



Review Article

The impact of nanoparticles-modified repair resin on denture repairs: a systematic review



Mohammed M. Gad^{a,*}, Ahmad M. Al-Thobity^b

^a Department of Substitutive Dental Sciences, College of Dentistry, Imam Abdulrahman Bin Faisal University, Saudi Arabia

^b Department of Substitutive Dental Sciences, College of Dentistry, Imam Abdulrahman Bin Faisal University, Dammam, Saudi Arabia

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ABSTRACT

This study aimed to evaluate the effect of nanoparticles on the mechanical properties of acrylic denture repairs. The review was designed following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guidelines. Database search was conducted involving articles published from 2000 to 2020 using the following keywords: PMMA/nanoparticles, denture repair/nanoparticles, and repair strength/nanoparticles. PubMed/MEDLINE, Embase, Google Scholar, Scopus, and EBSCOhost were used to find only those studies used repair resin reinforced with nanoparticles for denture repairs. Due to variations between nanoparticles types, sizes, and testing properties, the quantitative statistical meta-analysis couldn't be conducted. Therefore, a descriptive data analysis was applied. Out of 379 articles, 8 articles were included; three nanoparticles, zirconium oxide (nano-ZrO₂), silicon oxide (nano-SiO₂), and aluminum oxide (nano-Al₂O₃) nanoparticles were used as reinforcements to repair resin. Seven studies investigated the effects of 0.25–7.5 wt.% nano-ZrO₂ on the mechanical properties of repaired denture bases and reported positive effects with high concentrations. Two studies study investigated 0.25–0.75 wt.% nano-SiO₂ and found that low % nano-SiO₂ concentrations improved repair strength while, one study showed that 1 and 1.5 wt.% nano-Al₂O₃ increased the flexural strength. Although nanoparticles offer positive effects on the properties of denture repair, inadequate studies exist. Therefore, further investigations are required.

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1. Introduction

Polymethylmethacrylate (PMMA) has been used widely to fabricate removable dental prostheses. It exhibits favorable mechanical and optical features on intraoral functions [1]. However, the ease of fracture due to misuse, improper handling of the removable prosthesis, or the exertion of masticatory forces is counted as one of the main drawbacks of the material [2]. Fabricating a new prosthesis consumes clinical and laboratory time; it is costly; and it may not meet patients' expectations in relation to their previous denture experience(s) [3].

Therefore, a denture repair procedure serves as a suitable clinical step. Proper denture repair should maintain the original strength of the prosthesis, the dimensional accuracy, the aesthetic

merits, and the simplicity technique [4]. Until now, autopolymerized acrylic resin has been utilized as a repair material. However, its declined strength, porous nature, and high surface roughness has made it the subject of numerous investigations aimed at enhancing its properties [5,6]. Various researchers have attempted to improve the biomechanical behavior of the denture repair using different techniques and materials including microwave polymerized, visible light polymerized, and heat polymerized resins [7,8].

Another important factor affecting denture repair strength is repair material reinforcement [4]. Previously, improving denture repair strength has been investigated using reinforced materials such as metal wires, fibers, fillers, and micro-fillers and it has resulted in repairing dentures with reasonable mechanical properties [9,10]. Although these materials have improved the strength of denture repairs, researchers are still aiming to get repaired denture strength close to the original denture base strength and for it to have good physical properties. This has necessitated the search for new reinforcement materials.

* Corresponding author at: College of Dentistry, Imam Abdulrahman Bin Faisal University, P.O. Box 1982, Dammam 31441, Saudi Arabia.
E-mail address: mmjad@iau.edu.sa (M.M. Gad).

Recently, nanoparticles have been introduced in the dental field to improve the mechanical properties of acrylic resins [11,12]. The resulting nanocomposite products possess high properties compared to pure materials and this was demonstrated with a PMMA denture base reinforced with different nanoparticles [13]. According to the aforementioned improvement in the denture base with the addition of different nano-fillers, their potential to repair resin was suggested. Therefore, nanoparticles have been recently added to denture repair materials to explore their effects on the mechanical and antimicrobial properties of the acrylic resin. The aim of this systematic review was to explore the effect the nanoparticles on the mechanical properties of the repaired denture base materials.

2. Materials and methods

The following question was addressed in this review: Do nanoparticle materials positively influence the mechanical properties of repaired denture base materials? Studies included in this review were original laboratory reports whose results were based on the impact of the addition of nanoparticles to repair resin materials on the properties repaired denture. This review was performed according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guidelines (Fig. 1) [14].

2.1. Eligibility criteria

Articles included in this review were limited to peer-reviewed publications. Two investigators scrutinized the titles of the studies to exclude those that did not obviously examine the effects of nanoparticles on repair materials. Whenever the publications' titles were not sufficiently descriptive for judgment, abstracts were scrutinized to check their qualification for the study. Studies included in this review met the following inclusion criteria: Articles were original, in-vitro studies investigated effect of nanoparticles on mechanical properties, full-text publications, and published in English. Additionally, each study that was included involved specimens of adequate size with results that were statistically analyzed. All units mentioned in the included studies followed the international system of units (SI) while other units were converted to SI units. Each specimen's dimensions and testing methodology were in accordance with ADA specifications [15]. Excluded were review articles, letters to the editor, case report studies, literature reviews, commentaries, incomplete studies, abstracts, articles published in a language other than English, articles with missing brand names, and those involving reinforcement materials rather than nanoparticles.

2.2. Search strategy

An extensive search was performed through the following scientific databases: PubMed/MEDLINE, Embase, Google Scholar, Scopus, and EBSCOhost to find studies published from January 2000 to April 2020. A combination of the following keywords was used: PMMA, nanoparticles, denture repair, repair strength. A manual search was applied following the electronic search to check the references of the relevant review articles.

2.3. Data management, screening, and selection

Data were extracted by two investigators using an Excel format designed to include the following information: authors' names, publication year, nanoparticles (brand name, size, and treatment), sample dimensions, sample size, samples' conditioning, tested properties, effects, and outcomes (Table 1). Discussion between authors was made whenever the data were missing or ambiguous. Studies in which the data were not clearly stated were excluded

from the analysis. The effects of nanoparticles were tabulated per the properties.

2.4. Risk of bias assessment

After the search strategy was completed, modified Consolidated Standards of Reporting Trials (CONSORT) guidelines were performed to rate the articles' quality [16,17]. After assessing the individual article, the parameters were conveyed as yes or no (Table 2). The Cochrane risk of bias tool was used and adjusted to achieve the specified goal of the study [16,17]. The risk of bias was assessed according to the following criteria: interpretation of sample size calculation, sample allocation, and concealment, following ISO/ADA standards in the analysis methods [15], the operator blinding, and selective outcome reported. If the criteria written in the study were clear, it received a score of 0. If the required data was inadequately or indefinitely mentioned, the score was set at 1, and if a specific approach was undisclosed, the score was established as 2. Articles, which secured count 0 to 3 were determined as low risk of bias, counts between 4 to 7 as moderate, and between 8 to 10 as high-risk [18]. The assessment was applied individually by two authors, and then discussion was performed to resolve any uncertainty after a valid debate (Table 3).

2.5. Data analysis

For statistical analysis, due to the limited number of included studies and variations between tested properties and different methodologies, (different type, size, and concentrations of nanoparticles, tested properties, repair surface treatment), (which didn't fit any analysis model), quantitative statistical meta-analysis couldn't be conducted. Therefore, a descriptive data analysis was applied.

3. Results

3.1. Data selection

The initial search among 5 databases provided 379 studies (Fig. 1). Articles with titles that were clearly irrelevant to the research question were excluded from the list. Meanwhile, duplicated titles and studies not published in English were eliminated. Therefore, 81 articles were included for review of their abstracts, with an extensive focus on their relevance to our research question. This review yielded 28 studies, each of which was subjected to a full-text review to ensure that it met inclusion criteria for this study. Eight studies that met the inclusion criteria were included for data extraction and results analysis. Table 1 includes a summary of the study's methods, results, and outcomes.

3.2. Risk of bias

Table 3 presents the risk of bias for the included studies. The risks of bias generated were primarily attributed to the sample size estimation, allocation or concealment of specimens and blinding of the allocated interventions by investigators. None of the articles reported on whether or not blinding of the operator was performed during testing. All studies failed to explain the concealment technique and allocation method used to distribute samples into different groups while 2 other studies reported on sample size estimation clearly.

3.3. Data analysis

Applying the inclusion criteria, out of 379 articles, 8 articles were included; three nanoparticles, zirconium oxide nanoparti-

Table 1
Studies details of tested properties of various repaired PMMA denture base with different nanoparticles as stated in the included studies.

Article	Nano-filler type /wt.%/ size	Sample size	Conditioning of nanoparticles	Sample dimensions in mm	Repair Surface design / treatment/ repair gap	Tested properties	Effect Increase/ decrease	Outcome
Gad et al. 2016 [19]	Nano-ZrO ₂ 2.5%, 5% <100 nm	10	Unconditioned	65 × 10 × 2.5	45° bevel/ MMA(180 s) 2.5mm	Flexural strength (MPa)	Increase	Incorporation of nano-ZrO ₂ into the repair resin improved the flexural strength of repaired denture bases. Incorporation of nano-ZrO ₂ into the repair resin improved the flexural strength of repaired denture bases. Incorporation of nano-ZrO ₂ into the repair resin decreased impact strength, especially with high nano-ZrO ₂ concentrations.
Gad et al. 2016 [20]	Nano-ZrO ₂ 2.5%, 5% 7.5% 90 nm	10	Conditioned with silane	65 × 10 × 2.5	45° bevel/ Butt/ MMA(180 s) 2.5 mm	Flexural strength (MPa)	Increase	
	Nano-ZrO ₂ 2.5% 5% 7.5% 90 nm	10	Conditioned with silane	50 × 6 × 4, V-shaped notch	45° bevel/ Butt MMA(180 s) 2.5mm	Impact strength (kJ/m [2])	Decreased with high concentrations	
Tamore et al. 2018 [21]	Nano-Al ₂ O ₃ 1%, 1.5% <50nm	10	Conditioned with silane	65 × 10 × 2.5	Butt MMA(180 s) SCP 3mm	Flexural strength (MPa)	Increase	Repaired heat-polymerized acrylic resin incorporated with 1.5% Al ₂ O ₃ in the group surface treated with silicone carbide paper showed the highest flexural strength
Abushowmi et al. 2019 [23]	Nano-ZrO ₂ 0.25%, 0.5%, 0.75% 40 nm nano-SiO ₂ 0.25%, 0.5%, 0.75% 15 nm	10	Conditional Salinized	65 × 10 × 2.5	45°-Bevel	Flexural strength (MPa)	Increased as concentrations increased	Both nano-fillers increased the flexural and impact strengths of repaired denture. High concentrations of nano-ZrO ₂ (0.75%) and low concentration of nano-SiO ₂ (0.25%) - or proved to be a promising technique to enhance repair strength.
				55 × 10 × 10	45°-Bevel	Impact strength (kJ/m [2])		
				65 × 10 × 2.5	45°-Bevel	Flexural strength (MPa)		
Gad et al. 2019 [24]	nano-SiO ₂ 0.25%, 0.5%, 0.75% 12 nm	10	Conditioned with silane	65 × 10 × 2.5	Butt 45°-Bevel MMA/120 s	Flexural strength (MPa)	Increased with low concentrations while decreased significantly as the % increased	Nano-SiO ₂ addition to repair resin and 45°-beveled repair surface increased FS of repaired acrylic resin.
Gad et al. 2020 [25]	Nano-ZrO ₂ 2.5% 5% 7.5% 40 ± 2 nm	10	Conditioned with silane	65 × 10 × 2.5	45°-Bevel MMA(120 s) Alumina-blasting SCA Bonding agent	Flexural strength (MPa)	Increased	Nano-ZrO ₂ addition to repair resin in combination with surface treatment as a new adhesive method for denture repair increased the flexural strength
Gad et al. 2020 [26]	Nano-ZrO ₂ 2.5% 5% 7.5% 40 ± 2 nm	10	Conditioned with silane	32 × 6 × 2.5 ± 0.03	butt joints/ MMA (180 s) 2mm	Tensile strength (MPa)	Increased	Nano-ZrO ₂ addition to repair resin showed an improvement in tensile strength of repaired acrylic resin with different aging processes
Qaw et al. 2018 [22]	Nano-ZrO ₂ 2.5% 5% 7.5% 40 ± 2 nm	10	Conditioned with silane	Disc 15 × 10	MMA(180 s) Alumina-blasting SCA Bonding agent	Shear bond strength (MPa)	Increased	Nano-ZrO ₂ addition to repair resin in combination with surface treatment as a new adhesive method for denture repair improved the repair bond strength

Nano-ZrO₂; Zirconium oxide nanoparticles, MMA; methyl methacrylate, SCP; Silicon carbide paper, SCA; Saline coupling agent, *C. albican*; *Candida albican*.

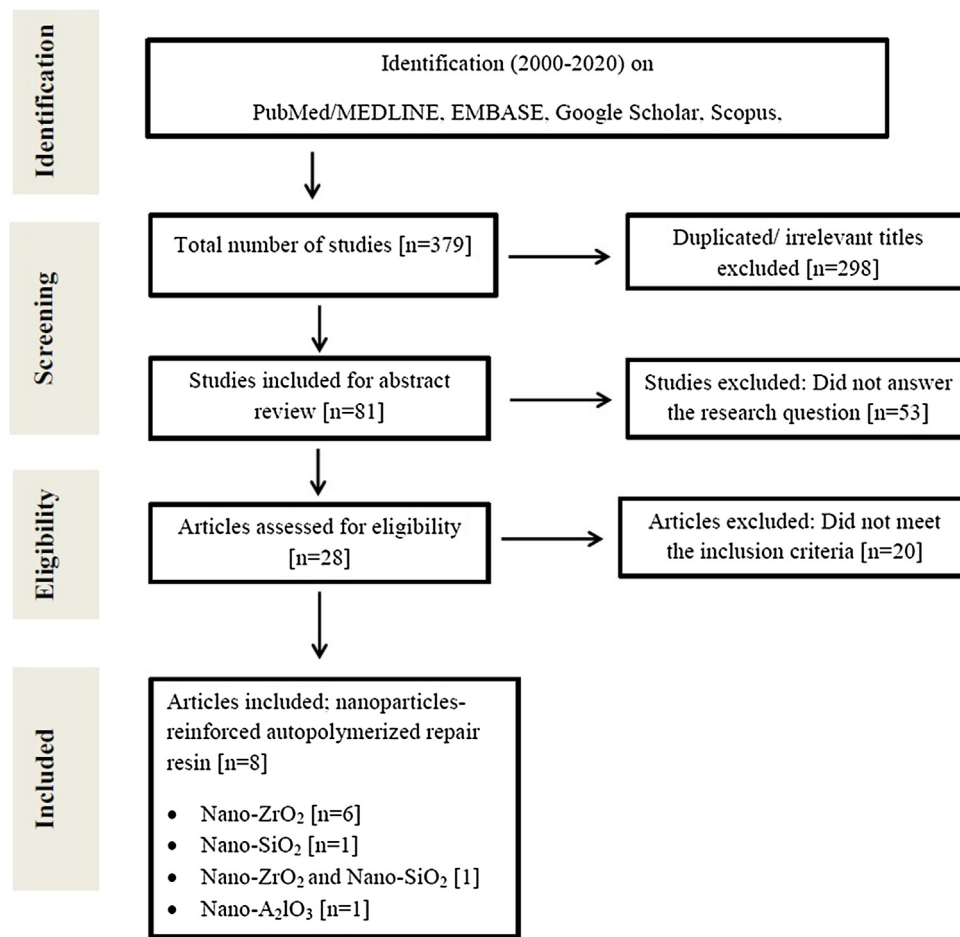


Fig. 1. PRISMA flow chart of study selection.

Table 2 Characteristics of included studies based on modified CONSORT criteria [16,17].

Article	Item grade														
	1	2a	2b	3	4	5	6	7	8	9	10	11	12	13	14
Gad et al. 2016 [19]	Yes	Yes	Yes	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	No
Gad et al. 2016 [20]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	No
Tamore et al. 2018 [21]	Yes	Yes	Yes	No	No	No	No	No	No	No	Yes	No	Yes	No	No
Abushowmi et al. 2020 [23]	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	No
Gad et al. 2020 [24]	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	No	No
Gad et al. 2020 [25]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	No
Gad et al. 2020 [26]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	No
Qaw et al. 2018 [22]	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	No	No

(1) Structured summary of trial design, methods, results and conclusions, (2a) scientific background and explanation of rationale, (2b) specific objectives and/or hypothesis, (3) the intervention of each group, including how and when it was administered, with sufficient detail to enable replication, (4) completely defined, pre-specified primary and secondary measured of outcome, including how and when they were assessed, (5) how the sample size was determined, (6) method used to generate the random allocation sequence, (7) mechanism used to implement the random allocation sequence, (8) who generated the random allocation, (9) who was blinded after assignment to intervention, (10) statistical methods used to compare groups, (11) results for each group and estimated size of effect and its precision, (12) trial limitations, addressing sources of potential bias, imprecision, and, if relevant multiplicity of analysis, (13) sources of funding and other support, (14) where to full trial protocol can be accessed [16].

Table 3 Risk of bias tool (adapted and modified from Cochrane risk of bias tool) [16,17].

Article	Allocationconcealment	Samplesize	Blinding	Assessmentmethods	Selective outcome reporting	Risk of bias
Gad et al. 2016 [19]	1	2	2	0	0	Moderate
Gad et al. 2016 [20]	1	2	2	0	0	Moderate
Tamore et al. 2018 [21]	1	1	2	1	1	Moderate
Abushowmi et al. 2019 [23]	1	2	2	0	0	Moderate
Gad et al. 2020 [24]	1	2	2	0	0	Moderate
Gad et al. 2020 [25]	1	2	2	0	0	Moderate
Gad et al. 2020 [26]	1	2	2	0	0	Moderate
Qaw et al. 2018 [22]	1	2	2	0	1	Moderate

cles (nano-ZrO₂), silicon dioxide nanoparticles (nano-SiO₂) and aluminum oxide nanoparticles (nano-Al₂O₃) were used as reinforcements to repair resin. All included studies [19–26] were used a sample size of 10 specimens for each group (control and test groups). Six studies investigated the effects of nano-ZrO₂ on flexural strength [19,20,23,25], impact strength [20,23] tensile strength [26] and shear bond strength [22]. One study investigated the effect of nano-SiO₂ on flexural strength [24] and one on flexural and impact strength [23] while one study [21] investigated the effects of nano-Al₂O₃ on flexural strength. In seven studies, nano-fillers' surfaces were silanized using silane coupling agents (SCA) [20–26].

As shown in Tables 1 and 4, for flexural strength, specimens' dimensions and testing using a 3-point bending test were performed according to ADA specifications [15]. Researchers leading nano-ZrO₂ studies [19,20] used intact specimens as a control group (negative control) and conventional repairs (positive control), while there was no intact group in the nano-Al₂O₃ study [21]. Comparing nano-fillers, nano-ZrO₂, nano-SiO₂, and nano-Al₂O₃ improved the flexural strength of repaired resin relative to their respective control groups [19,20,21]. Nano-ZrO₂ was added in 2.5%, 5%, and 7.5% concentrations; the increase in flexural strength was concentration-dependent [19,20,23,25]. Nano-ZrO₂ also added in low concentrations (0.25%, 0.5%, 0.75%) and increased flexural strength but reported values were less than high concentrations [23].

The flexural strength was increased with nano-SiO₂ addition in low concentrations (0.25%, 0.5%, 0.75%) but inverse relation was reported, as nano-SiO₂ increased the flexural strength decreased [24]. Nano-Al₂O₃ was added in concentrations of 1% and 1.5% where 1% showed higher values in the flexural strength compared to the control and 1.5%. Comparing values, the nano-ZrO₂ exhibited high values over nano-Al₂O₃ by 91.43 MPa and 50.40 MPa, respectively. Other factors that contributed to these improvements were repair surface design and surface treatment. Studies of nano-ZrO₂ studies [19,20,23,24] used a beveled surface design while scientists leading two studies [20,24] compared beveled with those that has a butt joint, beveled resulting in the improved flexural strength of reinforced groups.

With nano-Al₂O₃, only a butt joint was used to compare the different surface treatments as methyl methacrylate and silicon carbide paper. It was reported that flexural strength was improved with silicon carbide paper and this improvement was concentration-dependent in contrast to the methyl methacrylate treatment [21]. The nature of failure was reported in two nano-ZrO₂ study [20,25] and one nano-SiO₂ [24] where the fractured sides were evaluated for adhesive, cohesive, or mixed fractures. The nature of failure was mainly cohesive with a beveled surface and adhesive with a butt surface [20]. Adhesive fractures were the most common type of failure to occur in the nano-Al₂O₃ study [21], and indicating that the overall poor bond strengths were created between repair materials incorporated with Al₂O₃ particles and PMMA denture-based polymers. With nano-SiO₂ study [24] even with increased flexural strength, the most common failure mode was also adhesive indicating increased strength of repair material.

Two studies [20,23] have investigated the impact strength of repaired denture with nano-fillers (Table 5). One study [20] assessed the impact strength with nano-ZrO₂ additions in concentrations of (2.5%, 5%, and 7.5%) to repair the resin. The impact strength improved when only 2.5% nano-ZrO₂ was used. It was noted that the impact strength decreased significantly as the nano-ZrO₂ concentrations increased. Another study [23] compared nano-ZrO₂ and nano-SiO₂ in concentrations (0.25%, 0.5%, 0.75%) and found that impact strength was concentration dependent with a direct relation for the nano-ZrO₂ and inverse relation for nano-SiO₂ [23].

Tensile strength of repaired denture base was investigated with nano-ZrO₂ concentrations (2.5%, 5%, and 7.5%) addition and artificial ageing [26]. The results revealed that nano-ZrO₂ addition increased tensile strength of repaired acrylic resin with different aging processes [26]. Shear bond strength was evaluated with nano-ZrO₂ additions in combination with various surface treatment protocols [21]. In addition to the improvement of shear bond strength with mechanical surface treatment (alumina blasting) and chemicals (SCA or an MMA-based composite bonding agent) combined with a mechanical treatment, a significant increase in shear bond strength was found with the use of nano-ZrO₂. In summary, the 5% nano-ZrO₂ addition to repair resin in combination with a surface treatment (alumina blasting plus SCA) increased the shear bond strength in comparison to other nano-ZrO₂ modified and unmodified groups [22].

Scanning electron microscopy (SEM) revealed that all surface treatments (chemical, mechanical, or a combination) resulted in changes in repaired surfaces presenting as microspores, roughening, and/or pit formations [22]. Moreover, SEM findings of fractured surfaces exhibited a uniform distribution of nanoparticles within the resin matrix with low concentrations, while loosely attached clusters were presented with high concentrations. In addition to the presence of morphologic changes ranging from having a smooth, mirror-like appearance (represented by a brittle fracture mode with low-strength specimens) to having a rough surface with a flake-like appearance and a lamella appearance (represented by a ductile fracture mode with high-strength specimens) [20–26].

4. Discussion

Denture base improvements using nanoparticles have been investigated where an obvious enhancement in the properties of denture base resin material properties was found, depending on the application of nanoparticles and manipulation. Different nanoparticles were included in denture base materials such as aluminum oxide, zirconium oxide, titanium oxide, carbon (diamond), silver, gold, platinum, palladium, and hydroxyapatite. The addition of these nanoparticles has improved the performance of PMMA nanocomposite denture base materials [13]. By the same approach, the addition of nanoparticles to autopolymerized repair resins have been suggested; only three nanoparticles were investigated: nano-ZrO₂ [20,21,23,25,26], nano-SiO₂ [23,24], and nano-Al₂O₃ [21].

Nano-ZrO₂ is one of the metal oxides broadly used in dental application. It gained popularity due to its inherent properties such as adequate mechanical strength, proper surface properties, biocompatibility, and biological advantages [10,11,27]. The transformation toughness of ZrO₂ could be the key factor in improving its mechanical strength. Furthermore, when ZrO₂ is subjected to external stresses, the transformation occurs from the tetragonal phase to the monoclinic, accompanied with an increase in the crystals' size around the crack tip. This increase in the volume places the crack under compressive stresses, which help in arresting the crack propagation [10,20,25,26]. All these advantages collectively make nano-ZrO₂ a valuable form of nanocomposite material in the prosthodontic field, such as reinforcement of denture bases and repair resin materials [10,11,27]. The addition of nano-ZrO₂ at high concentrations adversely affects the translucency of the resin and its mechanical properties due to agglomeration of the nanoparticles [13]. Moreover, nano-ZrO₂ at high concentrations could increase the surface roughness of denture base resin above the clinically acceptable value causing discoloration and increased microbial adhesion [28]. Accordingly, the nanoparticles should be added in a proper concentration that improves the mechanical properties of acrylic resin without altering the esthetics [29].

Table 4
Mean values and standard deviation (SD) of Flexural Strength (MPa) for different nano-filler concentrations and surface design/treatment.

Article	Nano-filler type	Intact (Control)	Surface treatment					SCP	
			MMA	AB 45° bevel	AB+SCA	AB+MA	Butt		
Gad et al. 2016 [19]		0%	83.01 ± 3.03	44.85 ± 3.68					
		2%		65.43 ± 2.62					
		5%		70.77 ± 2.80					
Gad et al. 2016 [20]	Nano-ZrO ₂	0%	92.43	54.75				53.29	
		2.5%		86.91				81.74	
		5%		87.64				85.32	
		7.5%		91.43				84.51	
		0%		88.22 ± 1.59	47.69 ± 2.58				
Abushowmi et al. 2019 [23]	Nano-ZrO ₂	0.25%	88.22 ± 1.59	60.10 ± 1.69					
		0.5%		63.34 ± 1.66					
		0.75%		69.59 ± 1.73					
		0%		47.69 ± 2.58					
		0.25%		66.11 ± 3.07					
Gad et al. 2020 [25]	Nano-SiO ₂	0.5%	88.22 ± 1.59	57.97 ± 1.32					
		0.75%		51.24 ± 1.72					
		0%		57.30 ± 2	61.75 ± 3.3	66.45 ± 3.4	62.05 ± 1.7		
		0%(TC)		53.99 ± 2.3	62.73 ± 2.4	62.52 ± 2.1	58.43 ± 2.1		
		2.5%		71.12 ± 2.2	78.36 ± 2.5	84.11 ± 2	77.74 ± 2.9		
		2.5%(TC)		66.32 ± 1.9	77.93 ± 1.9	79.11 ± 1.9	62.64 ± 2.3		
		5%		79.62 ± 1.6	84.58 ± 2.9	86.55 ± 2.2	82.12 ± 1.8		
Gad et al. 2020 [24]	Nano-ZrO ₂	5%(TC)	88.22 ± 1.59	74.92 ± 2.5	82.45 ± 2.6	80.63 ± 2.7	63.75 ± 1.7		
		7.5%		81.18 ± 1.7	85.79 ± 2.3	89.63 ± 2	84.11 ± 1.5		
		7.5%(TC)		75.28 ± 1.9	84.01 ± 1.7	81.96 ± 1.9	65.69 ± 2.4		
		0%		61.34 ± 5.09			54.23 ± 5.21		
		0.25%		81.54 ± 6.93			75.43 ± 4.84		
Gad et al. 2020 [24]	Nano-SiO ₂	0.5%	88.22 ± 1.59	80.42 ± 4.05				73.06 ± 3.91	
		0.75%		79.82 ± 6.11				71.79 ± 6.32	
		0%						-	
Tamore et al. 2018 [21]	Nano-Al ₂ O ₃	1%	88.22 ± 1.59					37.68	44.28
		1.5%						25.92	50.4

^aMMA: Methyl methacrylate; SCP: Silicon carbide paper; AB, Alumina blasting; SCA, Silane coupling agent; (MA) Methyl methacrylate based composite bonding agent; (TC) Thermal cycling. (Solid cells), not stated.

Table 5
Mean values (SD) of impact strength (kJ/m²) for different nano-filler concentrations and surface treatment.

Article	Nano-filler type wt. %	Surface design and treatment with MMA				
		Intact	45° bevel	Butt		
Gad et al. 2016 [20]	Nano-ZrO ₂	Intact	3.04 ± 0.16	1.40 ± 0.19		
		0%			2.69	1.46
		2.5%				1.52
		5%				0.98
		7.5%				0.96
Abushowmi et al. 2019 [23]	Nano-ZrO ₂	Intact	3.04 ± 0.16	1.40 ± 0.19		
		0%				1.98 ± 0.12
		0.25%				2.38 ± 0.23
		0.5%				2.47 ± 0.25
		0.75%				
	Nano-SiO ₂	Intact	3.04 ± 0.16	1.40 ± 0.19		
		0%				3.01 ± 0.99
		0.25%				1.83 ± 0.27
		0.5%				1.48 ± 0.11

MMA: Methyl methacrylate; (Solid cells) not stated.

Nano-SiO₂ has been added to PMMA and exhibited remarkable effects on the mechanical properties [23,24]. It was found that the addition of nano-SiO₂ into PMMA denture base materials at low concentrations could improve the strength, crack resistance, and durability as well as could prevent or decrease nano-SiO₂ agglomeration and clusters formation [23,24,30]. In addition to two benefits of low nano-SiO₂ concentrations; the uniform distribution of nanoparticles within resin matrix and their ability to fill the spaces of inter-polymeric chain and limit their movement [30]. Also, the interfacial shear strength between nano-SiO₂ and resin matrix due to cross-linking or supra-molecular bonding which has

the ability to arrest cracks propagation [24]. It is suggested to add nano-SiO₂ at low concentration (0.05%) to avoid the formation of agglomerates [31]. In addition, the surface roughness of denture base resin increased as nano-SiO₂ concentration increased [28]. Minimal color change of denture base resin was found with low concentration of nano-SiO₂ and because its refractive index (1.45) [32] is very close to PMMA denture base (1.48) [29].

Nano-Al₂O₃ is commonly referred to as alumina and has a wide range of applications in industry as well as dental practice. The main nano-Al₂O₃ features include strong interatomic bonds, which present in different crystalline forms particularly during

the hexagonal alpha phase. Alumina is a strong material in the alpha phase and it possesses favorable hardness, thermal stability, and high dielectric merits, which make it an appropriate material for widespread applications in dentistry such as with the reinforcement of denture bases and the use of resin repair materials [13,21,33]. However, nano- Al_2O_3 causes discoloration and opacity of PMMA particularly when added at high concentration [13,34]. The adverse effect of nano- Al_2O_3 on esthetics could limit its use in invisible denture areas such as the palatal portion of upper and/or lingual flanges of lower dentures [35–37].

Gad et al. [20] reinforced the acrylic repair resin using 2.5% wt., 5% wt., and 7.5% wt. of nano- ZrO_2 at the butt and a 45° bevel joint design of the repair gap. They found that the addition of 7.5 wt.% of nano- ZrO_2 significantly increased the flexural strength of the repaired denture base, which was very close to the intact, heat-polymerized acrylic resin group. Nano- ZrO_2 was compared to nano- SiO_2 in low concentrations (0.25%, 0.5%, 0.75%), and both reported improvement in flexural strength but the concentration effect was opposite; flexural strength increased as nano- ZrO_2 increased and nano- SiO_2 decreased. Therefore, nano- SiO_2 is recommended at low concentrations [23,24]. The variations in this comparison between two nanofillers could be attributed to the difference in weight of nanoparticles (low weight of nano- SiO_2 resulted in high volume) so authors recommended percentages proportions by volumes instead of weight.

Tamore et al. [21] found that 1% and 1.5% nano- Al_2O_3 additions to repair the resin improved the flexural strength compared to the unmodified ones. Both nanoparticles improved the flexural strength of repaired specimens; however their behavior was different. Furthermore, the nano- ZrO_2 effect was concentration-dependent while in nano- Al_2O_3 , when the concentration increased the flexural strength decreased. This improvement in flexural strength could be attributed to the evenly distributed nanoparticles within the resin matrix, inherent properties of each nanoparticle, their ability to transform and arrest crack propagation, and bonding between nanoparticles and PMMA. In addition to the aforementioned factors, the functionality of nanoparticles using SCA is considered an important factor with metal oxide additions.

Based on this review, out of 8 included studies, 7 studies [20–26] functionalized nano- ZrO_2 , nano- SiO_2 , and nano- Al_2O_3 with SCA, resulting in a functional group that mainly depended on the functional groups of SCA. Accordingly, SCA has the ability to bond nanoparticles with PMMA the resin matrix resulted in the formation of chemical bonds [20–22,38].

Regarding nature of failure analysis, repair resin modified with nanoparticles exhibited more adhesive fractures with butt joint construction, confirming the strength effect of reinforced repair resin and poor adhesion at the repair/resin interface [20]. On the other side, the strength effect of nano- ZrO_2 with beveled repair surfaces as commonly in cohesive fractures, which necessitate more investigation to explain the behavior of repair/resin interfaces [24]. Moreover, this weakness could be explained by the presence of some unreacted nanoparticles (especially with high concentrations) on the surface interface, affecting proper resin bonding [20,24].

Although two studies investigated the impact strength with two different nanoparticles, results were close and reported same behavior [23]. Impact strength was changed with nano- ZrO_2 and nano- SiO_2 additions and as the concentration increased the impact strength decreased. This decrease may referred to the test type, as these nanoparticles might not react with sudden impact forces as it could with a compressive load [20,23].

Other tested properties (Tensile and shear bond strength) have been investigated in one study per each using only nano- ZrO_2 . Thereby, the comparison in this review was difficult but the overall performance could be evaluated. The behavior of nano- ZrO_2 in

tensile and shear bond strength was similar to flexural strength where its addition to the repair resin increased the bond strength [22,26]. In addition to the improvement with surface treatment which demonstrated the reinforcement effect of the nano- ZrO_2 addition [21]. Surface treatments which applied in different forms; chemical, mechanical, or combination played an important role in repair strength as it resulted in increased bonding surface area and subsequently improved repair bond strength [22,25]. Additional enhancement gained from the combination of surface treatment and repair material reinforcement with nano- ZrO_2 [22,25]. Besides the chemical bond, SCA wetted the repair surface and filled the microspores interlocking the repair material within these irregularities. Due to chemical bonds and micromechanical retention at the repair surface, SCA played a crucial role in improving repair bond strength. Other benefits of nano- ZrO_2 to repair resin include its antifungal activities.

The addition of nanoparticles to repair resins could improve its mechanical properties and accordingly improve its long-term use and reduce repeated fracture. The results showed that reinforcement denture repair resin with nanoparticles is affected by the type, concentration, dispersion, and the chemical and physical structure of nanoparticles, as well as surface treatment of nanoparticles. Nanoparticle-modified repair resins alone or with surface repair design and/or treatment improved the flexural strength, tensile strength and shear bond strength. However, further studies are recommended to assess other physical properties of repaired denture base.

The ideal nanoparticle-modified repair resin should restore the strength and color of the original denture base. According to the finding of this review, both nano- SiO_2 and nano- ZrO_2 could be recommended for reinforcement of repair material. Nano- SiO_2 might be more preferable than nano- ZrO_2 in term of color change. However, further studies are recommended on different types of nanoparticles as reinforcing materials of different types of repair resins. Also nanoparticle-modified repair resin could be investigated in combination with other factors that might influence the denture repair strength such as repair surface design (bevel), [19,20] repair gap [39], and repair surface treatment aiming to improve the bond strength at the repair/resin interface [22]. Additionally, the biocompatibility of nanoparticle-modified repair resins should be investigated in conditions simulating oral conditions to point out the clinical implication of nanoparticle-modified repair resins for denture repair.

5. Conclusions

Repair material reinforcements with nanoparticles could be promising for denture repair improvements and avoiding repeated fractures. However, due to the limited number of studies in which the effect of nanoparticles on the mechanical properties of denture repair resin have been evaluated, further investigations are required prior to recommendations for clinical applicability.

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Conflicts of interest

None.

Data availability statement

All the data associated with the study are presented within the manuscript.

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