RESEARCH PAPER

A Comparative Evaluation of Zirconia-Reinforced Denture Base Materials Versus Conventional Denture Base Materials: A Systematic Review

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Abstract

Objectives: To evaluate the mechanical, physical and clinical performance of zirconia-reinforced denture base materials when compared with conventional unreinforced denture base materials.

Methods: A systematic search was carried out in PubMed, Scopus, Web of Science, Cochrane Library and Google Scholar for studies published in English between January 2014 and October 2026. The review followed the PRISMA 2020 guidelines. In vitro studies and clinical studies that compared zirconia-reinforced denture base resin with unreinforced resin were included. The primary outcomes were flexural strength, impact strength and fracture toughness. The secondary outcomes were surface hardness, surface roughness, water sorption and solubility, colour stability, microbial colonisation and patient satisfaction. Risk of bias was assessed with the QUIN tool for in vitro studies, the RoB 2 tool for randomised trials and the ROBINS-I tool for non-randomised clinical studies.

Results: A total of 239 records were identified. After removal of 42 duplicates and screening, 41 studies were included: 38 in vitro studies, two randomised clinical trials and one non-randomised clinical study. Of the 22 in vitro studies that compared flexural strength with an unreinforced control, 18 reported an increase, mainly at zirconia concentrations of 0.5 to 7.5 wt%. Four studies reported a decrease, at high concentrations (10 to 20 wt%) or in some 3D-printed resins. Surface hardness increased in 13 of 14 studies. Results for impact strength, surface roughness and colour stability were mixed. Five of six in vitro studies and both randomised trials reported less Candida albicans colonisation with zirconia-modified resin. Twenty-four in vitro studies showed a medium risk of bias and 14 showed a high risk. One trial had some concerns, one had a high risk of bias and the non-randomised study had a serious risk of bias.

Conclusions: Zirconia reinforcement at low to moderate concentrations, preferably with silanised particles, improves the flexural strength and surface hardness of denture base resin. High concentrations may weaken the resin. Early clinical data suggest a reduction in microbial colonisation. Well-designed clinical trials with longer follow-up are needed before firm clinical recommendations can be made.

Keywords: Denture base; Polymethyl methacrylate; Zirconia; Zirconium oxide nanoparticles; Flexural strength; Reinforcement; Systematic review.

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INTRODUCTION

Complete dentures are still the most common treatment option for edentulous patients. Polymethyl methacrylate (PMMA) has been the main denture base material for many decades. It is easy to process, low in cost, acceptable in appearance and easy to repair [1]. In spite of these advantages, PMMA has poor mechanical strength. Fracture of the denture base is a common problem in daily practice. Midline fracture of the maxillary denture happens due to repeated flexing during function, and impact fracture happens when the denture is dropped [2]. Each fracture adds cost and inconvenience for the patient and the clinician.

Many methods have been tried over the years to make the denture base stronger. These include high-impact resins, metal wires and plates, and fibres such as glass, polyethylene and aramid [3, 4]. Metal reinforcement adds weight and affects appearance. Fibres are difficult to handle and to place in the correct position. In recent years, the addition of fillers and nanofillers to PMMA has received more attention, as they can be mixed directly with the polymer powder [4].

Zirconia (zirconium dioxide, ZrO2) is a ceramic with high flexural strength, high fracture toughness and good biocompatibility. Its white colour also suits denture base applications. Zirconia can resist crack growth through a process called transformation toughening [5]. When zirconia particles are well dispersed in PMMA, they can

transfer stress from the resin and block the spread of cracks [4]. However, results in the literature are not uniform. Some studies show a clear gain in strength, while others show no gain or a loss, mainly when the particles form clusters inside the resin [6].

An earlier systematic review on zirconia and PMMA included only laboratory studies published up to 2018 [6]. Since then, new denture base materials such as 3D-printed resins have come into use, and the first clinical studies with zirconia-modified denture bases have been published. A recent review also looked at zirconia together with other fillers such as titanium dioxide and glass fibres [7]. Hence, there is a need for an updated review that looks only at zirconia-reinforced denture base materials and compares them with conventional unreinforced materials, including newer processing methods and clinical data.

Therefore, the aim of this systematic review was to evaluate the mechanical, physical and clinical outcomes of zirconia-reinforced denture base materials in comparison with conventional unreinforced denture base materials.

MATERIALS AND METHODS

This systematic review was carried out and reported as per the PRISMA 2020 guidelines [8]. The protocol, which included the PICO framework, eligibility criteria and search strategy, was prepared before the search was started. The review protocol has been registered in PROSPERO

Structured Question and PICO Strategy

The review aimed to answer the following question: "In denture base materials used for the rehabilitation of edentulous patients, does the incorporation of zirconium dioxide, when compared with conventional unreinforced denture base material, result in improved mechanical, physical and clinical outcomes?". The question was framed using the Population, Intervention, Comparison and Outcome (PICO) format (Table 1).

The population (P) consisted of denture base material specimens prepared for laboratory testing, and edentulous adult patients (18 years and above) rehabilitated with complete dentures or overdentures in clinical studies. The intervention (I) was denture base material reinforced with zirconium dioxide in any form (micro-particles, nano-particles, 299anofibers, frameworks, silanised or non-silanised) and at any concentration, processed by any method. The comparison © was conventional denture base material of the same type without zirconia. The primary outcomes (O) were flexural strength, impact strength and fracture toughness. The secondary outcomes were surface hardness, surface roughness, water sorption and solubility, colour stability, microbial colonisation and patient satisfaction.

Table 1. PICO framework of the review

Element	Description
Population	Denture base specimens prepared for laboratory testing, and edentulous adults (18 years and above) treated with complete dentures or overdentures. Patients with HIV, hepatitis B or C, oral or systemic malignancy, uncontrolled diabetes mellitus, head and neck radiotherapy or severe xerostomia were not considered.
Intervention	Denture base material reinforced with zirconium dioxide in any form and concentration, processed by any method (heat-cure, auto-cure, injection moulding, CAD/CAM milling or 3D printing).
Comparison	Conventional unreinforced denture base material of the same type.
Outcomes	Primary: flexural strength, impact strength, fracture toughness. Secondary: surface hardness, surface roughness, water sorption and solubility, colour stability, microbial colonisation, patient satisfaction.

Search Strategy

Five electronic databases were searched: PubMed (MEDLINE), Scopus, Web of Science (Core Collection), Cochrane Library and Google Scholar. The search covered articles published in English from January 2014 to 13 October 2026. A ten-year window was chosen so that the review reflects the current state of denture base materials. Keywords and MeSH terms related to the denture base, zirconia and the outcomes of interest were combined using the Boolean operators "AND" and "OR". In PubMed, the search was limited by publication date and language. In Scopus, Web of Science and Cochrane Library, the filters available for study type and full-text availability were also applied. For Google Scholar, a simplified search string was used and the first 200 results were screened, as the platform does not support long Boolean strings. The search strings used for each database are given in Table 2.

Table 2. Search strategy used for each database

Database	Search string
PubMed	(("denture base"[MeSH Terms] OR "denture base"[tiab] OR "denture bases"[tiab] OR "denture base material"[tiab] OR "denture base resin"[tiab] OR "acrylic resin"[tiab] OR "polymethyl methacrylate"[tiab] OR "PMMA"[tiab] OR "complete denture"[tiab] OR "removable denture"[tiab]) AND ("zirconia"[tiab] OR "zirconium"[MeSH Terms] OR "zirconium oxide"[tiab] OR "zirconium dioxide"[tiab] OR "ZrO2"[tiab] OR "nano-zirconia"[tiab] OR "zirconia nanoparticles"[tiab]) AND ("flexural strength"[tiab] OR "impact strength"[tiab] OR "fracture resistance"[tiab] OR "fracture toughness"[tiab] OR "mechanical properties"[tiab] OR "surface hardness"[tiab] OR "surface roughness"[tiab] OR "water sorption"[tiab] OR "reinforcement"[tiab] OR "nanocomposite"[tiab]))
Scopus	TITLE-ABS-KEY (("denture base" OR "denture base material" OR "denture base resin" OR "acrylic resin" OR "polymethyl methacrylate" OR "PMMA" OR "complete denture" OR "removable denture") AND ("zirconia" OR "zirconium oxide" OR "zirconium dioxide" OR "ZrO2" OR "nano-zirconia" OR "zirconia nanoparticles") AND ("flexural strength" OR "impact strength" OR "fracture resistance" OR "fracture toughness" OR "mechanical properties" OR "surface hardness" OR "surface roughness" OR "water sorption" OR "reinforcement" OR "nanocomposite"))
Web of Science	TS = (("denture base" OR "denture base material" OR "denture base resin" OR "acrylic resin" OR "polymethyl methacrylate" OR "PMMA" OR "complete denture" OR "removable denture") AND ("zirconia" OR "zirconium oxide" OR "zirconium dioxide" OR "ZrO2" OR "nano-zirconia" OR "zirconia nanoparticles") AND ("flexural strength" OR "impact strength" OR "fracture resistance" OR "fracture toughness" OR "mechanical properties" OR "surface hardness" OR "surface roughness" OR "water sorption" OR "reinforcement" OR "nanocomposite"))
Cochrane Library	("denture base" OR "denture base material" OR "PMMA" OR "polymethyl methacrylate" OR "acrylic resin" OR "complete denture") AND ("zirconia" OR "zirconium oxide" OR "zirconium dioxide" OR "ZrO2" OR "nano-zirconia") AND ("flexural strength" OR "impact strength" OR "mechanical properties" OR "reinforcement" OR "fracture" OR "hardness")
Google Scholar	("denture base" OR "PMMA" OR "acrylic resin") AND ("zirconia" OR "zirconium oxide" OR "ZrO2") AND ("flexural strength" OR "reinforcement" OR "mechanical properties" OR "nanocomposite")

Eligibility Criteria

Studies were selected based on clearly defined inclusion and exclusion criteria.

Inclusion criteria

- In vitro studies, randomised controlled trials and prospective clinical studies that compared zirconia-reinforced denture base material with conventional unreinforced denture base material.
- Studies with a separate control group of unreinforced denture base material.
- Studies that reported at least one of the primary or secondary outcomes.
- Studies published in English between January 2014 and October 2026.

Exclusion criteria

- Case reports, case series, letters, editorials, narrative reviews, systematic reviews, theses and conference papers.
- Studies without an unreinforced control group.

- Studies in which zirconia was combined with another reinforcement (such as glass fibres, PEEK, titanium dioxide, magnesium oxide or aluminium borate) without a separate zirconia-only group, or in which the results of the zirconia-only group were not reported.
- Studies in which zirconia was added only to the repair resin of a fractured denture base.
- Studies on partial denture frameworks, denture teeth, denture liners, surface coatings, obturators, maxillofacial prostheses, orthodontic appliances, provisional restorations or fixed prostheses.
- Animal studies and studies on paediatric populations.
- Studies on PMMA–zirconia composites prepared for non-dental use, such as bone cement.
- Duplicate publications, and studies for which adequate information could not be obtained.

Study Selection

The records retrieved from all databases were combined in a single file. Duplicate records were removed by matching the titles and DOIs, followed by a manual check. The remaining records were screened by title and abstract against the eligibility criteria. The reports of potentially eligible studies were then sought. Eligibility was confirmed using the full text where it was available, and using the abstract and the reported summary data where the full text could not be accessed. Reports for which neither the full text nor an informative abstract could be obtained were recorded as not retrieved. Any doubt during selection was resolved by discussion. The reasons for exclusion at each stage were recorded, and the selection process is shown in the PRISMA flow diagram (Figure 1).

Data Extraction and Synthesis

Data were extracted using a standard form. The details recorded were the author and year, study design, type of denture base resin and processing method, form and concentration of zirconia, surface treatment of the particles, comparison group, sample size, outcomes tested and main findings. As the included studies differed widely in resin type, zirconia form and concentration, test methods and the way results were reported, a meta-analysis was not considered suitable. A narrative synthesis was therefore done and the results were grouped by outcome.

Risk of Bias Assessment

The risk of bias of the in vitro studies was assessed using the QUIN tool [9]. This tool has 12 criteria: clearly stated aims, sample size calculation, sampling technique, details of the comparison group, methodology, operator details, randomisation, method of outcome measurement, outcome assessor details, blinding, statistical analysis and presentation of results. Each criterion was scored as adequately specified (2), inadequately specified (1) or not specified (0). The total score was converted into a percentage, and the studies were graded as low risk (more than 70%), medium risk (50% to 70%) or high risk (less than 50%). The randomised clinical trials were assessed using the Cochrane RoB 2 tool [10], which covers five domains and grades each domain and the overall judgement as low risk, some concerns or high risk. The non-randomised clinical study was assessed using the ROBINS-I tool [11], which covers seven domains and grades the risk as low, moderate, serious or critical. The results were presented as traffic light plots.

RESULTS

Study Selection

A total of 239 records were obtained from the electronic search (PubMed, 167; Scopus, 20; Web of Science, 14; Cochrane Library, 3; Google Scholar, 35). Out of these, 42 duplicate records were removed and 197 unique records were screened by title and abstract. At this stage, 129 records were excluded. Most of these were studies on crowns, implant abutments and frameworks, fibre posts, veneers, denture teeth, provisional restorations, bone cement and PMMA–zirconia materials for non-dental use, along with reviews and studies published before 2014.

The reports of the remaining 68 records were sought, and 6 could not be retrieved. The remaining 62 reports were assessed for eligibility, and 21 were excluded. The reasons were: zirconia added only to the repair resin (n = 4), no zirconia-only group (n = 6), zirconia-only results not reported (n = 3), outcome not of interest (n = 4), control group not made of unreinforced resin (n = 2) and thesis or conference paper (n = 2). Finally, 41 studies were included in this review. The selection process is shown in Figure 1.

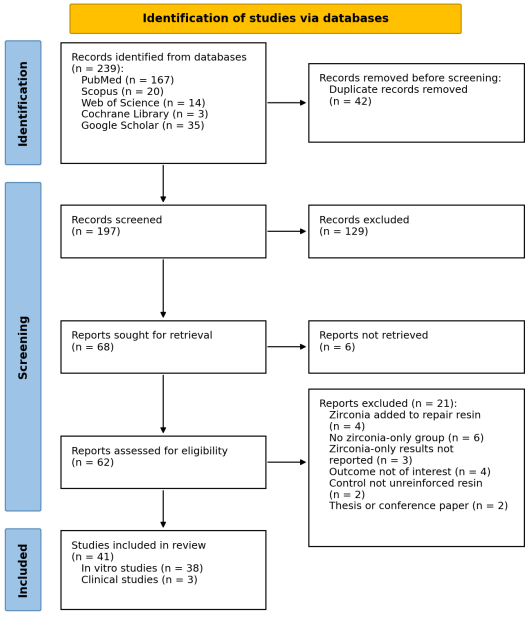

Figure 1. PRISMA 2020 flow diagram of the study selection process

Study Characteristics

The characteristics of the included studies are summarised in Table 3. The studies were published between 2014 and 2026. Thirty-eight were in vitro studies and three were clinical studies, of which two were randomised clinical trials [12, 13] and one was a non-randomised comparative study [14].

Among the in vitro studies, 28 used heat-cured PMMA, including six that used high-impact heat-cured resin [15–20]. Three studies used self-cured or cold-cured resin [21–23], and seven studies used 3D-printed denture base resin [24–30]. Zirconia was added as nanoparticles in most studies. Other forms were yttria-stabilised zirconia [15, 22, 29], recycled zirconia nanoparticles [23], zirconia microparticles from milled blanks [28] and electrospun zirconia nanofibres [30]. The particles were silanised in four studies [19, 30–32]. The concentration of zirconia ranged from 0.01 wt% [23] to 20 wt% [33]. Sample sizes ranged from 20 to 440 specimens.

The clinical studies included 20, 24 and 29 patients, with follow-up of 6 months, 18 months and up to 2 years, respectively [12–14]. Two used 3D-printed denture bases modified with zirconia nanoparticles [12, 13], and one used a CAD/CAM nano-zirconia framework inside the maxillary complete denture [14].

Table 3. Characteristics of the included studies

Study	Design	Denture base resin	Zirconia form and concentration	Comparator	Sample	Outcomes assessed
Ahmed & Ebrahim, 2014 [34]	In vitro	Heat-cured PMMA	Nano-ZrO2; 1.5, 3, 5, 7 wt%	Unmodified PMMA	NR	FS, FT, hardness
Kul et al., 2016 [35]	In vitro	Heat-cured PMMA	ZrO2 powder; 10 wt% (other fillers in separate groups)	Unmodified PMMA	144 (all groups)	FS, thermal conductivity
Gad et al., 2017 [21]	In vitro	Cold-cured PMMA (intact and repaired specimens)	Nano-ZrO2; 2.5, 5, 7.5 wt%	0 wt%	120	C. albicans adhesion
Ergun et al., 2018 [33]	In vitro	Heat-cured PMMA, thermocycled	Nano-ZrO2; 5, 10, 20 wt%	0 wt%	NR	Transverse strength, EM, Ra, hardness, WS, solubility
Begum et al., 2019 [36]	In vitro	Heat-cured PMMA	Nano-ZrO2; 3, 5, 7 wt%	Unmodified PMMA	40 bars; 40 denture bases	IS, dimensional accuracy
Zidan et al., 2019 [15]	In vitro	High-impact heat-cured PMMA	Yttria-stabilised nano-ZrO2; 1.5–10 wt%	0 wt%	NR	FS, FM, FT, IS, hardness

Study	Design	Denture base resin	Zirconia form and concentration	Comparator	Sample	Outcomes assessed
Alqahtani, 2020 [22]	In vitro	Self-cured PMMA	8Y-stabilised ZrO2 nanopowder (h-BN in separate groups)	Unmodified PMMA	NR	FS, EM, hardness
Gad et al., 2020 [37]	In vitro	Heat-polymerised PMMA	Nano-ZrO2; 0.5, 1, 2.5, 5 wt% (other fillers in separate groups)	0 wt%	260 (all groups)	Ra, hardness
Zidan et al., 2020a [16]	In vitro	High-impact heat-cured PMMA (complete dentures)	Nano-ZrO2; 3, 5 wt%	0 wt%	30 dentures	Equivalent FS with and without fatigue
Zidan et al., 2020b [17]	In vitro	High-impact heat-cured PMMA	Nano-ZrO2; 1.5–10 wt%	0 wt%	NR	WS, solubility (180 days)
Zidan et al., 2020c [18]	In vitro	High-impact heat-cured PMMA	Nano-ZrO2; 1.5–10 wt%	0 wt%	90	Colour change in water and cleansers
Gad et al., 2021a [38]	In vitro	Heat-polymerised PMMA	Nano-ZrO2; 2.5, 5 wt%	0 wt%	270	FS after cleanser immersion
Gad et al., 2021b [39]	In vitro	Heat-polymerised PMMA	Nano-ZrO2; 2.5, 5 wt%	0 wt%	420	Colour, Ra, hardness after cleanser immersion
Albasarah et al., 2021 [40]	In vitro	Heat-polymerised PMMA (1.0 to 2.5 mm thick)	Nano-ZrO2; 2.5, 5 wt%	0 wt%	120	FS, EM
Zidan et al., 2021 [19]	In vitro	High-impact heat-cured PMMA	Silanised and non-silanised nano-ZrO2; 3 wt%	0 wt%	45	FS, FM, hardness

Study	Design	Denture base resin	Zirconia form and concentration	Comparator	Sample	Outcomes assessed
Alhotan et al., 2021a [41]	In vitro	Heat-cured PMMA	Nano-ZrO2; 1.5, 3, 5, 7 wt% (other fillers in separate groups)	0 wt%	n = 10 per group	FS, hardness
Alhotan et al., 2021b [42]	In vitro	Heat-cured PMMA	Nano-ZrO2; 1.5, 3, 5, 7 wt% (other fillers in separate groups)	0 wt%	286 (all groups)	FT, IS
Alhotan et al., 2021c [31]	In vitro	Heat-cured PMMA	Silanised nano-ZrO2; 1.5, 3, 5, 7 wt% (other fillers in separate groups)	0 wt%	n = 5 per group	WS, solubility, hygroscopic expansion
Hamid et al., 2021 [43]	In vitro	Heat-polymerised PMMA, thermocycled	Nano-ZrO2; 1, 2.5, 5 wt%	0 wt%	NR	C. albicans adhesion, Ra, contact angle
Abualsaud et al., 2021 [44]	In vitro	Heat-polymerised PMMA	Nano-ZrO2; 2.5, 5, 7.5 wt%	0 wt%	20	Ra, C. albicans biofilm
Azmy et al., 2021 [45]	In vitro	Heat-polymerised PMMA	Nano-ZrO2; 3, 7 wt% (other fillers in separate groups)	0 wt%	280 (all groups)	Colour change after beverages
Gad et al., 2022 [46]	In vitro	Heat-polymerised PMMA (one-layer and two-layer packing)	Nano-ZrO2; 0.5, 1, 1.5 wt% (AgNPs in separate groups)	Unmodified resin	NR	FS, translucency, Ra, C. albicans adhesion

Study	Design	Denture base resin	Zirconia form and concentration	Comparator	Sample	Outcomes assessed
Alshaikh et al., 2022 [24]	In vitro	3D-printed resins (Next Dent, ASIGA); heat-polymerised reference	Nano-ZrO2; 0.5, 1, 3, 5 wt%	Unmodified 3D-printed resin	286	FS, EM, IS, hardness, Ra
Barapatre et al., 2022 [47]	In vitro	Heat-cured PMMA	Nano-ZrO2; 3 wt% (PEEK and hybrid in separate groups)	0 wt%	60	FS
Elzahar et al., 2022 [23]	In vitro	Cold-cured PMMA (sprinkle method)	Recycled HEMA-treated nano-ZrO2; 0.01–0.5 wt%	0 wt%	60	Transverse strength, IS, hardness, WS, solubility, cytotoxicity
Hada et al., 2022 [25]	In vitro	3D-printed photopolymer resin (0° and 90° print)	Zirconia filler; 3, 5, 10 wt%	0 wt%	NR	FS, EM, hardness
Azmy et al., 2022 [48]	In vitro	Heat-polymerised PMMA	Nano-ZrO2; 3, 7 wt% (other fillers in separate groups)	0 wt%	NR	FS, IS, hardness, wear
Khattar et al., 2023 [26]	In vitro	3D-printed resin, thermocycled; heat-polymerised reference	Nano-ZrO2; 0.5, 1, 3, 5 wt%	Unmodified 3D-printed resin	60	Ra, C. albicans adhesion
Srivastava et al., 2023 [20]	In vitro	High-impact heat-cured PMMA	ZrO2 powder (AgNPs in a separate group)	High-impact resin without filler	60	IS
Altaie, 2023 [49]	In vitro	Heat-cured PMMA	Nano-ZrO2; 5 wt% (other fillers in separate groups)	0 wt%	120 (all groups)	Hardness, wear, colour

Study	Design	Denture base resin	Zirconia form and concentration	Comparator	Sample	Outcomes assessed
Emam et al., 2024 [50]	In vitro	Heat-polymerised PMMA	Nano-ZrO2; 7.5 wt% (AgNPs in a separate group)	Unmodified resin	60 (all groups)	FS, EM, colour
Gad et al., 2024 [27]	In vitro	3D-printed resins (Next Dent, ASIGA) and heat-polymerised resin	Nano-ZrO2; 0.5, 1, 3, 5 wt%	0 wt%	440	Colour, Ra after cleanser immersion
Rostamzadeh et al., 2024 [32]	In vitro	Heat-cured PMMA	Silanised nano-ZrO2; 1, 5 wt% (TiO2 in separate groups)	0 wt%	25	FS
Zahari et al., 2024 [28]	In vitro	3D-printed resin; heat-polymerised reference	Zirconia microparticles from milled blanks; 2 wt%	Unmodified 3D-printed resin	NR	FS, FT, fungal adhesion
Majeed & Hamad, 2025 [29]	In vitro	3D-printed resin	Yttria-stabilised nano-ZrO2; 1, 3, 5, 7 wt%	Unmodified resin	100	FS, thermal conductivity
Wally et al., 2025 [51]	In vitro	Heat-cured PMMA	Nano-ZrO2; 0.5, 1 wt% (MgO groups separate)	0 wt%	280 (all groups)	FS, hardness, Ra, density
Syed & Fawzy, 2026 [30]	In vitro	3D-printed resin	Silanised electrospun zirconia nanofibres; 1, 3 wt%	0 wt%	NR	DC, hardness, FS, FM, FT, self-healing
Bhutoria et al., 2026 [52]	In vitro	Heat-cured PMMA (over denture base specimens, thermocycled)	Nano-ZrO2; 3, 7 wt%	0 wt%	36	FS, surface characteristics

Study	Design	Denture base resin	Zirconia form and concentration	Comparator	Sample	Outcomes assessed
Nishiyama et al., 2018 [14]	Non-randomised clinical study	Maxillary complete denture	CAD/CAM Ce-TZP/Al2O3 nano-zirconia framework	Conventional complete denture	29 patients; up to 2 years	Denture fracture, patient satisfaction
Albadwi et al., 2025 [12]	RCT (parallel)	3D-printed mandibular two-implant overdenture base	Nano-ZrO2; 3 wt%	Unmodified 3D-printed resin	20 patients; 6 months	Ra, peri-implant indices, bacterial and C. albicans counts
Ahmed Teama et al., 2025 [13]	RCT (three arms)	3D-printed maxillary complete denture	Nano-ZrO2; 0.4 wt% (TiO2 arm separate)	Unmodified 3D-printed resin	24 patients; 18 months	S. aureus and C. albicans counts, patient satisfaction

FS, flexural strength; FM, flexural modulus; EM, elastic modulus; FT, fracture toughness; IS, impact strength; Ra, surface roughness; WS, water sorption; DC, degree of conversion; h-BN, hexagonal boron nitride; HEMA, 2-hydroxyethyl methacrylate; AgNPs, silver nanoparticles; RCT, randomised controlled trial; NR, not reported in the available report.

Risk of Bias

The QUIN scores of the in vitro studies are given in Table 4, and the domain-level judgements are shown in Figures 2 and 3. None of the in vitro studies had a low risk of bias. Twenty-four studies had a medium risk and 14 had a high risk. All studies clearly stated their aims, and almost all described the comparison group well. However, none of the studies reported a sample size calculation, operator details, randomisation of specimens, details of the outcome assessor or blinding. Statistical methods and results were reported in most studies, but with varying detail.

Table 4. QUIN scores of the included in vitro studies

Study	Total score (out of 24)	Percentage	Risk of bias
Ahmed & Ebrahim, 2014 [34]	9	37.5%	High
Kul et al., 2016 [35]	13	54.2%	Medium
Gad et al., 2017 [21]	12	50.0%	Medium
Ergun et al., 2018 [33]	8	33.3%	High
Begum et al., 2019 [36]	11	45.8%	High
Zidan et al., 2019 [15]	12	50.0%	Medium
Alqahtani, 2020 [22]	8	33.3%	High
Gad et al., 2020 [37]	13	54.2%	Medium
Zidan et al., 2020a [16]	14	58.3%	Medium
Zidan et al., 2020b [17]	11	45.8%	High
Zidan et al., 2020c [18]	14	58.3%	Medium
Gad et al., 2021a [38]	12	50.0%	Medium
Gad et al., 2021b [39]	12	50.0%	Medium
Albasarah et al., 2021 [40]	14	58.3%	Medium
Zidan et al., 2021 [19]	13	54.2%	Medium
Alhotan et al., 2021a [41]	10	41.7%	High
Alhotan et al., 2021b [42]	12	50.0%	Medium

Study	Total score (out of 24)	Percentage	Risk of bias
Alhotan et al., 2021c [31]	13	54.2%	Medium
Hamid et al., 2021 [43]	12	50.0%	Medium
Abualsaud et al., 2021 [44]	13	54.2%	Medium
Azmy et al., 2021 [45]	13	54.2%	Medium
Gad et al., 2022 [46]	11	45.8%	High
Alshaikh et al., 2022 [24]	12	50.0%	Medium
Barapatre et al., 2022 [47]	13	54.2%	Medium
Elzahar et al., 2022 [23]	12	50.0%	Medium
Hada et al., 2022 [25]	12	50.0%	Medium
Azmy et al., 2022 [48]	11	45.8%	High
Khattar et al., 2023 [26]	14	58.3%	Medium
Srivastava et al., 2023 [20]	13	54.2%	Medium
Altaie, 2023 [49]	9	37.5%	High
Emam et al., 2024 [50]	12	50.0%	Medium
Gad et al., 2024 [27]	13	54.2%	Medium
Rostamzadeh et al., 2024 [32]	10	41.7%	High
Zahari et al., 2024 [28]	11	45.8%	High
Majeed & Hamad, 2025 [29]	10	41.7%	High
Wally et al., 2025 [51]	10	41.7%	High
Syed & Fawzy, 2026 [30]	10	41.7%	High
Bhutoria et al., 2026 [52]	14	58.3%	Medium



Figure 2. Traffic light plot of the risk of bias of the in vitro studies (QUIN tool)

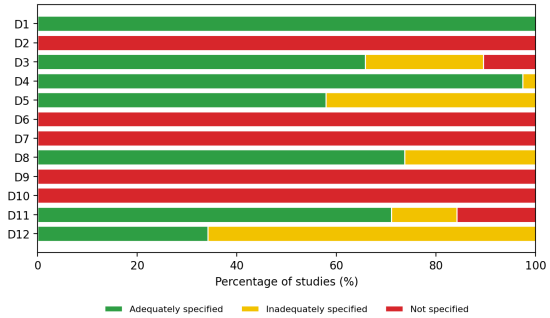

Figure 3. Summary of the QUIN judgements across the 12 domains

The RoB 2 judgements for the two randomised trials are shown in Figure 4. Both trials stated that patients were randomly allocated, but the method of sequence generation and allocation concealment was not clear, and blinding of patients and operators was not described. The trial by Albadwi et al. was judged to have some concerns overall [12]. The trial by Ahmed Teama et al. was judged to have a high risk of bias [13], mainly because patient satisfaction is a subjective outcome and was assessed without reported blinding. This trial was also registered retrospectively. The non-randomised study by Nishiyama et al. was judged to have a serious risk of

bias (Figure 5), mainly because of confounding due to the lack of randomisation and the unblinded assessment of patient satisfaction [14].

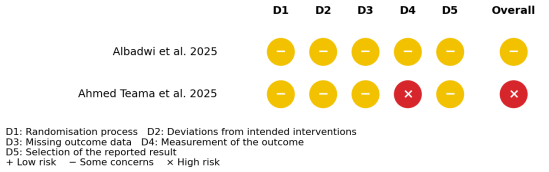

Figure 4. Traffic light plot of the risk of bias of the randomised clinical trials (RoB 2 tool)



Figure 5. Traffic light plot of the risk of bias of the non-randomised clinical study (ROBINS-I tool)

Outcomes

Table 5. Main findings of the included studies

Study	Main findings (zirconia-reinforced vs unreinforced)
Ahmed & Ebrahim, 2014 [34]	FS, FT and hardness increased significantly; best results at 7 wt%.
Kul et al., 2016 [35]	Thermal conductivity increased; FS decreased significantly with 10 wt% ZrO2.
Gad et al., 2017 [21]	C. albicans adhesion decreased significantly with ZrO2; lowest counts in intact cold-cured groups.
Ergun et al., 2018 [33]	Transverse strength decreased at all levels; hardness higher at 5 and 10 wt%; Ra higher at 20 wt%; WS and solubility increased with concentration.
Begum et al., 2019 [36]	IS decreased as concentration increased (lowest at 7 wt%); dimensional accuracy improved.
Zidan et al., 2019 [15]	FS increased at 3 wt% (84 ± 6 vs 72 ± 9 MPa); FM increased; FT rose but not significantly; IS decreased except at 5 wt%; hardness increased with concentration.
Alqahtani, 2020 [22]	FS, EM and hardness increased with filler content; hardness about four times higher with 5 wt% 8Y-ZrO2.
Gad et al., 2020 [37]	Hardness increased at all levels; Ra unchanged at 0.5 wt% but increased at higher levels.
Zidan et al., 2020a [16]	Equivalent FS of dentures increased at 5 wt% (134.9 ± 13.9 vs 106.3 ± 21.3 Mpa); fatigue loading slightly reduced strength.
Zidan et al., 2020b [17]	No significant difference in WS; lowest solubility at 3 wt%; solubility higher at 10 wt% in artificial saliva.
Zidan et al., 2020c [18]	Colour change increased with zirconia content and time; 3 wt% remained clinically acceptable.
Gad et al., 2021a [38]	FS of zirconia-modified resin decreased after 180 and 365 days in denture cleansers.
Gad et al., 2021b [39]	Cleansers increased Ra, reduced hardness and changed colour of both modified and unmodified resin.
Albasarah et al., 2021 [40]	FS and EM increased; highest FS with 5 wt% at 2 mm (125.4 ± 18.3 Mpa); 1.5 mm suggested as minimum thickness.
Zidan et al., 2021 [19]	Silanised ZrO2 increased FS (83.5 ± 6.2 vs 72.4 ± 8.6 Mpa) and hardness; non-silanised ZrO2 reduced FS (59.9 ± 7.1 Mpa).
Alhotan et al., 2021a [41]	FS increased at 3 wt%; hardness increased at 3 wt% and above.
Alhotan et al., 2021b [42]	FT increased at 1.5 and 3 wt%; no significant change in IS.
Alhotan et al., 2021c [31]	No significant increase in WS, solubility or hygroscopic expansion.
Hamid et al., 2021 [43]	C. albicans adhesion reduced before and after ageing; Ra increased; contact angle decreased.
Abualsaud et al., 2021 [44]	Ra increased; C. albicans count reduced, but not significantly.
Azmy et al., 2021 [45]	Lower colour change than unmodified resin after beverages; 3 wt% better than 7 wt%.
Gad et al., 2022 [46]	FS increased and C. albicans adhesion reduced; Ra unchanged; translucency reduced in one-layer specimens.

Study	Main findings (zirconia-reinforced vs unreinforced)
Alshaikh et al., 2022 [24]	FS, IS and hardness of 3D-printed resin increased; no change in Ra or EM; still weaker than heat-polymerised resin.
Barapatre et al., 2022 [47]	FS higher with 3 wt% ZrO2 (84.48 vs 74.86 Mpa).
Elzahar et al., 2022 [23]	Low concentrations improved transverse strength, IS, hardness, WS and solubility; optimum 0.3 wt%; reported to be safe on cytotoxicity testing.
Hada et al., 2022 [25]	FS and EM lower at 5 and 10 wt%; 3 wt% higher than control only at 90° print direction; hardness increased with content.
Azmy et al., 2022 [48]	FS, IS, hardness and wear resistance improved at 3 and 7 wt%.
Khattar et al., 2023 [26]	Ra unchanged at low levels and higher at 3 wt%; lowest C. albicans adhesion at 0.5 wt%.
Srivastava et al., 2023 [20]	IS highest in the zirconia group (7.5 vs 5.51 kJ/m² for unfilled high-impact resin).
Altaie, 2023 [49]	Microhardness and wear resistance higher; colour change higher than control.
Emam et al., 2024 [50]	FS and EM significantly higher; colour change increased.
Gad et al., 2024 [27]	Cleansers changed colour and increased Ra of both modified and unmodified 3D-printed resins.
Rostamzadeh et al., 2024 [32]	FS highest at 1 wt% (98.53 ± 2.77 Mpa; 22.08 Mpa above control); 5 wt% lower than 1 wt%.
Zahari et al., 2024 [28]	FS lower than unmodified printed resin (104.77 vs 122.17 Mpa) but higher than heat-polymerised resin; fewer microbial colonies.
Majeed & Hamad, 2025 [29]	FS and thermal conductivity of 3D-printed resin increased significantly.
Wally et al., 2025 [51]	FS increased and Ra decreased; hardness decreased as concentration increased.
Syed & Fawzy, 2026 [30]	FS, hardness and FT increased; degree of conversion decreased.
Bhutoria et al., 2026 [52]	After thermocycling, FS about 75% to 90% higher with 7 wt%; all groups above ISO minimum of 65 Mpa; Ra increased at higher levels.
Nishiyama et al., 2018 [14]	No denture fractures in either group over up to 2 years; satisfaction improved in both groups with no significant difference.
Albadwi et al., 2025 [12]	Over 6 months, lower Ra, better peri-implant indices and lower bacterial and C. albicans counts in the zirconia group.
Ahmed Teama et al., 2025 [13]	Strongest antifungal effect with zirconia at 12 and 18 months; higher patient satisfaction than unmodified dentures.

FS, flexural strength; FM, flexural modulus; EM, elastic modulus; FT, fracture toughness; IS, impact strength; Ra, surface roughness; WS, water sorption.

Flexural strength

Flexural strength was tested in 23 in vitro studies. Of the 22 studies that compared it with an unreinforced control, 18 reported an increase in at least one zirconia group [15, 16, 19, 22–24, 29, 30, 32, 34, 40, 41, 46–48, 50–52]. In heat-cured PMMA, the flexural strength of the control groups was about 72 to 75 Mpa, and it rose to about 84 Mpa with 3 wt% zirconia [15, 47]. Higher values were seen in some studies, such as 125.4 Mpa with 5 wt% zirconia [40] and 98.53 Mpa with 1 wt% silanised zirconia [32]. When whole complete dentures were tested, 5 wt% zirconia increased the equivalent flexural strength from 106.3 to 134.9 Mpa [16].

Four studies reported a decrease in strength. Two of these used high concentrations of 10 to 20 wt% [33, 35], and two used 3D-printed resins [25, 28]. The effect also depended on the concentration within the studies that showed a gain. Several studies found the best results at low to moderate levels, between 0.3 and 5 wt% [15, 23, 32, 41]. However, three studies found good results at 7 or 7.5 wt% [34, 50, 52]. Surface treatment of the particles was also important. Silanised zirconia increased strength, while the same amount of non-silanised zirconia reduced strength below that of the control [19]. Zirconia also helped to keep the strength of thin denture bases, and a thickness of 1.5 mm was found to be acceptable [40]. After ageing, strength was reduced by fatigue loading [16] and by long-term immersion in denture cleansers [38], but reinforced overdenture bases stayed above the ISO minimum of 65 Mpa after thermocycling [52].

In 3D-printed resins, the results were mixed. Three studies reported higher flexural strength with

zirconia [24, 29, 30], while two reported lower strength than the unmodified printed resin [25, 28]. Even when zirconia improved the printed resin, it remained weaker than heat-polymerised resin in one study [24].

Impact strength and fracture toughness

Impact strength was tested in seven studies, and the results were mixed. It increased in four studies [20, 23, 24, 48], decreased in two [15, 36] and did not change in one [42]. Fracture toughness was tested in four studies. It increased in three studies [30, 34, 42], and a small rise that was not significant was seen in one study [15].

Elastic modulus

Elastic or flexural modulus increased with zirconia in four studies [15, 22, 40, 50]. Two studies found no significant change [19, 24], and one found lower values at 5 and 10 wt% in a 3D-printed resin [25].

Surface hardness

Surface hardness was compared between zirconia and control groups in 14 studies. Thirteen reported an increase [15, 19, 22–25, 30, 33, 34, 37, 41, 48, 49], and one reported a decrease at higher concentrations [51]. In general, hardness rose as the zirconia concentration increased. A nearly four-fold rise was seen with 5 wt% yttria-stabilised zirconia in self-cured resin [22]. Long-term use of denture cleansers reduced the hardness of both modified and unmodified resin [39].

Surface roughness

Surface roughness increased with zirconia in six studies, usually at higher concentrations [26, 33, 37, 43, 44, 52]. It did not change in two studies [24, 46] and decreased in one [51]. At low concentrations of about 0.5 wt%, roughness was not affected [26, 37]. Denture cleansers increased the roughness of both modified and unmodified resins [27, 39].

Water sorption and solubility

Four studies tested water sorption and solubility. Two found no significant increase with zirconia [17, 31], one found an improvement at low concentrations [23] and one found an increase as the concentration rose up to 20 wt% [33]. Solubility was higher at 10 wt% in artificial saliva [17].

Colour stability

Colour stability was tested in six studies, with mixed results. Zirconia improved the colour stability of PMMA after immersion in beverages in one study [45]. In three studies, colour change was higher with zirconia [18, 49, 50], although 3 wt% remained within clinically acceptable limits [18]. Denture cleansers changed the colour of both modified and unmodified resins [27, 39]. Zirconia also reduced translucency in one-layer packed specimens [46].

Microbial colonisation

Six in vitro studies tested microbial colonisation. Five reported lower Candida albicans adhesion or fewer microbial colonies with zirconia [21, 26, 28, 43, 46], and one found a reduction that was not significant [44]. The effect was seen even after artificial ageing [43] and was greatest at low concentrations in one 3D-printed resin [26].

Other properties

Zirconia increased the thermal conductivity of PMMA [29, 35], improved the dimensional accuracy of denture bases [36] and improved wear resistance [48, 49]. Zirconia 311anofibers reduced the degree of conversion of 3D-printed resin [30]. Recycled zirconia nanoparticles were reported to be safe on cytotoxicity testing [23].

Clinical outcomes

Three clinical studies were included. In patients with maxillary complete dentures, a CAD/CAM nano-zirconia framework was compared with conventional dentures. No denture fractures were seen in either group during up to 2 years of follow-up, and patient satisfaction improved in both groups without a significant difference [14]. In patients with two-implant mandibular overdentures, 3 wt% zirconia in a 3D-printed base resulted in lower surface roughness, better peri-implant tissue health and lower bacterial and *Candida albicans* counts over 6 months [12]. In patients with maxillary complete dentures, 0.4 wt% zirconia in a 3D-printed base showed the strongest antifungal effect at 12 and 18 months, and patient satisfaction was higher than with the unmodified denture base [13].

DISCUSSION

This systematic review evaluated the performance of zirconia-reinforced denture base materials in comparison with conventional unreinforced materials. Most of the included in vitro studies showed that zirconia improved the flexural strength and surface hardness of denture base resin. The clinical studies suggested a reduction in microbial colonisation. However, the gain in strength was not seen in every study, and it depended on the concentration, the surface treatment of the particles and the type of resin.

The improvement in strength can be explained by the properties of zirconia. Zirconia particles are much stronger and harder than PMMA. When they are spread evenly in the resin, they take up part of the load and stop or turn away cracks as they grow [4]. Zirconia can also resist crack growth by transformation toughening, where a change in its crystal phase near the crack tip creates compressive stress [5]. The rise in surface hardness seen in almost all studies is also expected, as zirconia is a hard ceramic filler.

The concentration of zirconia played a major role. Most studies found the best results between about 1 and 5 wt% [15, 32, 41]. At high levels of 10 to 20 wt%, strength fell below that of the control [33, 35]. At such levels, the particles tend to form clusters. These clusters act as weak points where stress builds up and cracks start [4, 6]. A few studies found good results even at 7 or 7.5 wt% [34, 50, 52], which may be due to differences in particle size, mixing method and dispersion. Surface treatment of the particles

was also important. Silane improves the bond between the inorganic zirconia and the organic resin. Without silane, zirconia reduced the strength of the resin [19]. This agrees with an earlier review, which suggested that silanised nanoparticles give better results [4].

The results for impact strength were not consistent. Zirconia makes the resin stiffer, and a stiffer material may absorb less energy before breaking. This may explain why impact strength fell in some studies, including one on high-impact resin, which already contains rubber-like phases to absorb impact [15, 36]. On the other hand, impact strength improved in four studies [20, 23, 24, 48]. Hence, zirconia seems to be more helpful against flexural fatigue fracture than against impact fracture, but more studies are needed on this point.

3D-printed denture bases are now widely used, but they are weaker than heat-polymerised PMMA [24]. The results for zirconia in printed resins were mixed. Some studies found a gain in strength [24, 29, 30], while others found a loss [25, 28]. Zirconia may interfere with light curing, as it reduced the degree of conversion of printed resin in one study [30], and this may explain the lower strength seen in some studies. Print direction also changed the effect of zirconia [25]. These points should be kept in mind before zirconia-modified printed resins are used in high-stress situations.

Long-term behaviour is important for any denture base material. Zirconia-modified resin lost some strength after fatigue loading [16] and after long immersion in denture cleansers [38]. Cleansers also increased roughness and changed colour, whether or not zirconia was present [27, 39]. Hence, zirconia does not protect the denture base from the effects of cleansers, and patients should still be advised to use mild cleansers. Water sorption and solubility were generally not affected at low concentrations [17, 31], but increased at very high concentrations [33]. The effect on colour was mixed, and higher zirconia levels tended to cause more colour change [18, 49, 50]. Surface roughness also tended to increase at higher concentrations, which may favour plaque retention [37, 43]. On the positive side, reinforced overdenture bases kept their strength above the ISO limit after thermocycling [52], and zirconia allowed thinner denture bases without loss of strength [40].

Zirconia also reduced Candida albicans adhesion in most in vitro studies and in both randomised trials [12, 13, 21, 26, 43, 46]. This may be due to changes in surface properties, such as a smoother surface or lower contact angle [12, 43], and to the antimicrobial effect reported for zirconia nanoparticles. Lower fungal load may help to reduce denture stomatitis. However, the clinical evidence is limited. The three clinical studies were small and had a short to medium follow-up. Only one reported denture fracture, and no fractures occurred in either group [14]. Therefore, the clinical benefit in terms of fewer fractures has not yet been shown.

The findings of this review agree with the earlier systematic review on zirconia and PMMA, which also found that zirconia increases flexural strength and that the concentration has the greatest influence on the result [6]. The present review adds newer studies on 3D-printed resins, ageing in denture cleansers, overdenture bases, microbial colonisation and the first clinical studies. A recent review that combined zirconia with other fillers also reported improved mechanical strength with zirconia [7].

From a clinical point of view, a zirconia-reinforced denture base may be useful in patients with a history of repeated denture fracture, in thin denture bases and over implant attachments, where the base is weak. Based on the current evidence, a concentration of about 1 to 5 wt% of silanised nanoparticles appears to be a reasonable choice for heat-cured resin, while high concentrations should be avoided.

Limitations

This review has some limitations. Most of the included studies were in vitro studies, and their results may not fully apply to the oral environment. The studies differed in resin type, zirconia form and concentration, specimen size and test methods, so a meta-analysis could not be done. No in vitro study had a low risk of bias, mainly because sample size calculation, randomisation and blinding were not reported. For some studies, data were taken from the abstract and the reported summary values, as the full text could not be accessed. In Scopus and Google Scholar, only the records exported after filtering were screened, and six reports could not be retrieved, so some eligible studies may have been missed. Only English-language studies were included. Finally, the clinical studies were small, had limited follow-up and mostly did not report fracture of the denture.

CONCLUSION

Within the limitations of this review, the following conclusions can be drawn:

- The addition of zirconia improves the flexural strength and surface hardness of heat-cured and self-cured denture base resin in most in vitro studies.
- The best results are seen at low to moderate concentrations, mainly between 1 and 5 wt%. High concentrations of 10 wt% or more, and non-silanised particles, may reduce strength.
- The effect of zirconia on 3D-printed denture base resins, impact strength, surface roughness and colour stability is not consistent.
- Zirconia does not prevent the adverse effects of denture cleansers on strength, roughness and colour.

- Zirconia reduces Candida albicans colonisation in most in vitro studies and in early clinical trials.
- Well-designed randomised clinical trials with longer follow-up, and with denture fracture as an outcome, are needed before firm clinical recommendations can be made.

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