DEVELOPMENT AND DESIGN OF ARTIFICIAL PALATE MATERIALS FOR SPEECH TREATMENT: A REVIEW

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Abstract

With the advancement of technology, various denture base materials have been developed with enhanced mechanical and physical properties. Because the mechanical properties of the denture base play a significant role in its clinical lifespan, this systematic review aims to examine the effects of various additives added to polymethyl methacrylate (PMMA) denture base materials on the physical (surface properties, water sorption) and mechanical (flexural strength, impact strength, thermal conductivity) properties of the denture base and can then be used to produce artificial palates. An electronic database search of peer-reviewed published papers in English was conducted using relevant keywords between the 23rd of August 2016 and the 24th of August 2022. The database yielded 1048 relevant published articles. However, 21 articles were qualified for this study after considering the inclusion and exclusion criteria. A substantial body of literature demonstrates that zirconium ZrO2 is widely used as an additive in the modification of PMMA. Meanwhile, flexural strength is the most conducted test based on the literature.

Keywords: Denture base modification, Denture materials, Mechanical properties, PMMA, Systematic review

Introduction

Sound production begins in the lungs. The air travels from the lungs to the throat and then to the mouth or nose (1). During production, the vocal cord is a vital organ. Two small membranes placed in the throat of the vocal cord produce the sound. When stretched taut and close together, the vocal cords vibrate rapidly, more than 100 times per second, to produce a louder sound. When the vocal cord is relaxed, the sound is reduced to a whisper. Aside from that, the vocal cord influences the production of the sound pitch. Pitching is a type of voice production in which a high or low sound is produced. Human voice is produced by three parts: the lungs, the articulator, and the vocal cords (1). Meanwhile, six organs were designated as articulators: the lips, tongue, soft palate, lower teeth, upper teeth, and hard palate.

There are two types of palates: hard palates and soft palates (2). The hard palate separates the oral cavity from the nasal cavity by acting as the roof of the oral cavity. It creates a semilunar arch by extending posteriorly and medially from the maxillary alveolar ridge to the palatine bone's posterior edge. Meanwhile, the soft palate extends all the way to the back of the hard palate. The soft palate is made up of the palatine aponeurosis, the muscular part, the mucosa, the uvula muscle, and the palatopharyngeus. The pharyngeal wall is connected to the posterior part of the soft palate surface. During swallowing, the soft palate rises and approaches the pharynx (3).

The hard palate influences sound production. As a result, a cleft palate or other abnormally hard palate will produce a different sound. According to Wendy et al., people with cleft palate have different hearing and speech difficulties, as well as a different facial appearance (3). This result in different sound production compared to the normal hard palate. The cleft palate is an oral malformation that occurs early during pregnancy, as the baby develops inside the mother. A cleft palate can be the malformation of the hard palate and/or the soft palate (4). A cleft occurs when insufficient tissue in the mouth or lip area or the available tissue does not join or intersect correctly. Cleft palates are manifested as splits or openings in the roof of the mouth.

Therefore, the use of an artificial palate is one of the ways to help patients during speech therapy, particularly for cleft palate patients. Speech therapy requires the assessment and treatment of communication problems and speech disorders. There are many methods used in speech therapy. One of the methods is using Electropalatography (EPG). EPG is a real-time recording system for tongue and palate activity during speech production. EPG includes an artificial palate that is embedded with a sensor that detects the location of the tongue and hard palate. The sensor sends the signal to a computer for analysis and display.

Many studies have been conducted to improve the EPG system. In the 1970s, a study investigated the use of flexible material in developing the artificial palate. This study, however, had to be halted due to difficulties in obtaining approval from the Food and Drug Administration (FDA). Nevertheless, the methodology and materials selection for fabricating the artificial palate is similar to the methodology and materials used in fabricating a denture (5). Therefore, this article aims to examine the effects of various additives added to PMMA denture materials on the physical properties (surface, water sorption) and mechanical properties (flexural and impact strength, thermal conductivity) of the denture base that is used to produce artificial palates.

PMMA was invented 70 years ago and is still the most used material for denture bases (6). The benefits of PMMA include its aesthetic properties, high processing and polishing abilities, relining and rebasing capability, and low cost. However, PMMA has dimensional instability, contains residual monomers, and, importantly, possesses poor mechanical properties (7). Due to its poor mechanical properties, the denture base may fracture either from the inside or outside.

Several studies have been conducted to improve and investigate the mechanical properties of PMMA by incorporating filler particles and fibres. Studies found that combining zirconia (ZrO2) fillers with PMMA enhanced properties such as flexural strength, impact strength, surface hardness, and thermal conductivity (8-14). Similarly, incorporating titanium (TiO2) particles may improve fracture toughness, impact strength, flexure strength, hardness, and thermal conductivity (14-18). Other research has shown that glass fibre (E-glass fibres, flock fibres, and polyethylene fibres) can improve the toughness, flexural strength, impact strength, and Vickers hardness of acrylic resin (19-23). This article suggests the best additive materials for producing dentures, which are necessary for producing artificial palates.

Materials and Methods

The databases Scopus, Web of Science (WoS) and PubMed were last searched on the 24th of August, 2022. Only journals related to materials science were chosen, and the articles was collected for further analysis. Table 1 lists the keywords used in the search strategy.

Table 1: Manuscript search strategy

Source	Details
Database engine	PubMed, Web of Science, Scopus
Date of publication	23rd August 2016 – 24th August 2022
Keywords	PMMA denture base, Reinforcement denture base PMMA, Fibre, Nanoparticle, Filler
Inclusion criteria	Denture base material, Open Access
Exclusion criteria	Review paper, Case study, Drug modification, Studies related to meta-analysis, Implant, Biological properties,
Journal category	Materials science, Dental, Medline
Type of study	Article
Language	English

Eligibility Criteria

Electropalatography is a real-time instrument used for detecting tongue and hard palate contact during continuous speech. The main part of the EPG is an artificial palate. Artificial palates are fabricated similarly to dentures. PMMA was the standard material used to fabricate the denture or artificial palate.

Inclusion and Exclusion criteria

Inclusion criteria: The study aimed to identify the modification of PMMA denture based, i.e., nanoparticles, fibres, and fillers. Besides, this systematic study only focuses on materials and biomaterials journals.

Exclusion criteria: Denture repair and fixed prostheses or overdentures-related studies. Review articles, literature reviews, meta-analyses, case reports/series, preliminary studies, and articles written in a language other than English were excluded.

Results

According to the search engine, a total of 1048 articles were retrieved from electronic data sources. The data was selected from the 23rd of August 2016 to the 24th of August 2022. The keyword of searching is PMMA denture base, reinforcement PMMA denture base, fibre, nanoparticle and filler. Out of 1048 articles, 477 were open access, and a total of 109 articles consisting of systematic review/review and case reports were excluded. A total of 119 were identified as duplications, and 228 articles were excluded based on exclusion criteria. Finally, 21 articles were chosen based on the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) Statements. Figure 1 shows the

PRISMA flowchart of the identified papers and the inclusion and exclusion criteria.

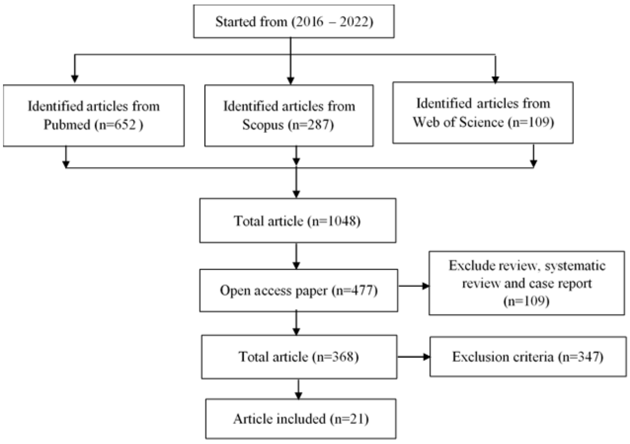

Figure 1: PRISMA flowchart of identified papers

The outcome of this systematic review generated 21 studies (24-44). Zirconium nanoparticles (nano-ZrO2) were seen as very common nanoparticles used as additives in the modification of PMMA in a majority of the papers (27-28, 33-39). Another composite that enhanced the PMMA was titanium dioxide (TiO2) (29, 37, 39). Additionally, several studies used E-glass nanoparticles as an additional composite for PMMA (27, 37, 39). Two studies used zinc oxide nanoparticles ZnO (40, 44), gold nanoparticles (Au) (32, 41) and alumina nanoparticles (Al2O3) (26, 30), respectively, in improving the PMMA. Other studies by Emera, R. M. K., and Abdallah, R. M. (2021) used BioHPP (30), hydroxyapatite (HA) (31), graphene-silver (Gr-Ag) nanoparticles (42), copper oxide (CuO) (29) and boron nitride nanosheets (h-BNNs) and silver nanoparticles (AgNPs) (43). Besides, there were studies on improving PMMA with cellulose incorporated with octyltriethoxysilane (OTES) and methyldimethoxysilane (MPMS) (24) and a combination of PMMA and oleic acid (OA) (25). Table 2 shows the type of additives and objective of the study of the selected articles.

Table 2: Type of additives and the objective of study

No	Authors (Year)	Objective	Additive Materials	Reference Number
1	Taczała, J, et al. (2020)	Modifed cellulose as an active filler of PMMA	Cellulose	[24]
2	Petrovic, M, et al. (2022).	Investigated oleic acid for antifungal preservation and surface modification of PMMA	Oleic Acid	[25]
3	Earar, K, et al. (2021)	Investigated different sizes of alumina particles on PMMA	Al_2O_3	[26]
4	Gad, MM, et al. (2019)	Examined various ratios of hybrid reinforcement of zirconium oxide nanoparticles and glass fibres	Nano-$ZrO_{2,}$ Glass fibres	[27]
5	Zidan, S, et al. (2021)	Investigated mechanical properties of high-impact heat-cured acrylic resin reinforced with zirconia nanoparticles	Nano- ZrO_2	[28]
6	Giti, R, et al. (2022)	Evaluated different concentrations of titanium dioxide and copper oxide nanoparticles on water sorption and solubility of heat-cure PMMA	CuO, TiO_2	[29]
7	Emera, RMK, and Abdallah, RM. (2021)	Investigated mechanical properties, adaptation, and retention of alumina nanoparticles versus BioHPP	Nano-$Al_2O_{3,}$ BioHPP	[30]
8	Fouly, A, et al. (2021)	Investigated properties of PMMA reinforced with different low loading fractions of nano-hydroxyapatite	Nano-HA	[31]

9	Tijana, A, et al. (2021)	Investigated antimicrobial properties of heat-polymerized PMMA using combination of PMMA gold nanoparticles	Nano-Au	[32]
10	Gad, MM, et al. (2016)	Evaluated the effects of zirconia nanoparticles on the flexural and impact strength of PMMA	Nano-ZrO_2	[33]
11	Gad, MM, et al. (2017)	Evaluated the effect of zirconia nanoparticles added to cold-cured acrylic resin on *Candida Albicans* adhesion	Nano-ZrO_2	[34]
12	Gad, MM, et al. (2018)	Examined translucency and tensile strength of PMMA with zirconia nanoparticles addition	Nano-ZrO_2	[35]
13	Zidan, S, et al. (2019)	Investigated fracture and mechanical properties of high impact, heat-cured dentures base acrylic resin impregnated with different concentrations of yttria-stabilized zirconia	Nano -ZrO_2	[36]
14	Alhotan, A, et al. (2021)	Examined flexural strength and surface hardness of heat-cured PMMA with nano-ZrO_2, nano-TiO_2, and E-glass fibre at different concentrations	Nano -ZrO_2, Nano-TiO_2, E-glass fibre	[37]
15	Zidan, S, et al. (2021)	Characterized mechanical properties of high impact heat-cured acrylic resin PMMA reinforced with silane-treated zirconia nanoparticles	Nano -ZrO_2	[38]
16	Alhotan A, et al. (2021)	Investigated fracture toughness and impact strength of PMMA with E-glass fibre, ZrO_2 and TiO_2 nanoparticles at different concentrations	E-glass fibre, ZrO_2, TiO_2	[39]
17	Cierech M, et al. (2019)	Examined microorganisms surface deposition using zinc oxide polymethyl methacrylate (ZnO-PMMA) nanoparticles	ZnO	[40]
18	Oyar, P, et al. (2018)	Investigated flexural strength of PMMA using gold nanoparticles	Au	[41]
19	Bacali, C, et al. (2019)	Analyzed mechanical properties, water absorption, and morphological properties of PMMA resin incorporated with graphene-silver nanoparticles (Gr-Ag).	Gr-Ag	[42]

20	Li, M, et al. (2022)	Examined antibacterial properties and mechanical properties of PMMA enriched with boron nitride nanosheets/ silver nanoparticles.	h-BNNs/AgNPs	[43]
21	Cierech, M, et al. (2018)	Identified properties of ZnO nanocomposites incorporated with PMMA that can influence the microorganism on surface.	ZnO-PMMA	[44]

A summary of the 21 studies in terms of testing method, group testing, and outcome has been shown in Table 3. Flexural strength testing is the most commonly conducted test, with 13 studies. Followed by 12 studies is surface testing which includes the surface roughness, fractured surface and surface hardness. In addition, there are four studies on water absorption testing and three studies on impact strength. There are two studies for thermal stability test, prevention of Candida, water solubility and tensile test. Meanwhile, Gad, M. M., et al. (2018) conducted a study to determine the translucency values between pure PMMA and a combination PMMA with ZrO_2 (35).

An essential property of denture materials is their hardness, indicating their resistance to deformation due to abrasion. Another factor to consider during the development of dentures is the surface properties of the materials used (45). Prosthetic appliances, especially dentures, should have a smooth surface to maintain patient safety (4). Another property that should be considered for the development of dentures or artificial palates is water sorption (46).

Table 3: Result of testing method, group testing and the outcome of the included paper

Reference Number	Testing Method	Group Testing	Outcome
[24]	1. Flexural Strength 2. Thermal Stability	Group control: pure PMMA Group 1: PMMA + pure cellulose Group 2: PMMA + cellulose + OTES Group 3: PMMA + cellulose + MPMS	Flexural strength: Group 3 (94.0 MPa) > Group 2 (88.0 MPa), 1 (70.9 MPa), Control (89.0 MPa). Thermal stability: Group 3 (143.92 °C) > Group 2 (135.16 °C), 1 (128.81 °C).
[25]	1. Surface Properties 2. Preventing *Candida Albican*	Group control (pure PMMA) Group 1 (PMMA + 3 weight percent (wt.%) OA) Group 2 (PMMA + 6 wt.% OA) Group 3 (PMMA + 9 wt.% OA) Group 4 (PMMA + 12 wt.% OA)	PMMA incorporated with >3% OA significantly reduces the metabolic activity of biofilm. PMMA_OA increased hydrophilic surface properties. OA prevents filamentation. It inhibits *Candida Albicans* biofilm formation on the PMMA_OA composite surface.
[26]	1. Flexural Strength	Group control (pure PMMA) Group 1 (PMMA + 6 wt.% Al_2O_3_40nm) Group 2 (PMMA + 6 wt.% Al_2O_3_150nm) Group 3 (PMMA + 6 wt.% Al_2O_3_500nm) Group 4 (PMMA + 1 wt.% Al_2O_3) Group 5 (PMMA + 6 wt.% Al_2O_3) Group 6 (PMMA + 11wt.% Al_2O_3) Group 7 (PMMA + 16 wt.% Al_2O_3)	The addition of smaller particle sizes shows better mechanical properties (Group 1 with 2.21 MPa $m^{1/2}$, Group 2 with 2.09 MPa $m^{1/2}$ and Group 3 with 1.93 MPa $m^{1/2}$) but lower resistance to water adsorption (Group 1 with 17.68 ± 0.74 µg/mm3 and Group 3 with 15.33 ± 0.61 µg/mm3) and solubility (Group 1 with 1.21 ± 0.05 µg/mm^3, Group 3 with 1.12 ± 0.04 µg/mm^3. The properties of dental composites can be improved by using low concentrations of nanoparticle fillers.

[27]	1. Flexural Strength 2. Impact Strength	Group control (pure PMMA) Group A (PMMA + ZrO_2) Group B – G (PMMA + ZrO_2 + glass fibre)	Flexural strength increases in all reinforced groups when compared to the control group. (Group with 2.5% nanoZrO^2 + 2.5% GFs produced highest flexural strength 94.05 ± 6.95 MPa while, control group shows the value of flexural strength is 64.52 ± 5.76 MPa) Compared to the control group, the impact strength of all reinforced groups increases except group E,F, and G.
[28]	1. Flexural Strength 2. Flexural modulus 3. Fractured surface	Group control (pure PMMA) Group A (non-silanized ZrO_2) Group B (silanized ZrO_2)	Improved surface hardness and flexural strength. (Group B (20.1 ± 2.3 kg/mm^2) >Group A (15.0 ± 0.2 kg/mm^2) and control (17.1 ± 0.9 kg/mm^2). The flexural modulus of group B (83.5± 6.2 MPa) > group control (72.4±8.6 MPa).
[29]	1. Water sorption 2. Water solubility	Group control (Pure PMMA) Group 1 (2.5 wt.% TiO_2) Group 2 (7.5 wt.% TiO_2) Group 3 (2.5 wt.% CuO) Group 4 (7.5 wt.% CuO)	Water sorption: Group 3 < control; Group 1 and 2 = control. Water solubility: Group 3 = control; Group 1 and 2 > control.
[30]	1. Flexural Strength 2. Surface hardness	Group control (pure PMMA) Group 1 (PMMA + 2.5 wt.% Al_2O_3), Group 2 (PMMA + 5.0 wt.% Al_2O_3) Group 3 (PMMA + BioHPP)	Surface hardness: Group 3 (114.800 ± 0.839 MPa) > Groups 2 (99.000 ± 1.344 MPa), 1 (90.450 ±1.323 MPa), control (79.000 ±0.183 MPa). Flexural strength: Group 4 (PMMA + BioHPP) > Groups 3, 2, control.
[31]	1. Hardness 2. Young modulus 3. fracture toughness	Group control (pure PMMA) Group 2 (PMMA + 0.2 wt.% HA) Group 3 (PMMA + 0.4 wt.% HA) Group 4 (PMMA + 0.6 wt.% HA) Group 5 (PMMA + 0.8 wt.% HA)	Compared to the control, increasing the HA wt.% increases hardness, Young's modulus (Group 5 increases 70.8%), compressive yield strength (Group 5 increases 29.96%), ductility (increased up to 9% when loading 0.8 wt.% HA), and fracture toughness. Adding HA nanoparticles into a PMMA matrix causes a change to the wear mechanism and decreases the weight loss during a friction process.
[32]	1. Flexural properties 2. Thermal conductivities	Group control (pure PMMA) Group 1 (PMMA + 0.12 wt.% Au) Group 2 (PMMA + 0.43 wt.% Au) Group 3 (PMMA + 0.74 wt.% Au)	No significant difference between the control and AuNps groups for flexural strength and elastic modulus. The fractured surfaces in groups 1, 2, and 3 had similar surface texture to the control group A, with slightly more cracking. The thermal conductivity and microhardness of PMMA/Au nanocomposites were improved gradually by increasing the wt.%.
[33]	1. Flexural strength	Group control (Pure PMMA) Group A (2.5 wt.% nano-ZrO_2 + PMMA) Group B (5.0 wt.% nano-ZrO_2 + PMMA) Group C (7.5 wt.% nano-ZrO_2 + PMMA)	The control group's flexural strength was significantly higher (92.43MPa) than all repaired groups (Group A: 86.91MPa, Group B: 87.64MPa, Group C: 91.43MPa). The difference between the nanoZrO_2-reinforced auto polymerized acrylic resin group, and the nano-ZrO_2-unreinforced auto polymerized group was significant. All repaired groups' mean values were significantly lower than the control.

[34]	1. Candida adhesion	Group 1: comprised heat-polymerized specimens that were sectioned at the centre and prepared to create a 2 mm repair area that was repaired with cold-cured resin reinforced with 0 wt.%, 2.5 wt.%, 5.0 wt.%, and 7.5 wt.% zirconia nanoparticles. Group 2 contained intact cold-cured acrylic resin specimens reinforced with 0 wt.%, 2.5 wt.%, 5.0 wt.%, and 7.5 wt.% zirconia nanoparticles.	The lowest *Candida* count was found in intact cold-cured groups and groups repaired with cold-cured resin reinforced with 7.5 wt.% zirconia nanoparticles.
[35]	1. Tensile test 2. Translucency values	Group control (pure PMMA) Group A (2.5 wt.% nano ZrO_2) Group B (5.0 wt.% nano ZrO_2) Group C (7.5 wt.% nano ZrO_2)	The tensile test showed Groups A (63.55 MPa), B (66.32 MPa), C (69.59 MPa) > control (58.07 MPa). The translucency values of Groups A, B, C < control.
[36]	1. Flexural strength 2. Fracture toughness 3. Impact Test 4. Hardness test	Group control (pure PMMA) Group A (1.5 wt.% ZrO_2) Group B (3.0 wt.% ZrO_2) Group C (5.0 wt.% ZrO_2) Group D (7.0 wt.% ZrO_2) Group E (10.0 wt.% ZrO_2)	An optimum concentration of 3.0 & 5.0 wt.% ZrO_2 improved the flexural strength, flexural modulus, fracture toughness and surface hardness compared to the control group. The impact strength of the nanocomposites decreased except for the 5.0 wt.% ZrO_2 group.
[37]	1. Flexural strength 2. Surface hardness 3. Fracture surface	Group Control (pure PMMA) Group A (E-glass fibre) Group B (ZrO_2 nanoparticles) Group C (TiO_2 nanoparticles)	The 3.0 wt.% of $ZrO_{2,}$ 5.0 and 7.0 wt.% of E-glass fibre improved the flexural strength The optimal filler concentrations for increasing PMMA resin flexural strength were 3.0-5.0 wt.%. ZrO_2, 1.5 wt.% TiO_2, and 3.0-7.0 wt.% E-glass fibre. A 3.0 wt.% or higher filler concentration would significantly improve hardness in all composites.
[38]	1. Flexural strength 2. Surface hardness	Group control (pure PMMA) Group B (Non-silanized ZrO_2) Group C (silanized ZrO_2)	The flexural strength for Group C (83.5 ±6.2MPa) > Group B (59.9± 7.1 MPa). Surface hardness for Group C (20.1 ± 2.3 kg/mm^2) > Group B (15.0 ± 0.2 kg/mm^2).
[39]	1. Fracture toughness 2. Impact strength	Group Control (pure PMMA) Control A (E-glass fibre) Group B (ZrO_2 nanoparticles) Group C (TiO_2 nanoparticles)	Fracture toughness was significantly higher in groups with 1.5 and 3.0 wt.% ZrO_2, 1.5 wt.% TiO_2, and all E-glass fibre concentrations compare to the control group. The impact strength of 3.0 wt.%, 5.0 wt.% and 7.0 wt.% E-glass fibres > control group, ZrO_2 and TiO_2 = Control Group.
[40]	1. Surface hardness 2. Hydrophilicity 3. Surface roughness	Group control (pure PMMA) Group A (ZnO 2.5 wt.%) Group B (ZnO 5 wt.%) Group C (ZnO 7.5 wt.%)	Hardness: Group C > Group control. Hydrophilicity: Group C > Group control. Roughness: Did not change for all composites.

[41]	1. Flexural strength	Group control (pure PMMA) Group 1 (PMMA + 45 nm 0.05 wt.% AuNPs) Group 2 (PMMA + 45 nm 0.2 wt.% AuNPs) Group 3 (PMMA + 55 nm 0.05 wt.% AuNPs) Group 4 (PMMA + 55 nm 0.2 wt.% AuNPs) Group 3 (PMMA + 65 nm 0.05 wt.% AuNPs) Group 4 (PMMA + 65 nm 0.2 wt.% AuNPs)	Flexural strength: Group containing AuNPs> control group. Flexural strength same particle size: Groups containing 0.05 wt.% AuNPs > groups containing 0.2 wt.% AuNPs. Flexural strength difference nanoparticle size: No significant difference for the experimental group.
[42]	1. Flexural strength 2. Tensile strength 3. Water absorption	Group control (pure PMMA) Group 1 (PMMA + 1 wt.% GrAg) Group 2 (PMMA + 2 wt.% Gr-Ag)	Group 1 had the sufficient concentration for the material to endure higher applied loads and exhibit higher flexural strength and tensile characteristics than the Group control. Group 2 lower ratios of absorbed water, which could reduce the risks of water-mediated degradation effects.
[43]	1. Mechanical properties 2. Surface properties	Group control (pure PMMA) Group 1 (PMMA + 0.2 wt.% h-BNNs/AgNPs) Group 2 (PMMA + 0.6 wt.% h-BNNs/AgNPs) Group 3 (PMMA + 1.0 wt.% h-BNNs/AgNPs) Group 4 (PMMA + 1.4 wt.% h-BNNs/AgNPs) Group 5(PMMA + 1.8 wt.% h-BNNs/AgNPs)	The flexural strength and compressive strength: Group with h-BNNs/AgNPs produce better than pure PMMA. The nanocomposites did not disturb the water absorption and dissolution capacity of the PMMA.
[44]	1. Roughness hardness 2. Water absorbability	Group Control (pure PMMA), Group 1 (PMMA + 2.5 wt.% ZnO) Group 2 (PMMA + 5.0 wt.% ZnO) Group 3 (PMMA + 7.5 wt.% ZnO	The surface of PMMA does not change after being modified with ZnO nanoparticles. The presence of more ZnO-NPs in nanocomposites increases the material's hydrophilic properties. The hardness study shows a statistically significant difference between 5.0 wt.% and 7.5 wt.% nanocomposites and pure PMMA.

Discussion

Although PMMA is an established material for making dentures, many improvements of PMMA have been carried out until now. The modification of PMMA became the main focus of researchers. This improvement may increase flexural ability, improve mechanical properties, and reduce denture stomatitis. The results of this review revealed that different treatment methods, such as the addition of ZrO_2, TiO_2, E-glass nanoparticles, ZnO, Au, Al_2O_3, CuO, BioHPP, HA, Gr-Ag and boron nitride/silver (h-BNNs/AgNPs) on PMMA could improve the use of PMMA, particularly in mechanical properties, water absorption and thermal conductivity.

Nine studies investigated ZrO_2 as an added composite to enhance the pure PMMA. Most studies investigated fracture surface, tensile strength, surface hardness, impact strength and flexural strength properties. (27) and (28) found that adding ZrO_2 may increase flexural and impact strength. According to the article (27), PMMA with 2.5% nano-ZrO_2 + 2.5% glass fibres had the greatest impact strength of 3.89 ± 0.46 kJ/m^2 and flexural strength of 94.05 ± 6.95 MPa. Meanwhile, (38) found that the silanized ZrO_2 (83.5 ± 6.2MPa) had better flexural strength than the non-silanized ZrO_2 (59.9 ± 7.1 MPa). However, both silanized and non-silanized may not change in impact strength. Besides, both experimental groups produce better than the control group. This statement was supported by (37), which found that silanized ZrO_2 builds better flexural modulus and flexural strength.

The findings of the article (32) contradict previous findings that the flexural strength of the pure PMMA group was superior to other additive groups. Moreover, nano-ZrO_2 reinforced auto-polymerized acrylic resin group was statistically significant difference to the nano-ZrO_2 unreinforced auto-polymerized group. However, (33) aimed to evaluate the effect of zirconia nanoparticles added to cold-cured acrylic resin on *Candida Albicans* adhesion. The study discovered that the lowest *Candida Albicans* counts were found in both intact cold-cured and cold-cured resin reinforced with 7.5 wt.% ZrO_2 nanoparticles. There was a significant difference between the enhanced and intact cold-cured groups. Meanwhile, article (25) investigated the combination of PMMA with oleic acid to prevent the *Candida Albicans* associated with the development of dentures. The finding indicated that increasing oleic acid decreased the water contact angle and metabolic activity of planktonic cells and, consequently, reduced *Candida Albicans* biofilm formation on dentures.

Several studies investigated the effect of titanium dioxide (TiO_2) addition on the PMMA properties. According to the articles (34, 37), adding TiO_2 particles may not improve flexure strength. Meanwhile, (28) found that adding 7.5 wt.% TiO_2 into PMMA significantly decreased water absorption compared to pure PMMA. According to article (37), the incorporation of ZrO_2 nanofillers within the PMMA matrix increased the flexural strength of PMMA by 10.3% compared to the control group. However, adding TiO_2 nanoparticles to PMMA reduced the flexural strength by 1%. Besides, article (39) shows that adding 3 wt.% of TiO_2 nanoparticle increases the fracture toughness to 1.7 ± 0.16 MPa compared to the control group.

The PMMA surface after modification with ZnO nanoparticle does not change compared to pure PMMA (43). Besides, the increasing amounts of ZnO-nanoparticles, particularly nanocomposites, increase the material's hydrophilic properties. Furthermore, the hardness study demonstrates a statistically significant difference between 5.0 wt.% composites, 7.5 wt.% nanocomposites, and pure PMMA. Another study investigated zinc oxide release and cytotoxicity testing of the PMMA reinforced with ZnO nanocomposites (40). According to the findings, no cytotoxic effects were captured due to the zinc oxide released from dental prostheses into the oral cavity.

Studies (31) and (41) used Au as an additive composite in PMMA. Study (31) used the elastic modulus and flexural strength on the sample resulting in no significant difference between group Au+ PMMA and pure PMMA. Besides, the fractured surfaces in Au + PMMA exhibited a similar surface texture to pure PMMA. In addition, the microhardness and thermal conductivity of PMMA/Au nanocomposites enhanced gradually when the volume was increased. However, article (40) found that Au with higher wt.% produces better flexural strength and tensile characteristics. Meanwhile, lower absorbed water ratios may mitigate the risks of water-mediated degradation effects. In addition, article (43) indicated that the nanocomposite (h-BNNs / AgNPs) did not intrude on the water absorption and dissolution capacity of the PMMA.

Article (26) used Al_2O_3 to investigate flexural strength. The finding indicated that adding smaller particle sizes shows better mechanical properties but lower resistance to water adsorption and solubility. Dental composite properties can be increased by adding nanoparticle fillers at small concentrations. However, the composition of BioHPP +PMMA was found to be better than Al_2O_3 + PMMA (29). Meanwhile, a study (24) used cellulose incorporated with OTES and MPMS to determine flexural strength and thermal stability. The finding indicated that a combination of PMMA, cellulose and MPMS (94.0 MPa) produced better flexural strength than pure PMMA (89.0 MPa), PMMA + pure cellulose (70.9 MPa) and PMMA + cellulose + OTES (88.0 MPa). Article (31) shows that increasing the HA weight had better results regarding Young's modulus (increases 70.8%), compressive yield strength (increases 29.96%), and ductility (increases up to 9%) than the control group. Furthermore, incorporating HA nanoparticles into PMA altered the wear properties and reduced weight loss during friction.

Conclusion

Most of the articles successfully prove the use of additives to enhance the structure, mechanism and properties of PMMA. 21 studies were selected based on the inclusion and exclusion criteria explained previously. A total of 9 articles use ZrO_2 as an additive to improve PMMA, followed by TiO_2, E-glass nanoparticles, ZnO, Au, Al_2O_3, BioHPP, HA, OA, Gr-Ag, and h-BNNs/AgNPs. Meanwhile, the flexural strength test, surface test, water absorption test, impact strength test, thermal stability test, antimicrobial test, water solubility and tension test are the tests carried out to determine the performance of PMMA structure. In conclusion, ZrO_2 is the most commonly used material to enhance PMMA, and the flexural strength test is the most common test used in fabricating a new denture base. However, this study did not analyze the polymerization process during denture fabrication or the chemical bond between the additive material and PMMA.

Competing interests

The authors declare that they have no competing interests.

Consent

This study does not require ethical approval.

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