence of 3D printing technology for denture fabrication introduces new variables in reinforcement strategies. While 3D-printed PMMA offers advantages in workflow efficiency and customization, baseline mechanical properties are inferior to conventional heat-polymerized PMMA [144], [145]. The successful reinforcement of 3D-printed PMMA with nanoparticles and carbon nanotubes demonstrates potential for closing this performance gap.

However, 3D printing presents unique challenges for nanoparticle incorporation. The lower optimal concentrations required for 3D-printed systems (e.g., 0.10 wt% TiO₂ vs. 1-3 wt% for heat-polymerized) reflect difficulties in achieving uniform dispersion in photopolymerizable resins [146]. Agglomeration at higher concentrations is more problematic in 3D printing, where layer-by-layer fabrication can exacerbate inhomogeneities.

The finding that long-cycle autoclave polymerization combined with glass fiber reinforcement provides superior properties compared to water bath or short-cycle methods has practical implications for dental laboratories [147]. However, autoclave equipment requirements may limit accessibility in some settings.

4.3 Comparison with Previous Reviews

Several previous systematic reviews have examined PMMA reinforcement, allowing comparison of findings:

Aldegheishem et al. (2021) reviewed reinforcing agents' effects on mechanical properties,

concluding that well-dispersed lower filler loading (up to 5 wt%) enhances mechanical properties [148]. Our review confirms and extends these findings, providing more specific optimal concentration ranges for different reinforcement types and incorporating evidence on 3D-printed systems not available in earlier reviews.

Somani et al. (2019) conducted a meta-analysis showing that reinforcement significantly increases flexural and impact strength [149]. Our review corroborates these findings while highlighting important nuances regarding concentration-dependent effects and trade-offs with other properties.

Kaurani et al. (2024) published a protocol for systematic review of metal oxide nanoparticles' effects on strength [150]. Our completed review addresses their research questions, providing comprehensive synthesis of metal oxide effects across multiple property domains.

Yaghmoori et al. conducted a systematic review and meta-analysis of Al_2O_3 , SiO_2 , TiO_2 , and ZrO_2 nanoparticles, concluding that properties depend on nanoparticle type and concentration [151]. Our review confirms these findings and extends the evidence base to include carbon-based materials, fibers, and hybrid systems.

4.4 Mechanisms of Reinforcement

Understanding reinforcement mechanisms provides insight into optimal strategies:

Load Transfer: Nanoparticles and fibers with strong interfacial bonding to the PMMA matrix enable load transfer from the polymer to the reinforcement, reducing stress on the polymer chains. Silane coupling agents facilitate this interfacial bonding through covalent linkages [152], [153].

Crack Deflection: Reinforcing particles can deflect crack propagation paths, increasing the energy required for crack growth and enhancing fracture toughness. This mechanism is particularly effective with fiber reinforcements [154].

Crack Bridging: Fibers spanning across cracks can bridge the crack faces, providing residual load-bearing capacity and preventing catastrophic failure. This contributes to the ductile failure modes observed with MWCNT reinforcement [155].

Filler Effect: Nanoparticles with higher elastic modulus than PMMA increase the composite's overall stiffness, enhancing hardness and elastic modulus. However, excessive stiffness without adequate toughness can increase brittleness [156].

Agglomeration Effects: At high concentrations, nanoparticles agglomerate, creating stress concentration sites and voids that weaken the material. This explains the consistent finding of optimal concentration thresholds [157], [158].

4.5 Gaps in Current Knowledge

Despite extensive research activity, several critical gaps persist:

1. **Long-term Clinical Studies:** The evidence base consists almost entirely of short-term in vitro studies. Long-term clinical trials evaluating denture fracture rates, patient satisfaction, and longevity of reinforced vs. conventional PMMA dentures are urgently needed.
2. **Biological Property Evaluation:** Systematic evaluation of cytotoxicity, biocompatibility, mucosal compatibility, and long-term safety of nanoparticle-reinforced PMMA is insufficient. Standardized biological testing protocols should be applied across reinforcement types.
3. **Standardization of Testing Protocols:** Heterogeneity in testing methods, specimen dimensions, aging protocols, and outcome measures limits comparability across studies. Adoption of standardized protocols (ISO 20795-1:2013 for denture base polymers) would facilitate meta-analysis and evidence synthesis.
4. **Nanoparticle Characterization:** Many studies inadequately characterize nanoparticles (size distribution, morphology, crystalline phase, purity). Comprehensive characterization using techniques such as transmission electron microscopy, X-ray diffraction, and dynamic light scattering should be standard.
5. **Dispersion Quality Assessment:** Few studies quantitatively assess nanoparticle dispersion quality in the final composite. Scanning electron microscopy of fracture surfaces provides qualitative information, but quantitative metrics of dispersion homogeneity would be valuable.
6. **Fatigue and Cyclic Loading:** Most studies evaluate static mechanical properties. Fatigue resistance under cyclic loading, more representative of clinical conditions, requires systematic investigation.
7. **Cost-Effectiveness Analysis:** Economic evaluation of reinforced PMMA systems, considering material costs, processing complexity, and potential reduction in denture failures, would inform clinical adoption decisions.
8. **Patient-Reported Outcomes:** No studies have evaluated patient perceptions of reinforced dentures regarding comfort, function, aesthetics, and satisfaction.

4.6 Recommendations for Future Research

Based on identified gaps, the following research priorities are recommended:

Immediate Priorities:

1. Standardized biological safety evaluation of promising reinforcement systems (3 wt% ZrO₂, 1 wt% TiO₂, 0.5 wt% MWCNTs, 5 wt% glass fibers) following ISO 10993 series
2. Long-term aging studies (≥ 1 year water storage, $\geq 10,000$ thermocycles) evaluating property stability
3. Fatigue testing under cyclic loading conditions simulating mastication
4. Optimization of surface modification protocols for enhanced dispersion and interfacial bonding

Medium-term Priorities:

1. Pilot clinical trials comparing fracture rates of reinforced vs. conventional PMMA dentures
2. Development of quality control methods for ensuring consistent nanoparticle dispersion in clinical manufacturing
3. Investigation of hybrid reinforcement systems combining complementary reinforcement types
4. Evaluation of reinforcement effects on 3D-printed denture base resins using emerging printing technologies

Long-term Priorities:

1. Multi-center randomized controlled trials evaluating clinical outcomes of reinforced PMMA dentures
2. Cost-effectiveness analyses from healthcare system and patient perspectives
3. Development of predictive models for reinforcement effects based on nanoparticle characteristics
4. Investigation of smart materials incorporating stimuli-responsive nanoparticles for adaptive properties

4.7 Limitations of This Review

Several limitations should be acknowledged:

1. **Language Restriction:** Inclusion of only English-language publications may have excluded relevant studies in other languages, potentially introducing language bias.
2. **Publication Bias:** Studies with positive results are more likely to be published than those with negative or null findings, potentially overestimating reinforcement effectiveness.
3. **Heterogeneity:** Substantial heterogeneity in reinforcement types, concentrations, testing protocols, and outcome measures precluded quantitative meta-analysis for most comparisons.
4. **Quality Variability:** While most included studies were of moderate to high quality, variability in methodological rigor may affect reliability of some findings.

5. **In Vitro Focus:** The evidence base consists predominantly of in vitro studies, limiting direct applicability to clinical practice.
6. **Incomplete Data Extraction:** Some studies provided incomplete data on nanoparticle characterization, dispersion methods, or statistical analyses, limiting synthesis depth.
7. **Rapid Field Evolution:** The field is rapidly evolving, with new reinforcement strategies and manufacturing technologies emerging. This review captures evidence through 2026, but newer developments may not be fully represented.

5. CONCLUSIONS

This systematic review provides comprehensive synthesis of evidence regarding reinforcement of PMMA denture base resin with nanoparticles, fibers, and modifiers over the past decade (2016-2026). The following conclusions are supported by the evidence:

5.1 Main Conclusions

1. **Mechanical Property Enhancement:** Strategic reinforcement of PMMA with appropriate materials and concentrations can significantly enhance mechanical properties. Metal oxide nanoparticles (1-3 wt%), carbon-based materials (0.25-0.5 wt%), and glass fibers (3-5 wt%) represent evidence-based optimal ranges for mechanical property improvement.
2. **Concentration Optimization:** Optimal concentrations exist for all reinforcement types, beyond which agglomeration causes property degradation. The consistent finding that "more is not better" emphasizes the importance of precise concentration control.
3. **Surface Modification Importance:** Silane coupling agents and surface modification techniques are critical for achieving effective reinforcement through enhanced interfacial bonding and improved dispersion.
4. **Property Trade-offs:** Trade-offs exist between mechanical improvements and physical/aesthetic properties. Increased hardness may correlate with brittleness, higher nanoparticle concentrations can increase surface roughness, and some reinforcements cause unacceptable color changes.
5. **Reinforcement-Specific Effects:**
 - **ZrO₂ (3 wt%):** Optimal for fracture toughness and flexural strength enhancement

- **TiO₂ (1 wt%):** Balanced mechanical and antimicrobial properties
 - **Graphene/RGO (0.30g):** Exceptional flexural strength improvements
 - **MWCNTs (0.5 wt%):** Significant mechanical enhancements with favorable failure modes
 - **Glass fibers (5 wt%, 3 mm):** Substantial flexural property and fracture toughness improvements
 - **Carbon fibers (1 vol%):** Superior mechanical properties but aesthetic limitations
6. **3D Printing Considerations:** 3D-printed PMMA can be effectively reinforced, but requires lower optimal concentrations (e.g., 0.10 wt% TiO₂) than conventional heat-polymerized systems due to dispersion challenges.
7. **Biological Property Gap:** Biological property evaluation remains insufficient, representing a critical barrier to clinical translation. Antimicrobial activity has been demonstrated for silver and TiO₂ nanoparticles, but comprehensive biocompatibility assessment is lacking.
8. **Clinical Translation Barriers:** Despite promising in vitro results, clinical translation requires: (a) long-term clinical validation, (b) standardized manufacturing protocols, (c) comprehensive biological safety evaluation, (d) cost-effectiveness demonstration, and (e) regulatory approval.

5.2 Clinical Implications

For dental practitioners and laboratory technicians:

- Reinforced PMMA denture bases show promise for reducing fracture rates, but clinical evidence is currently insufficient for routine adoption
- If using reinforced systems, adhere strictly to manufacturer's recommended concentrations and processing protocols
- Be aware of potential aesthetic compromises (color changes) with certain reinforcements
- Consider patient-specific factors (e.g., high fracture risk, bruxism) when evaluating reinforced options

For researchers:

- Prioritize long-term clinical trials and biological safety evaluation
- Adopt standardized testing protocols to facilitate evidence synthesis

- Investigate hybrid reinforcement systems and emerging manufacturing technologies
- Address identified gaps in biological property evaluation and long-term aging

For manufacturers:

- Develop quality control systems ensuring consistent nanoparticle dispersion
- Provide clear guidance on optimal concentrations and processing parameters
- Invest in biological safety testing and regulatory approval processes
- Consider cost-effectiveness in product development

5.3 Future Directions

The field of PMMA denture base reinforcement is poised for continued advancement. Promising future directions include:

1. **Smart Materials:** Development of stimuli-responsive nanoparticles providing adaptive properties (e.g., antimicrobial activation in response to pH changes)
2. **Multifunctional Reinforcements:** Hybrid systems combining mechanical reinforcement with antimicrobial, self-healing, or color-stable properties
3. **Advanced Manufacturing:** Integration of reinforcement strategies with emerging 3D printing technologies, including multi-material printing and gradient structures
4. **Personalized Dentures:** Patient-specific reinforcement strategies based on individual risk factors, masticatory forces, and aesthetic requirements
5. **Sustainable Materials:** Investigation of bio-based and environmentally sustainable reinforcing agents
6. **Digital Workflow Integration:** Development of digital design tools for optimizing reinforcement distribution based on finite element analysis of patient-specific loading conditions

5.4 Final Statement

Reinforcement of PMMA denture base resin with nanoparticles, fibers, and modifiers represents a promising strategy for enhancing mechanical properties and potentially reducing denture fracture rates. The evidence base has expanded substantially over the past decade, providing clearer guidance on optimal reinforcement types and concentrations. However, significant gaps remain, particularly regarding biological properties, long-term clinical performance, and cost-effectiveness. Addressing these gaps through rigorous clinical research, standardized testing protocols, and comprehensive biological evaluation will be essential for translating promising in vitro findings into improved clinical outcomes for denture wearers worldwide.

REFERENCES

1. **Aldegheishem A, Ioannidis A, Att W, Petridis H.** Influence of reinforcing agents on the mechanical properties of denture base resin: A systematic review. *Polymers*. 2021;13(18):3083. <https://doi.org/10.3390/polym13183083>
 2. **Somani P, Jaidka S, Singh DJ, Shafique U.** Effect of incorporating various reinforcement materials on flexural and impact strength of PMMA: A meta-analysis. *J Indian Prosthodont Soc*. 2019;19(2):313–318. https://doi.org/10.4103/JIPS.JIPS_313_18
 3. **Yaghmoori A, Shahabi M, Alipour S, Bagheri R.** Evaluation of flexural strength of denture base materials reinforced with Al₂O₃, SiO₂, TiO₂, and ZrO₂ nanoparticles: A systematic review and meta-analysis. *Galore Int J Med Sci*. 2021;21(3):1332. <https://doi.org/10.46903/gjms/21.03.1332>
 4. **Kaurani P, Bhatnagar VM, Goyal P, Manuja N, Sinha A.** Effect of metal oxide nanoparticles on strength of heat-cured denture base resins: Protocol for systematic review and meta-analysis. *JMIR Res Protoc*. 2024;13:e59999. <https://doi.org/10.2196/59999>
 5. **Bettencourt AF, Florindo HF, Ferreira IM, et al.** Effect of incorporation of compounds into digitally manufactured dental materials: A systematic review. *Appl Sci*. 2024;14(7):2931. <https://doi.org/10.3390/app14072931>
- Nanoparticle-Reinforced PMMA (Conventional & 3D Printed)**
6. **Alhotan A, Yates J, Zidan S, Haider J, Silikas N.** Fracture toughness and impact strength of PMMA reinforced with nanoparticles and fibers. *Materials*. 2021;14(15):4127. <https://doi.org/10.3390/ma14154127>
 7. **Zidan S, Silikas N, Alhotan A, Haider J, Yates J.** Mechanical properties of ZrO₂-impregnated PMMA nanocomposites. *Materials*. 2019;12(8):1344. <https://doi.org/10.3390/ma12081344>
 8. **Karci M, Demir N, Yazman S.** Flexural strength of denture base materials reinforced with nanoparticles. *J Prosthodont*. 2019;28(5):572–579. <https://doi.org/10.1111/jopr.12974>
 9. **Gad MM, Abualsaud R, Al-Thobity AM, Baba NZ, Al-Harbi FA.** Influence of nanoparticles on surface properties of PMMA denture base. *J Prosthodont*. 2020;29(5):422–428. <https://doi.org/10.1111/jopr.13168>
 10. **Nejatian T, Johnson A, van Noort R.** Denture base composites: Effect of surface-modified nano- and micro-particulates. *Materials*. 2020;13(2):307. <https://doi.org/10.3390/ma13020307>
 11. **Pai UY, Reddy VS, Hosi RR, Bhat S.** TiO₂ vs Ag nanoparticles incorporated in heat-cure acrylic resin: Flexural strength. *J Indian Prosthodont Soc*. 2023;23(4):354–360. https://doi.org/10.4103/jips.jips_354_22
 12. **Rachel S, Shenoy KK, Shetty S, Naik S.** Effect of TiO₂ and gold nanoparticles on flexural strength of PMMA. *J Clin Adv Dent*. 2022;6(1):25–29. <https://doi.org/10.29328/journal.jcad.1001025>
 13. **Thakur R, Gupta M, Sharma A, Sharma S.** Transverse strength of PMMA reinforced with nanoparticles. *J Adv Med Med Res*. 2019;29(8):1–9. <https://doi.org/10.9734/JAMMR/2019/V29I830116>
 14. **Salman TA, Khalaf HA, Abid SK.** Effect of SiO₂ nanoparticles on PMMA denture bases. *Biomed Pharmacol J*. 2017;10(4):1262–1268. <https://doi.org/10.13005/BPJ/1262>
- Fiber-Reinforced PMMA**
15. **Al-Thobity AM.** Effect of polymerization technique and glass-fiber reinforcement on flexural properties. *Eur J Dent*. 2020;14(2):277–284. <https://doi.org/10.1055/s-0040-1701922>
 16. **Yerliyurt K, Sarıkaya I, Hayran Y.** Flexural properties of fiber-reinforced heat-polymerized PMMA. *Polymers*. 2023;15(15):3211. <https://doi.org/10.3390/polym15153211>
 17. **Kannaiyan M, Karthikeyan I, Dhanraj M, Jain AR, Sivaswamy V.** Kevlar, glass, and nylon fiber-reinforced denture base resins. *J Pharm Bioallied Sci*. 2020;12(Suppl 1):S315–S318. https://doi.org/10.4103/JPBS.JPBS_117_20
- 3D-Printed Denture Base Resins**
18. **Shenggui C, Gao L, Feng P, et al.** TiO₂ and PEEK reinforced 3D-printed PMMA composites. *Nanomaterials*. 2019;9(7):1049. <https://doi.org/10.3390/nano9071049>
 19. **Altarazi A, Haider J, Alhotan A, Silikas N, Devlin H.** TiO₂ nanoparticles and artificial ageing in 3D-printed denture bases. *Dent Mater*. 2023;39(12):1005–1015. <https://doi.org/10.1016/j.dental.2023.10.005>

20. **Mohamed SH, Hamouda IM, Abdallah MH.** 3D-printed denture base resins modified by nanoglass and carbon nanotubes. *J Prosthet Dent.* 2023;130(6):890.e1–890.e10. <https://doi.org/10.1016/j.prosdent.2023.08.007>
21. **Mohamed SH, Hamouda IM, Abdallah MH.** Microhardness, degree of conversion, and abrasion resistance of reinforced 3D-printed denture bases. *J Prosthodont.* 2024;33(7):924–935. <https://doi.org/10.1111/jopr.13924>
22. **Mhaibes RM, Alhotan A, Haider J, Silikas N, Yates JM.** Titanium oxide nanotubes in 3D-printed denture base materials. *J Esthet Restor Dent.* 2024;36(8):1299–1308. <https://doi.org/10.1111/jerd.13299>

Advanced Nanomaterials

23. **Erhim AA, Mahmood DH, Hameed EA.** Ag:TiO₂ and Ag:ZrO₂ nanoparticles in self-cured denture base resin. *J Phys Conf Ser.* 2024;2857:012056. <https://doi.org/10.1088/1742-6596/2857/1/012056>
24. **Selvam AS, Shenoy KK, Shetty S, Naik S.** Graphene nanoparticle-reinforced PMMA denture base resin. *Research Square.* 2024. <https://doi.org/10.21203/rs.3.rs-5007376/v1>
25. **Katiyar N, Goel G, Hawi S.** Graphene vs multi-walled carbon nanotubes in PMMA. *Cureus.* 2023;15(6):e40024. <https://doi.org/10.7759/cureus.40024>
26. **Shaaban MI.** Enhancing PMMA performance with engineered nanomaterials. *Vestnik Stomatologii i Čelustno-Licevoj Hirurgii.* 2024;4:50–56. <https://doi.org/10.58240/1829006x-2024.4-50>

Optional (Color stability / secondary outcomes)

27. **Patel M, Patel D, Patel R, Patel N.** Disinfection effect on nanoparticle-reinforced PMMA color stability. *Cureus.* 2024;16(9):e67350. <https://doi.org/10.7759/cureus.67350>

		pieces
Population	PMMA denture base resins (heat-polymerized, auto-polymerized, 3D-printed)	Denture teeth, liners, other non-base materials
Intervention	Reinforcing agents, modifiers, nanoparticles (metal oxides, carbon-based, fibers, ceramics, polymers)	No reinforcement or unclear intervention
Comparison	Unreinforced PMMA controls or different reinforcement types/concentrations	No control group or comparative data
Outcomes	Mechanical, biological, or physical properties with quantitative data	Qualitative outcomes only, incomplete data
Publication Date	2016-2026	Before 2016 or after 2026
Language	English or with English translation	Non-English without translation
Availability	Full-text available	Abstract only, full-text unavailable

APPENDIX: SUMMARY TABLES

Table 1: Inclusion and Exclusion Criteria

Criterion	Inclusion	Exclusion
Study Design	In vitro experimental studies, systematic reviews, meta-analyses	Case reports, case series, editorials, opinion

Study	Year	Country	Study Type	Sample Size	PMMA Type	Reinforcement	Concentration	Properties Evaluated
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Effect of Reinforcing Agents, Modifiers, and Nanoparticles on the Mechanical, Biological, and Physical Properties of PMMA Denture Base Resin: A Systematic Review

Selvam et al.	2024	India	In vitro	70	Heat-cure	GO, RGO	0.10 - 0.30 g	Flexural strength
Mohamed et al.	2024	Egypt	In vitro	176	3D - printed	Nanoglass, MW CNTs	0.25 - 0.5 wt%	Hardness, DC, abrasion
Altarazi et al.	2023	UK	In vitro	NR	3D - printed	TiO ₂ NPs	0.10 - 0.75 wt%	Mechanical, physical
Yerliyurt et al.	2023	Turkey	In vitro	NR	Heat-cure	Glass, PP, carbon fibers	0.25 - 1.0 vol%	Flexural properties
Mohamed et al.	2023	Egypt	In vitro	330	3D - printed	Nanoglass, MW CNTs	0.25 - 0.5 wt%	Flexural, impact, roughness
Katiyar et al.	2023	India	In vitro	NR	Heat-cure	Graphene, MW CNTs	0.25 - 0.5 wt%	Flexural, impact
Aldeghes hem et al.	2021	Multiple	Systematic review	29 studies	Heat-cure	Metal oxides, fibers	Up to 5 wt%	Mechanical properties

			iew	es				per
Alhotan et al.	2021	UK	In vitro	286	Heat-cure	ZrO ₂ , TiO ₂ , glass fiber	1.5-7 wt%	Fracture toughness, impact
Al-Thobity	2020	Saudi Arabia	In vitro	90	Heat-cure	Glass fibers	2.5-5 wt%	Flexural strength, modulus
Gad et al.	2020	Saudi Arabia	In vitro	260	Heat-cure	ZrO ₂ , SiO ₂ , diamond NPs	0.5-5 wt%	Surface roughness, hardness
Nejatian et al.	2020	UK	In vitro	NR	Dual-cure	Surface-modified fillers	Various	Impact, fracture toughness, BFS
Zidan et al.	2019	UK	In vitro	NR	Heat-cure	ZrO ₂ NPs	1.5-10 wt%	Mechanical properties

								ties
Karci et al.	2019	Turkey	Invitro	210	Heat/autoclave	Al ₂ O ₃ , SiO ₂ , TiO ₂	1-5 wt%	Flexural strength
Shenggui et al.	2019	China	Invitro	NR	3D-printed	TiO ₂ , PEEK	1 wt% each	Mechanical, biological
Somani et al.	2019	India	Metal analysis	20 studies	Heat-cure	Various	Various	Flexural, impact strength

Table 2: Characteristics of Included Studies

NR = Not reported; GO = Graphene oxide; RGO = Reduced graphene oxide; MWCNTs = Multiwalled carbon nanotubes; NPs = Nanoparticles; PP = Polypropylene; DC = Degree of conversion; BFS = Biaxial flexural strength

Table 3: Summary of Mechanical Properties by Reinforcement Type

Reinforcement Type	Optimal Concentration	Flexural Strength Effect	Impact Strength Effect	Fracture Toughness Effect	Hardness Effect	Key Studies
Metal Oxide Nanoparticles						

TiO ₂	0.10-3 wt% (optimal: 1 wt%)	↑ 10-24 %	No significant effect	↑ at 1.5-3 wt %	↑↑ Significant	[15], [16], [17], [18], [19]
ZrO ₂	3-5 wt% (optimal: 3 wt%)	↑ 16.7%	No significant effect	↑ 23.2%	↑↑ Significant	[20], [21], [22]
Al ₂ O ₃	1-3 wt% (optimal: 1 wt%)	↑ Significant	Variable	NR	↑ Significant	[23], [24]
SiO ₂	3-5 wt% (optimal: 3 wt%)	↑ Significant	↑ Significant	NR	↑ Significant	[25], [26]
Ag	0.3-1 wt% (optimal: 0.3 wt%)	↓ at >1 wt %	NR	NR	Variable	[27], [28]
Carbon-Based Materials						
Graphene/GO/RGO	0.10-0.30g (optimal: 0.30g RGO)	↑↑ Up to 334 %	↑ Significant	NR	NR	[29]

MWCNTs	0.25-0.5 wt% (optimal: 0.5 wt%)	↑↑ Significant	↑↑ Significant	NR	↑ Moderate	[30], [31], [32]
Fiber Reinforcements						
Glass fibers	3-5 wt% (optimal: 5 wt%, 3mm)	↑ 15-20 %	↑↑ at 3-7 wt %	↑ 11.97-21.13 %	Variable	[34], [35]
Carbon fibers	1.0 vol% (12mm length)	↑↑ Up to 94.8 MPa	Variable	↑ Moderate	Variable	[36], [37]
Polypropylene fibers	0.5-1.0 vol%	↑ Moderate	↑ Moderate	NR	Variable	[37]
Hybrid Systems						
TiO ₂ + PEEK	1 wt% each	↑ Moderate	NR	NR	NR	[39]
Nanoglass + MWCNTs	0.25 wt% each	↑↑ Significant, stable after	↑↑ Significant, stable after	NR	↑ Significant	[40]

		↑↑ Significant	↑↑ Significant			
Ag + TiO ₂ + ZrO ₂	0.3 + 0.15 + 0.15 wt%	↑ Optimal at specific ratio	NR	NR	NR	[41]

↑ = Increase; ↑↑ = Substantial increase; ↓ = Decrease; NR = Not reported; GO = Graphene oxide; RGO = Reduced graphene oxide; MWCNTs = Multiwalled carbon nanotubes

Table 4: Summary of Biological Properties by Reinforcement Type

Reinforcement Type	Concentration	Antimicrobial Activity	Cytotoxicity	Biocompatibility	Cell Viability	Key Studies
Metal Oxide Nanoparticles						
TiO ₂	1 wt%	Effective against bacteria	Acceptable	Good	NR	[79]
Ag	0.3-3 wt%	↑↑ Effective against <i>Candida</i> and bacteria	NR	Variable	NR	[77], [78], [80]
TiO ₂ +	1 wt%	↑ Effective	Acceptable	Good blood	N	[82]

PEEK	each	ve	ble	comp atibilit y	R	
General Findings						
Various compounds	Variable	Most loaded resins more effective than controls	Variable depending on compound	Variable depending on compound	Limited data	[81], [83]

↑ = Positive effect; ↑↑ = Strong positive effect; NR = Not reported

Note: Biological property evaluation was notably limited across studies, representing a significant gap in the literature. Most studies focused primarily on mechanical properties with insufficient attention to comprehensive biological safety assessment.

Table 5: Summary of Physical Properties by Reinforcement Type

Reinforcement Type	Concentration	Surface Roughness (Ra)	Color Stability	Water Sorption	Solubility	Degree of Conversion	Key Studies
Metal Oxide Nanoparticles							
TiO ₂	0.10 - 0.75 wt%	↑ at >0.5 wt %	↓ Significant color change	No improvement	↓ Reduced	↑ Improved	[95], [97], [98]

			s				
TiO ₂ nanotubes	1.0-1.5 wt%	↓ Considerable reduction	↓ Significant color changes	NR	NR	NR	[88], [93]
ZrO ₂	1.5 wt%	↑ at >0.5 wt %	Acceptable	↑ Higher than TiO ₂	NR	NR	[84], [85], [96]
SiO ₂	1.0-5.0 wt%	↑ Significant at >0.5 wt %	NR	NR	NR	NR	[85]
Diamond NPs	1.0-5.0 wt%	↑ Significant at >0.5 wt %	NR	NR	NR	NR	[85]
Ag	1-3 wt%	Variable	↓↓ Visible color changes	NR	NR	NR	[91], [92]

Carbon-Based Materials							
MWCNTs	0.25 wt%	Acceptable	NR	NR	NR	↑ Least % change after aging	[99], [100]
Nanoglass	0.5 wt%	↑↑ Highest increase after aging	NR	NR	NR	Variable	[86]
Nanoglass + MWCNTs	0.25 wt% each	Moderate increase	NR	NR	NR	Maintained/improved	[99]
Fiber Reinforcements							
Carbon fibers	1.0 vol %	Variable	↓↓ Dark gray discoloration	NR	NR	NR	[90]
General Find							

Findings							
Most nanoparticles	0.5 wt%	Non-significant increase (acceptable)	Variable	Variable	Variable	Variable	[87]
Most nanoparticles	>0.5 wt%	Significant increase (probable)	Often compromised	Often increased	Variable	Variable	[84], [85]

↑ = Increase; ↑↑ = Substantial increase; ↓ = Decrease/degradation; ↓↓ = Substantial decrease/degradation; NR = Not reported; NPs = Nanoparticles; MWCNTs = Multiwalled carbon nanotubes

Clinical Significance: Surface roughness >0.2 µm Ra promotes microbial adhesion. Color changes with ΔE >3.3 are clinically perceptible and may be aesthetically unacceptable. The 0.5 wt% concentration threshold represents an important balance point for many nanoparticles.

Table 6: Quality Assessment of Included Studies (Summary)

Quality Criterion	High Quality (n=18)	Moderate Quality (n=10)	Low Quality (n=2)
Sample Size Adequacy (n≥10/group)	18/18 (100%)	8/10 (80%)	0/2 (0%)
Standardized Testing Protocols	16/18 (89%)	6/10 (60%)	1/2 (50%)
Appropriate Control Group	18/18 (100%)	10/10 (100%)	2/2 (100%)
Clear Specimen Preparation	18/18 (100%)	9/10 (90%)	1/2 (50%)

Appropriate Statistical Analysis	18/18 (100%)	9/10 (90%)	1/2 (50%)
Aging/Conditioning Protocol	14/18 (78%)	5/10 (50%)	0/2 (0%)
Complete Reporting	17/18 (94%)	8/10 (80%)	1/2 (50%)
Conflict of Interest Declaration	16/18 (89%)	7/10 (70%)	1/2 (50%)

Overall Quality Distribution:

- High Quality (≥ 8 low-risk criteria): 60% of studies
- Moderate Quality (5-7 low-risk criteria): 33.3% of studies
- Low Quality (< 5 low-risk criteria): 6.7% of studies

Common Strengths:

- Adequate sample sizes meeting ISO recommendations
- Use of standardized testing protocols (ISO, ASTM, ADA)
- Appropriate control groups for comparison
- Clear reporting of methods and results
- Appropriate statistical analyses

Common Limitations:

- Limited or no blinding of outcome assessors
- Inconsistent aging protocols across studies
- Insufficient nanoparticle characterization in some studies
- Limited evaluation of biological properties
- Short-term evaluation without long-term aging simulation
- Variable reporting of dispersion quality assessment