

Enhancing Mechanical and Physical Properties of Polymethyl Methacrylate Denture Bases with Ceramic Nanoparticle Reinforcements: A Review



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ABSTRACT: Despite Polymethyl Methacrylate's (PMMA) biocompatibility and aesthetic advantages, concerns remain about its poor mechanical properties when used to fabricate synthetic dentures. A thorough review of the mechanical and physical properties enhancement of PMMA dentures using ceramic nanoparticles needs to be carried out to understand and optimize PMMA-based dentures' strength and durability in the oral environment. Thus, this systematic review is aimed at presenting a comprehensive review of the effects of ceramic nanoparticle reinforcements on the mechanical and physical properties of PMMA denture bases, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Using the keywords "PMMA denture reinforcement" and "ceramic nanoparticles," many search engines, including Scopus, PubMed, Wiley Online Library, and Google Scholar, were used to find academic publications published between 1997 and 2025. A total of 250 articles were found using these search parameters. The inclusion principle was then used to reduce the gathered results to 145 citations for this analysis. The mechanical and physical properties of PMMA dentures reinforced with various ceramic nanoparticles are reviewed, with a focus on zirconia nanoparticle-reinforced PMMA denture bases. Flexural strength, flexural modulus, impact strength, hardness, fracture toughness, elastic modulus, and transverse strength were reviewed. The in-vitro studies reviewed showed that the mechanical properties of PMMA denture composites were significantly improved by ceramic nanoparticles, demonstrating their effectiveness as reinforcing fillers. 3D-printed dentures, which exemplify how digital technology is transforming dental prosthetics, were reviewed. Hybrid reinforcement systems that leverage the synergistic effects of different filler types to improve denture performance were also highlighted.

KEYWORDS: Ceramic nanoparticles, Denture bases, Mechanical properties, Polymethylmethacrylate, Reinforcement.

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I. INTRODUCTION

Ceramics are one of the most biocompatible materials used in dental restorations. The past decade has witnessed a growing interest in all-ceramic restorations, driven by advancements in materials and processing technologies, making them visually appealing, more robust, and challenging (Alhotan et al., 2021a). The application of ceramics in dentistry is mainly due to their inherent aesthetic properties and high mechanical, optical, thermal, and chemical properties (Nejatian et al., 2006). Irrespective of these advantages, the brittle nature of ceramics, sensitivity to defects, low tensile strength, and fracture toughness restrict the application of these materials in dental restorations (Nejatian et al., 2006).

Most of the recent innovations have resulted in the creation of fully ceramic restorations in different forms of dental work, such as insets, dental casts, veneers, crowns, and fixed partial denture (FPD) designs that can be placed in the anterior and posterior parts of the oral cavity (as illustrated in Figure 1) (Sayeed et al., 2017; Totu et al., 2017). In dental

prosthetics, the best all-ceramic system should be biocompatible, provide a good marginal fit, be aesthetically acceptable, and be adaptable to all dental applications.

The major issues dental technicians and practitioners are addressing are ensuring the materials used are biocompatible, look natural, and withstand the tough conditions in the mouth (Alhotan et al., 2021b). Surface and internal flaws arising from thermal, chemical, or mechanical processes frequently impair ceramics' mechanical properties, thereby diminishing their overall performance (Pollington & van Noort, 2009). As a denture material, dentures are subjected to many forces during use, including compressive, tensile, and shear stresses, which can lead to premature fracture in real practice. Intra-oral chewing and unintentional falls outside of the mouth cause fatigue of denture bases and consequent fractures (Kanie et al., 2000; Zappini et al., 2003). The need for improved mechanical properties is underscored by the fact that 68% of denture fractures occur after three years of production. (Jagger et al., 1999, Sasaki et al., 2016). In previous studies, about 70% of detachable dentures fractured within 3 years of use. Further,

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29% and 30% of the midline fractures and detached teeth, respectively, were repaired (Ebrahim et al., 2019). This is the aim of current prosthodontic efforts to improve the mechanical properties of denture materials, thereby enhancing the longevity, strength, and overall function of denture patients. Oral functionality and appearance restoration have mostly been enabled by PMMA, which is a primary component of denture production (Zafar, 2020). The flaws of PMMA, such as its brittleness and wear resistance, have led to extensive research into new methods of reinforcement. It has been discovered that using ceramic particles has become one of the most promising approaches that can be used to enhance the reinforcement (Zafar, 2020; Wang et al., 2016). Consequently, scientists have tried to reinforce PMMA denture bases to enhance their mechanical properties (Hamdy, 2024; Hameed et al., 2024). Various studies have determined high flexural, impact strength, and surface hardness of heat-cured and ZrO₂ nanoparticle-reinforced PMMA denture composite bases (Gad et al., 2016, 2020; Hamdy, 2024). Also, silver nanoparticles have been shown to improve the mechanical and physical properties of PMMA, including

compressive strength and thermal conductivity. However, they have poor stability to colour during integration in PMMA (Hamed-Rad et al., 2014), and a major downside can be the agglomeration of nanoparticles at high loading of weight percentage that leads to stress concentrations (Fu et al., 2019). This review evaluates the effects of ceramic nanoparticle reinforcement on the physical and mechanical properties of PMMA dentures, including surface hardness, wear resistance, impact strength, fracture toughness, flexural strength, elastic modulus, and dimensional stability. The wide variety of ceramics, including titanium dioxide (TiO₂) and silica (SiO₂), as well as hydroxyapatite, zirconia nanoparticles, and calcium carbonate, offers the greatest opportunities to transform PMMA into a stronger and more resilient denture material. The review also highlights the significant effects of ceramic nanofiller reinforcements, including hybrid reinforcement fillers, on PMMA dental applications, based on the outcomes of various studies. Recent studies on Additive Manufacturing using CAD/ 3D-Printing of Denture bases were also highlighted.

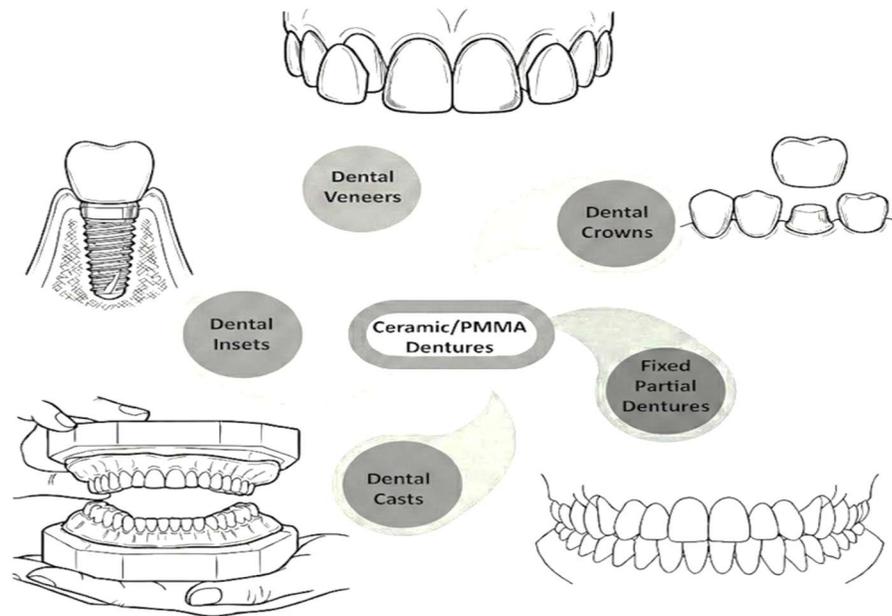


Figure 1 An illustration showing applications of ceramic particle reinforcement in PMMA dental appliances

II. REVIEW METHODOLOGY

A systematic literature search, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, on reinforcement of PMMA denture bases using various nanofillers, including their effects on their mechanical and physical properties, was done using electronic databases, including Scopus, PubMed, Wiley Online Library, and Google Scholar in November 2024, with an additional search done in September 2025 to add more updated articles. The keywords used for the search include: (“ceramic nanoparticles”, “denture bases”, “mechanical properties”, “polymethylmethacrylate”, “reinforcement”). Using these search criteria, a total of 250 were found.

Inclusion criteria were in-vitro studies evaluating the mechanical and physical properties of ceramic nanoparticle-reinforced PMMA dentures. Properties include flexural strength, flexural modulus, impact strength, hardness, fracture toughness, elastic modulus, and transverse strength. Reinforcement by other natural and metallic nanofillers were also included. 3D-printing, a recent denture base fabrication method, and hybrid filler reinforcement of PMMA dentures were also included. 145 research articles were cited using the inclusion criteria. Clinical trials, studies related to overdentures, in-vivo studies, and studies in other languages were excluded.

III. POLYMETHYL METHACRYLATE (PMMA) FOR DENTURE BASE FABRICATION

Polymethyl methacrylate (PMMA) is an important material in dentistry, widely used to manufacture dental prostheses, including baseplates, interim crowns, orthodontic retainers, and full and partial dentures. With its beneficial characteristics, which comprise high transparency, biocompatibility, hemocompatibility, low costs, low weight, ease of processing, and malleability, polymethyl methacrylate (PMMA) is still the material of choice to use in making dentures, even though dental implants are gaining popularity (Alhotan et al., 2021b; Ali Sabri et al., 2021; Hassan et al.,

2019; Nejatian et al., 2020; Sayeed et al., 2017; Zidan et al., 2020). Restoration of oral function and aesthetics has greatly been made achievable by PMMA, a mainstay in denture production (Zafar, 2020). PMMA is a methacrylate polymer fabricated through in-chain polymerization of methyl methacrylate. It is a durable, low-weight polymeric substance with excellent biocompatibility and great transparency (Ali et al., 2015; Kumari et al., 2023). Polymethyl Methacrylate (PMMA) key properties (unreinforced and reinforced), in comparison with ideal denture base material properties, are shown in Table 1. A complete PMMA denture is shown in Figure 2.



Figure 2 Complete Polymethyl Methacrylate (PMMA) Denture

Table 1 Polymethyl Methacrylate's key properties vs. ideal denture base material properties

Ideal denture properties	PMMA's key properties	Modified and filler-reinforced PMMA composite's key properties
Biocompatibility	Biocompatibility enhanced by long polymerization cycle (Thaitamyanon et al., 2018).	Biocompatibility and negative cytotoxicity. (Kumari et al., 2023). (Roato et al., 2023)
Good mechanical properties.	Inherently low flexural and impact strength, as well as a brittle nature. (Yang et al., 2017; Zidan et al., 2020).	Mechanical properties enhanced by reinforcement fillers (Hamdy, 2024; Hameed et al., 2024). (Gad et al., 2016, 2020).
Good wear and abrasion resistance	Less wear resistance, thus prone to abrasion. (Zafar, 2019)	Enhanced wear and abrasion resistance (Azmy et al., 2022). (Alshammari et al., 2025)
Dimensional Stability in the oral environment.	Enhanced dimensional stability the oral environment due to decreased polymerization shrinkage (Ali Sabri et al., 2021, Turagam & Prasad, 2013)	Enhanced by adding cross-linking agents and long polymerization cycles. (Ali et al., 2015).

Inert to chemicals and dietary minerals in oral fluids	Somewhat soluble in ketones, alcohols, and esters. (Diez-Pascual, 2022)	Addition of Crosslinking agents like ethylene glycol dimethacrylate to reduce solubility in organic solvents (Arima et al., 1996)
Low density and durability	Lightweight. (Ali et al., 2015; Kumari et al., 2023).	Low density, enhanced strength, and durability
Reproducibility	Ease of fabrication and repair	Ease of fabrication
Affordability	Low cost and quite affordable	Affordability is enhanced by reinforcing with natural fillers (Fouly et al., 2024; Monem et al., 2021).
Good aesthetics	Transparent, colorless, with good aesthetics and ease of pigmenting (Alqutaibi et al., 2023, Zafar, 2020).	Transparent pigments added to improve aesthetics
Adequate Thermal conductivity	Low thermal conductivity of $(5.7 \times 10^{-4} \text{ }^\circ\text{C}\cdot\text{cm}^{-1})$ (Alla et al., 2015)	Enhanced thermal stability (Yerou et al., 2026).
Sorption < 32 $\mu\text{g}/\text{mm}^3$. Solubility < 1.6 $\mu\text{g}/\text{mm}^3$ (Saini et al., 2016).	Solubility below 1.6 $\mu\text{g}/\text{mm}^3$. 0.02 and 0.04 mg/cm^2 in water and hydrocarbons, respectively. (Alla et al., 2015) .	-
Good color stability during use	Likelihood to discolor after sometime during use (Sagsoz et al., 2014). Color stability is enhanced by a long polymerization cycle.	Addition of cross-linkers to reduce water absorption and discoloration (Arima et al., 1996)
Radiopacity	Radiolucent polymeric material (Aldabib, 2020)	Modification using triphenylbismuth to enhance radiopacity. (Lang et al., 2000)

A. Properties of Polymethyl Methacrylate for Denture Base Applications

1). Biological properties

Biocompatibility is a highly notable biological property, outlined as a material's capacity to function in a biological setting without any adverse effects on the host. Studies have examined the cytotoxicity, surface roughness, and translucency of a PMMA acrylic denture base reinforced with bioactive glasses (Alhotan, et al., 2023a). The MTT assay was done to assess the biocompatibility of PMMA composites, and the 5 wt.% of ZrO_2 in the PMMA composite showed good cell viability at 530 nm (Kumari et al., 2023). Investigations into the biological properties of PMMA/ Al_2O_3 composites for dental implant Abutments revealed no cytotoxic effects (Roato et al., 2023).

2) Mechanical properties

In the oral environment, denture bases are subjected to intricate masticatory stresses. For denture base materials to function effectively, they must have appropriate mechanical properties. Given the importance of mechanical properties,

numerous steps have been taken to modify PMMA's flexural, impact, and fracture toughness. PMMA denture bases, however, have several disadvantages that may affect their effectiveness and durability. Their inherently low flexural and impact strength, as well as brittle nature, tend to increase the risk of mechanical breakdown and fracture during masticatory loading or unavoidable collisions, which is a major drawback (Yang et al., 2017; Zidan et al., 2020). Surface defects (scratches or other minor flaws) may initiate crack propagation, leading to denture failure (Ellakwa et al., 2008). Furthermore, PMMA is more prone to abrasion during routine tasks such as brushing, biting, and cleaning, as it has lower wear resistance than dental porcelains (Zafar, 2019).

3) Chemical properties

PMMA $(-\text{CH}_2-\text{C}[\text{COOCH}_3][\text{CH}_3]_{n-})$ is a translucent, amorphous thermoplastic with a molecular weight of several million. It is usually formulated by adding free radicals and polymerizing methyl methacrylate. Dental base substances are inert to chemicals and dietary minerals in oral fluids. In contrast, PMMA has a somewhat high solubility in ketones

and esters. Alcohols should also be avoided during the storage and cleaning of dentures because they function as plasticizers, which can reduce the glass transition temperature (T_g) of PMMA (Díez-Pascual, 2022). Water molecules can seep into the polymer chains when immersed in water, plasticizing them, leading to expansion that affects the material's dimensional stability (Miettinen & Vallittu, 1997). During the fabrication of denture base composites, coupling agents such as silane and titanate are added to strengthen the molecular link between the inorganic filler and the organic matrix. Excellent load transfer from the matrix to the reinforcement particles is achieved by strengthening the interfacial bond, thereby improving the mechanical properties of the reinforcement particles. By efficiently decreasing water sorption, this bond also enhances the PMMA composite's stability in the mouth, including retaining its property (Ali Sabri et al., 2021). Likewise, considerable dimensional changes and flaws may be caused by polymerization shrinkage during denture fabrication (Wang et al., 2016). Strict adherence to appropriate polymerization techniques can prevent this, thereby improving its volumetric stability. Additionally, PMMA lacks antibacterial qualities and radiopacity, which are necessary in dental materials to assist in its detection in radiographs (Zafar, 2020, Aldabib, 2020).

4) Physical properties

PMMA is an amorphous acrylic polymer which has a density of 1.18 g/cm^3 at 23°C , and a glass transition temperature (T_g) of 100°C to 130°C (Kumari et al., 2023). Due to its low wear resistance and tendency to stain, it will likely need to be replaced over time. Moreover, PMMA has poor color stability because of the leaching of unused monomers, which causes increased water absorption and discoloration (Sagsoz et al., 2014). Though PMMA fulfils some requirements for use as a dental material, it has some downsides like poor rigidity, low wear resistance, brittleness, discoloration, and susceptibility to fracture, which have driven

researchers to explore reinforcements and modifications to enhance its mechanical and physical properties, thereby expanding its range of application (Aldabib, 2020; Aldabib & Ishak, 2020; Al-Thobity, 2020).

IV. ENHANCING THE MECHANICAL PROPERTIES OF POLYMETHYL METHACRYLATE DENTURE BASE USING CERAMIC NANOPARTICLES

The addition of ceramic nanoparticles to Polymethyl Methacrylate (PMMA) improves its mechanical properties for denture applications. A study of various types of ceramic reinforcing nanoparticles, including zinc oxide (ZnO), zirconia (ZrO_2), silica (SiO_2), calcium carbonate (CaCO_3), and hydroxyapatite (HA), presents a comprehensive knowledge of their numerous impacts on PMMA denture bases' mechanical properties (Balos et al., 2020; El-Tamimi et al., 2022; Fouly et al., 2021; Gad et al., 2020). The diagram that classifies ceramic nanoparticles into four major classes is shown in Figure 3. The type and individual chemicals in each group are shown by the examples given for each category. According to Figure 3, oxide ceramics nanoparticles include metal oxides (e.g., TiO_2 , ZnO), rare-earth oxides (e.g., Y_2O_3), alkaline earth oxides (e.g., CaO), and spinels (e.g., MgAl_2O_4). Non-oxide ceramics encompass nitrides (e.g., Si_3N_4), carbides (e.g., SiC), borides (e.g., TiB_2), sulfides (e.g., CdS), and more.

Calcium phosphate and hydroxyapatite, which are essential for biomedical applications, are found in bioceramics. Complex ceramics, such as ternary oxides and solid electrolyte ceramics (e.g., YSZ), are examples of composite and hybrid ceramics that demonstrate the sophisticated integration of elements for specific purposes. Based on assessments of impact resistance and flexural strength, and considering surface hardness, the role of ceramic nanoparticles in reinforcing PMMA emerges as a crucial aspect of denture material research. This section explores the perceptual benefits of using ceramic nanoparticles, highlighting their various impacts and contributions to the mechanical integrity of PMMA denture bases.

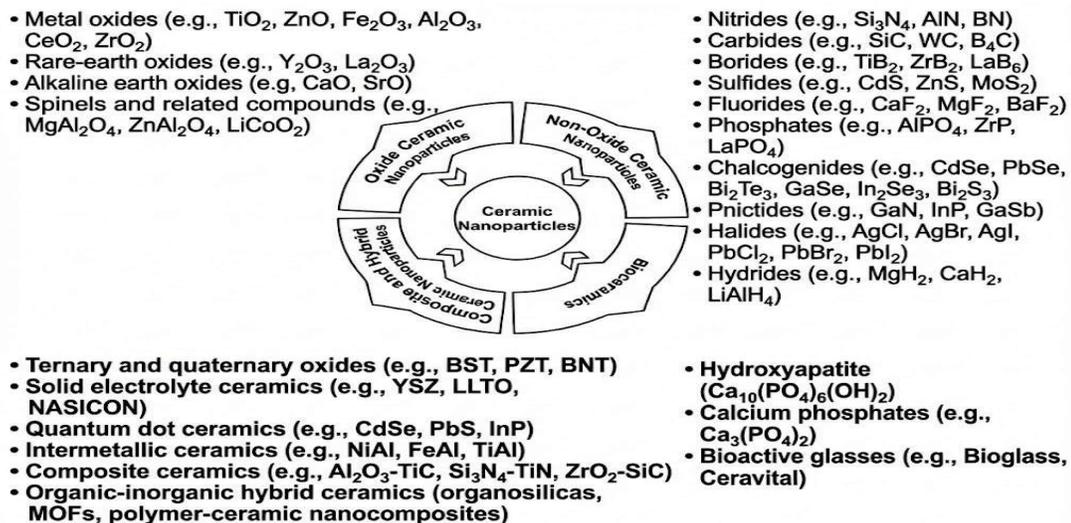


Figure 3 Classification of ceramic nanoparticles

A. Metal Oxides-Based Ceramic Reinforced Polymethyl Methacrylate.

1) Alumina (Al_2O_3) nanoparticles

Nanoparticles of alumina are porous, bioinert, and shaped like corundum. Due to its almost 100% purity and use as a dental alloy substitute for surgical metal alloys, alumina (Al_2O_3), which was first used in dentistry in the 1970s to create denture-based implants, is very unique (Hassan et al., 2021; Nabhan et al., 2023). Al_2O_3 nanoparticles possess a high surface area, outstanding thermal strength, and are characterized by permeability, low cost, and biocompatibility. Furthermore, they possess exceptional mechanical, medicinal, and physical properties, such as resistance to chemicals, wear, and abrasion, including weak electric conductivity (Díez-Pascual, 2022). Techniques for synthesizing alumina nanoparticles are straightforward and inexpensive. These include gas decomposition, solution reduction, laser ablation, and ball milling. These qualities, alongside their bio-inertness and ease of surface functionalization, render alumina nanoparticles suitable for biomedical applications (Díez-Pascual, 2022).

Research on the impacts of alumina nanoparticles reinforcement on PMMA has demonstrated a positive improvement in the properties of acrylic resin (Jehan et al., 2022; Pokuri et al., 2021). It is noteworthy that Ellakwa et al. (2008) established that flexural strength considerably improved after reinforcing with 10 wt. % alumina, and the thermal diffusivities were remarkably greater than those of the control samples (Ellakwa et al., 2008). Flexural strength was improved by 6.7% at 2.5 wt. % as stated by Vojdani et al. (2012), while the Vickers hardness number improved by 27% at 5 wt. % alumina nanoparticles reinforcement compared to the control sample (Vojdani et al., 2012). Pokuri et al. (2021) observed that flexural strength was enhanced at 2.5 wt. % alumina reinforcement before reducing at higher wt. % (Pokuri et al., 2021).

It is important to note that not all research demonstrates similar effects of Al_2O_3 reinforcement on the mechanical properties of PMMA denture bases. For instance, Al-Mahdy & Eltayeb, (2000) observed that flexural strength steadily decreased from 0 wt. % to 5 wt. % Al_2O_3 , with a slight increase at 3 wt. % reinforcement (Al-Mahdy & Eltayeb, 2000). Also, certain studies have established a decrease in tensile and impact strength at a particular wt. % of Al_2O_3 reinforcement, although hardness values on average increase with increasing alumina content (Abdulhamed & Ali, 2010).

Reinforcing PMMA with alumina offers some benefits but also has drawbacks. One disadvantage is that the PMMA/alumina denture composite can only be used in unexposed regions due to the likelihood of resin discoloration (Gad et al., 2017). While Al_2O_3 nanoparticles enhanced thermal conductivity, other investigations show that the increase in flexural strength was quite minimal (Gad et al., 2017). Nevertheless, depending on the specific use and denture specifications, significant evaluation is needed to ascertain the best possible concentration of Al_2O_3 reinforcement and any possible trade-offs between various mechanical properties (Gad et al., 2017; Hassan et al., 2021).

2) Titanium dioxide (TiO_2)

Titanium dioxide (TiO_2) nanoparticles used for reinforcing PMMA dentures have gained huge attention as a result of their outstanding mechanical properties, remarkable thermal conductivity, high water affinity, and strong antibacterial activity (Díez-Pascual, 2022; Dul et al., 2020; Totu et al., 2017). They are mostly used to produce antibacterial coatings for dental and medical applications (Ataol et al., 2018; Zore et al., 2022). Sol-gel, hydrothermal, and solvothermal techniques, precipitation, and electrochemical procedures are synthetic methods for producing TiO_2 nanoparticles that use titanium chloride, titanium isopropoxide, or titanyl sulfate as precursors.

The impacts of TiO_2 nanoparticle reinforcement on PMMA's properties, comprising its hardness, impact strength, flexural strength, thermal conductivity, and fracture toughness, have been the focus of several studies (Abdelraouf et al., 2022; Alshahrani et al., 2024; Azmy et al., 2022; Jehan et al., 2022). A number of studies have discovered that adding little wt. % TiO_2 nanoparticles slightly increased impact strength (Ahmed et al., 2016). Conversely, compared to the unreinforced PMMA sample, the higher wt. % TiO_2 nanoparticles (1 wt. % and 5 wt. %) considerably reduced the impact strength (Ahmed et al., 2016). The microhardness of PMMA has also been found to be reduced by 1 wt. % TiO_2 nanoparticle reinforcement, but at greater concentrations of 5 wt.% TiO_2 nanoparticles can enhance microhardness to levels that are comparable to 2.5 wt. % ZrO_2 nanoparticle reinforcement percentage (1.70 kJ/m²) (Ahmed et al., 2016). Due to likely filler agglomeration within the PMMA matrix, which can lead to weakened sections, some studies have found no noticeable increase in flexural strength after adding TiO_2 nanoparticles (Salih et al., 2015).

A new investigation has shown that the flexural strength and surface hardness of PMMA composites can be increased by adding 2.5 wt. % silane-treated TiO_2 nanoparticles (Jehan et al., 2022). Further research established that adding TiO_2 nanotubes to PMMA improved flexural strength and hardness; 2.5 and 5 wt. % TiO_2 nanotube-reinforced PMMA demonstrated superior values to the control samples (Ataol et al., 2018). A different study revealed that adding 1.5 and 3 wt. % TiO_2 nanoparticles to the PMMA denture base composite improved fracture toughness with minimal effect on impact strength (Alhotan et al., 2021b).

The antibacterial attributes of TiO_2 nanoparticles were studied in PMMA/ TiO_2 nanotube and nanoparticle composites, demonstrating potential as an effective antimicrobial material (Ataol et al., 2018; Zore et al., 2022). Furthermore, it has been observed that adding $BaTiO_3$ to PMMA enhances density and improves temperature stability, which may have an impact on denture acrylic retention (Ahmed et al., 2016). Compared to water bath curing, microwave curing of TiO_2 -reinforced PMMA dentures did not affect color stability or heat conductivity. However, it has been shown that adding 3 wt. % TiO_2 nanoparticles improved impact and color stability with no effects on heat conductivity.

In general, TiO_2 nanoparticle reinforcement has been thoroughly investigated to improve the mechanical properties of PMMA dentures. TiO_2 concentrations between 1 and 5

weight percent have been found to increase fracture toughness, flexural strength, impact strength, and hardness (Abdelraouf et al., 2022; Alhotan et al., 2021b; Alshahrani et al., 2024; Azmy et al., 2022; Jehan et al., 2022).

Additive Manufacturing using CAD/ 3D-Printing of Denture bases is another promising technology that has revolutionized denture base manufacturing in recent times (AlGhamdi et al., 2024; Alshaikh et al., 2022; Alshammari et al., 2025; Altarazi et al., 2024; Mohamed et al., 2025). It can

produce complex denture designs at very high speed and accuracy, thereby enhancing patient comfort, improving fit, and reducing manufacturing time and material waste. Popular techniques for producing additive-manufactured dentures include stereolithography (SLA) and Digital Light Processing (DLP). **Figure 4** illustrates the use of modern CAD modeling and 3D printing techniques to fabricate dental prostheses, showcasing the practical application of these advanced materials in dentistry (Dimitrova et al., 2023).

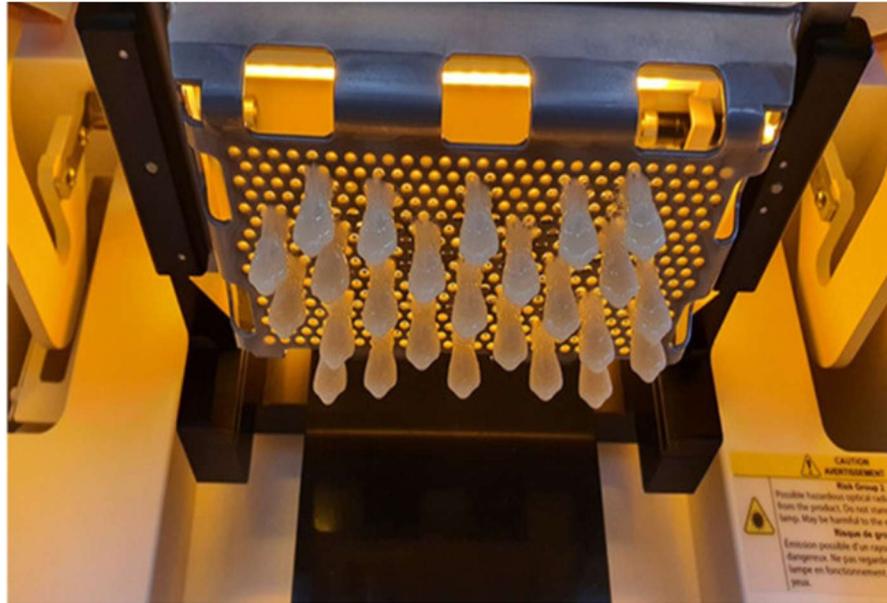


Figure 4 3D-printing of denture artificial teeth in the 3D printer NextDent 5100. Reproduced under the terms of the CC-BY 4.0 license, (Dimitrova et al., 2023) Copyright 2023, The Authors, published by MDPI

3) Zinc Oxide (ZnO) nanoparticles

Addition of zinc oxide nanoparticles (ZnO-NP) in different wt. % greatly improved the PMMA denture composite's flexural strength, with the highest value at 1.4 wt.%, demonstrating a significant 48.8% increase (Cierech et al., 2016, 2018; Vikram & Chander, 2020). Likewise, the PMMA flexural strength of the PMMA denture base reinforced with zinc oxide-NP was investigated, and the results were compared with those of heat-cured, conventional, unreinforced acrylic (Khan et al., 2020). According to Rudolf et al. (2020), energy dispersive X-ray spectroscopy (EDS) and scanning electron microscopy (SEM) characterizations were used to verify the effective dispersion of ZnO-NPs (Rudolf et al., 2020). The red spots in Figures 5a–c, which are images from Energy-Dispersive X-ray (EDX) mapping, show that

ZnO-NPs were uniformly dispersed throughout the PMMA matrix. For the composite material to have enhanced mechanical reinforcement, this uniform dispersion is fundamental. To enhance the composite's homogeneity and evaluate its mechanical strength, microbiological characteristics, and biocompatibility for potential therapeutic applications, the study underscores the need for additional research. The compressive testing (Figure 5d) highlights that reinforcement of PMMA using of ZnO-NPs can affect the fracture behavior, signifying potential areas for additional optimization to improve the material's mechanical strength and toughness.

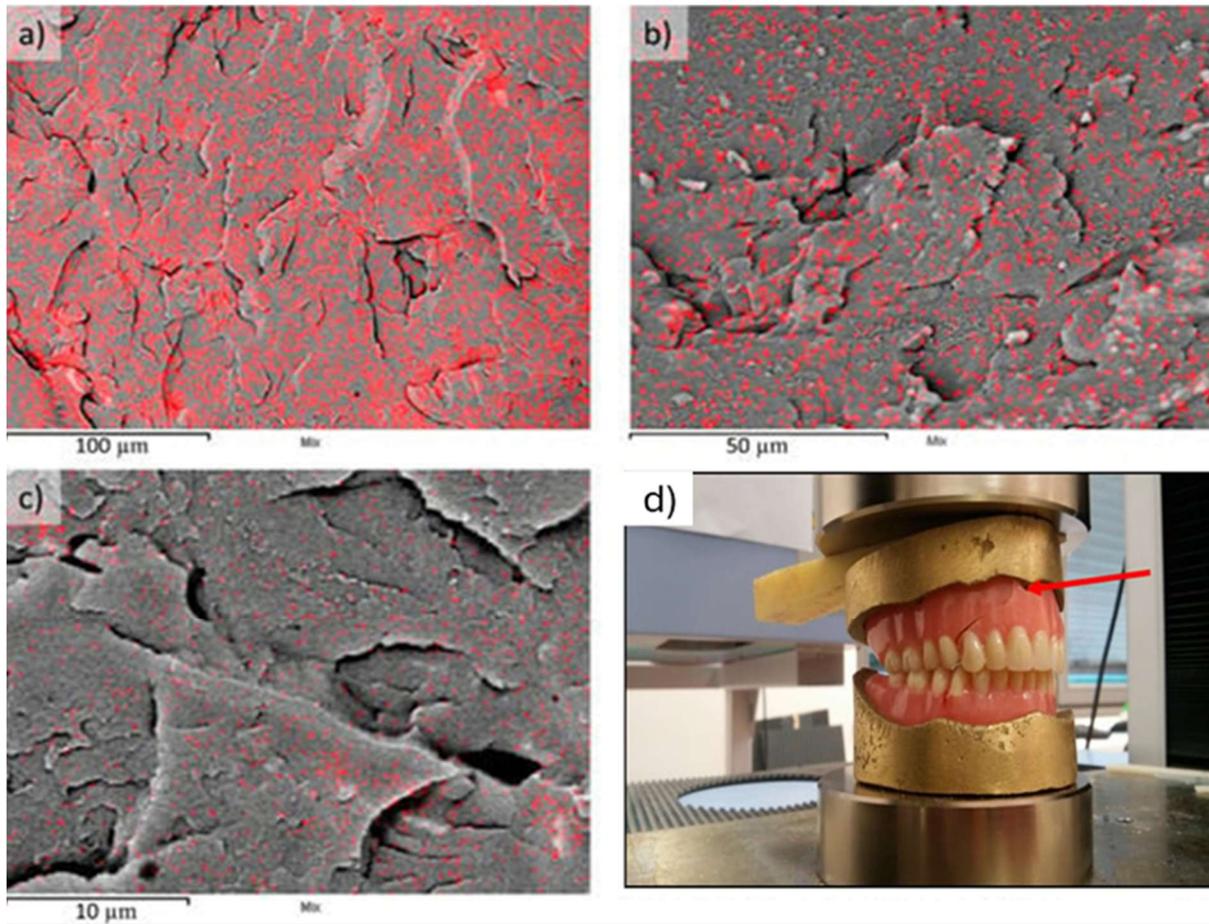


Figure 5 Elemental mapping via (EDX) illustrating the surface distribution of ZnO-NP incorporated into a PMMA matrix at (a) low, (b) medium, and (c) high magnification. (d) PMMA/ZnO nanoparticle tooth denture specimen after compressive mechanical testing. Reproduced under the terms of the CC-BY 4.0 license (Rudolf et al., 2020) Copyright 2020, The Authors, published by MDPI.

B. Glass/ Ceramics Reinforced Polymethyl Methacrylate

1) Silica nanoparticles ($\text{SiO}_2\text{-NP}$)

Silica nanoparticles ($\text{SiO}_2\text{-NP}$) are porous (2-50nm), biocompatible, stable in thermal environments, and amenable to simple, wide-ranging synthesis methods. Usually produced from tetraethyl orthosilicate, which is sourced from silica. Hydroxide is added to this silica source to hydrolyze the silicate. Sol-gel and hydrothermal treatment can also be used to synthesize $\text{SiO}_2\text{-NP}$.

The incorporation of silica nanoparticles ($\text{SiO}_2\text{-NP}$) as a reinforcement in PMMA dentures has been proven to enhance thermal stability, elastic modulus, flexural strength, impact strength, and surface toughness (Alshahrani et al., 2024; Azmy et al., 2022; Balos et al., 2020). In a study, the nanocomposite with 5 wt.% SiO_2 showed the greatest average transverse strength, reaching 124.562 MPa. Meanwhile, the nanocomposite with 7 wt.% showed an average value of 111.6 MPa and represented the lowest strength in this (Alnamel & Mudhaffer, 2014). In terms of hardness, the 7 wt. % nanocomposite exhibited the highest average value, indicating a 2% increase in comparison with the control sample. It is noteworthy, though, that adding more of these nanoparticles can lead to agglomeration issues, like crack propagation,

which would reduce hardness and resistance to fracture (Balos et al., 2020).

Addition of 1 wt. % and 5 wt. % untreated silicon nanoparticles to PMMA did not increase its flexural strength; in contrast, they negatively affected its flexural properties (Cevik & Yildirim-Bicer, 2018). A separate study, led by Kamil et al. (2018), examined the effect of silanized silicon carbide nanoparticles on the physical properties of PMMA. At 0.125 wt. % filler loading, it enhanced surface hardness, texture, and thermal stability, while reducing transverse and impact strength (Kamil & Al-Judy, 2018).

2) Zirconia nanoparticles (ZrO_2)

Owing to its outstanding properties, zirconia (ZrO_2), a ceramic material, has attracted significant interest as a reinforcement filler for PMMA dentures (Aldabib 2020; Alhotan et al. 2021b). It has exceptional fracture toughness and resistance to wear, weathering, and attrition, including compressive and flexural toughness (Díez-Pascual, 2022). Zirconia is suitable for biomedical applications in an oral environment due to its small grain size, which produces outstanding surface textures with distinct sharpness (Shin et al., 2016). Using a Hounsfield universal testing machine, the experimental setup and representation shown in Figures 6a and

6b provide a systematic method for evaluating the mechanical performance of denture specimens under bending loads. The failure modes that have been observed, such as cracks, localized fractures, and midline fractures, shed light on the resilience and durability of the nanocomposite material under stress (Figure 6c) (Zidan et al., 2020). Adding 3 wt. % silanized ZrO_2 nanoparticles greatly enhanced the flexural modulus and hardness of PMMA, as shown by the bar charts in Figures 6d and e. In particular, the flexural modulus exceeds the recommended British Standard value, indicating improved strength and stiffness. The effective load transfer between the PMMA matrix and ZrO_2 -NP is almost certainly the cause of this improvement (Albasarah et al., 2021; Zidan et al., 2021).

Yttria-stabilized zirconia, also known as YSZ, is a special type of ceramic material used in many industrial applications because of its unique properties (Elhmalı et al., 2025). Its composition, which includes zirconium dioxide (ZrO_2) stabilized with yttrium oxide (Y_2O_3), led to the term "Yttria-Stabilized Zirconia." Yttria is added to prevent zirconia from losing its crystal form at room temperature. Zirconia would undergo disorder phase transitions in the absence of yttria or other associated stabilizing chemicals, seriously damaging the substance. Outstandingly stable at high temperatures and resistant to thermal shock are two attributes that make yttrium-stabilized zirconia nanoparticles useful for numerous applications. This makes them suitable for use in difficult situations where other materials would fail. Its outstanding mechanical strength and hardness make it suitable for use in high-stress and abrasive situations; its strong resistance to chemical assault makes it useful primarily in applications where the material is exposed to corrosive substances; and it is typically considered biocompatible (Kazi & Yamagiwa, 2020; Garzo, 2025), and thus a suitable option for dental applications; also, it has visual appeal (Park et al., 2022) (Yarahmadi et al., 2023).

Zirconia nanoparticles are usually stabilized using 3 mol. % yttria for dental products, leading to outstanding mechanical properties of ZrO_2 , which are linked to stress-induced change from tetragonal to monoclinic, resulting in a 4.5% volume increase (Denry & Kelly, 2014; Ghaemi et al., 2017). The formation of a compression zone effectively improves strength by shielding the developing fracture tip and preventing further crack propagation. However, it is noteworthy that ZrO_2 is opaque, which could diminish its aesthetic qualities, and that moisture content can accelerate its aging, increasing surface irregularity and possibly crack propagation, which could affect its functions and properties.

Numerous studies have focused on incorporating modified zirconia nanoparticles, such as yttria-stabilized tetragonal zirconia polycrystals (Y-TZP), to improve the properties of standard heat-cured dentures (Díez-Pascual, 2022). This type of ZrO_2 nanoparticle (ZrO_2 -NP) exhibits higher mechanical qualities and excellent surface characteristics, making it an appealing choice for a broad range of dental products. Reinforcing PMMA with ZrO_2 -NP has been shown to significantly improve various mechanical properties, including flexural strength, fracture toughness, impact strength, and rigidity. For instance, Gad and co-researchers observed a steady improvement in tensile strength

with increased ZrO_2 concentration, albeit with a subsequent reduction in translucency (de Souza Leão et al., 2020; Gad et al., 2016; Zidan et al., 2020). Auto-polymerized resin reinforcement using 2 or 5 wt.% ZrO_2 exhibited the best transverse strength. Bending tests on heat-polymerized, 3 and 5 wt.% ZrO_2 reinforced PMMA dentures demonstrated enhanced flexural strength in the 5 wt.% zirconia-reinforced PMMA, approximately 27% higher than the control sample under fatigue loads.

Several other studies have confirmed that PMMA- ZrO_2 particle reinforcement significantly improves flexural strength, with some reporting that impact strength and flexural toughness can both rise by up to 40% and 30%, respectively, by adding 2 wt.% ZrO_2 (Ayad et al., 2008; Kul et al., 2016). However, it is noteworthy to state that adding ZrO_2 nanoparticles may not significantly impact surface toughness or water solubility of PMMA composites (Ayad et al., 2008). Furthermore, incorporating high concentrations of ZrO_2 (10% and 20 wt.%) has been found to reduce surface hardness and impact strength (Asopa et al., 2015).

It was also observed that at 5 wt. % reinforcement, the flexural strength increased by 16.6% for PMMA enhanced with silanised Zirconia Nanoparticles (Zidan et al., 2020). In a different investigation, flexural strength and surface hardness increased by 10.7% and 24.4%, respectively, for 3 weight percent treated zirconia, while they decreased by 17.3% and 15.6%, respectively, for 3 weight percent untreated zirconia composite (Zidan et al., 2021). The mechanical characteristics of polymer nanocomposites are determined by the adhesion and dispersion of the fillers within the matrix. Further research employing different wt. %. The percentage of zirconia nanoparticle filler reinforcement in different acrylic resin systems was recommended to better understand how zirconia nanoparticle reinforcement affects the mechanical properties of acrylic resins. In dentistry, 3D printing of dentures reinforced with zirconia nanoparticles, such as zirconium oxide ceramics, has been reported and has drawn significant interest (Bors et al., 2024; Frackiewicz et al., 2023; Majeed & Hamad, 2025).

Silane coupling agents are used to strengthen the bonds between zirconia nanoparticles and PMMA, as it has been determined that inadequate wettability between the polymer matrix and reinforcing particles is a limiting factor in improving PMMA denture mechanical properties. It is crucial to remember that adding more nanofiller than 2.5 weight percent can cause agglomeration, which lowers flexural and impact strength. As a result, especially at high zirconia-NP concentrations, ZrO_2 -NP/PMMA grafting was shown to improve flexural strength while decreasing impact strength. Moreover, it has been established that ZrO_2 nanotubes (NTs) perform better than ZrO_2 nanoparticles as reinforcement fillers (Gad et al., 2017).

Zirconia nanoparticles have attracted attention as a potential reinforcing material for PMMA dentures because they offer improved mechanical properties, including rigidity, impact strength, fracture toughness, and flexural strength. However, the ideal ZrO_2 -NP wt. % depends greatly on the desired property; hence, it is necessary to balance enhancing desired properties with reducing potential negative impacts,

such as decreased translucency and agglomeration, thereby reducing impact strength at higher concentrations. Effects of

ZrO₂-NP and their hybrid mixtures on the mechanical characteristics of PMMA denture bases are shown in **Table 2**.

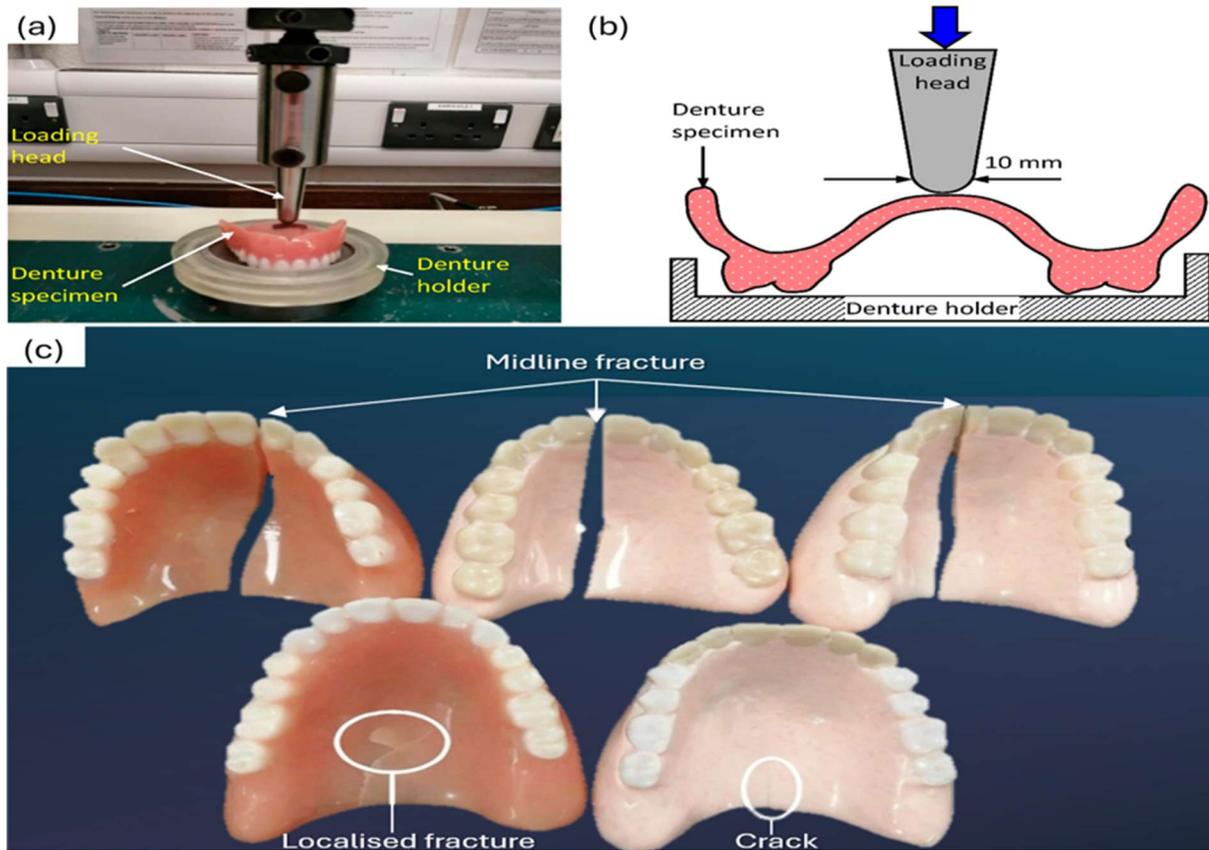


Figure 6 (a) Denture specimen experimental setup for three-point bending tests (b) Diagrammatic depiction of the bending load arrangement. (c) Typical failure modes observed in denture specimens during flexural testing. Reproduced in accordance with the CC-BY 4.0 license (Zidan et al., 2020) Copyright 2020, The Authors, published by MDPI

Table 2 Effects of Zirconia nanoparticles (ZrO₂ NPs) and their hybrid mixtures on the mechanical properties of Polymethyl Methacrylate denture bases

Matrix + reinforcement samples	Properties enhanced in comparison to control samples	References
PMMA + (nano-ZrO ₂) particles + micro-lignin particles	Tensile modulus increased by 86% for (PMMA+2 wt. % micro-lignin) composite. Compressive strength increased by 104% for PMMA+2% nano- ZrO ₂ composite. Hardness value increased by 6.96% for (PMMA+2% micro-lignin) composite.	Olewi, J., & Hamad, Q. (2018).
PMMA + polyetheretherketone (PEEK) nanoparticles + ZrO ₂ NPs	At (1.5wt% PEEK + 1.5wt% ZrO ₂), flexural strength was the highest and increased by 31.9%. At 3% PEEK, flexural strength increased by 15.2%. At 3% ZrO ₂ , it increased by 12.9%.	Barapatre, D., Somkuwar, S., Mishra, S., & Chowdhary, R. (2022).
PMMA + Al ₂ O ₃ NWs + ZrO ₂ NPs	At 0.5 and 0.7 weight percent loadings, the micro-hardness increased by 67.26% and 59.08%, respectively.	Hassan, A., El-Sheikh, M., Ali, W. Y., & Rohim, M. (2021).

	At 0.5 and 0.7 weight percent loading, the elastic modulus increased by 47 and 61.88 %, respectively.	
PMMA+(1% Silanized ZrO ₂ nano filler +2.5% electrospun Poly Styrene (PS) fibres).	1 wt. % zirconia-NP increased microhardness by 3%. At 1 wt. % silanized zirconia (ZrO ₂ /MEMO) composites, the hardness value increased by 29%. The impact strength improved by 70% for 1% Silanized ZrO ₂ nanofiller + 2.5% electrospun PS fibre reinforced PMMA.	Elmadani, A. A., Radović, I., Tomić, N. Z., Petrović, M., Stojanović, D. B., Heinemann, R. J., & Radojević, V. (2019).
PMMA+ ZrO ₂ + TiO ₂ + E-glass fibre.	The flexural strength increased by 10.3% at 3 wt.% ZrO ₂ then decreased marginally by adding 7 wt.% ZrO ₂ , to 1%.	Alhotan, A., Yates, J., Zidan, S., Haider, J., & Silikas, N. (2021a)
PMMA+ Silanized ZrO ₂ -NP	Silane-treated zirconia nanofiller enhanced the surface hardness and flexural strength of the composite.	Zidan, S., Silikas, N., Al-Nasrawi, S., Haider, J., Alshabib, A., Alshame, A., & Yates, J. (2021).
PMMA+ ZrO ₂ NP	Micro tensile bond strength increased to its highest value by 4.65% at 5 wt. %. It reduced by 25.3% and 21% at 1.5 wt. % and 3 wt. % respectively.	El-Tamimi, K. M., Bayoumi, D. A., Ahmed, M. M. Z., Albaijan, I., & El-Sayed, M. E. (2022)
PMMA + ZrO ₂ +TiO ₂ + Al ₂ O ₃ -NP	2.5 wt. %ZrO ₂ enhanced the flexural strength and surface hardness of the PMMA composite more than TiO ₂ + Al ₂ O ₃	Jehan, A., Ahila, S., & Muthukumar, B. (2022).
PMMA + ZrO ₂ , TiO ₂ , and SiO ₂ - NP	3 wt. % Nanofillers significantly enhanced Flexural strength, Impact strength, and Wear resistance.	Azmy, E., Al-kholy, M. R., Al-Thobity, A. M., Gad, M. M., & Helal, M. A. (2022).
PMMA + Digital Light Processed ZrO ₂ NP	58.3% and 13.7% decrease in Wear rate and COF of PMMA composite, respectively	Alshammari, S., Asiri, J. M., Najafi, A., Hashemi Soudmand, B., Hassan, H. Z., Hazzazi, F., & Ghazouani, N. (2025)
PMMA + MgO + ZrO ₂ -NP	Flexural strength and density significantly enhanced at low wt. % MgO + ZrO ₂ -NP reinforcement.	Wally, Z. J., Al-Jubouri, O. M., Al-Jlaihawi, Z. G., Almusawi, R. M., Alamoush, R. A., & Haider, J. (2025).
3D-Printed Resins + ZrO ₂ , and SiO ₂ - NP	1 wt. % ZrO ₂ , and SiO ₂ – NP, enhanced surface hardness, with no effect on surface roughness.	AlGhamdi, M. A., Alatiyyah, F. M., Almedarham, R. F., Al Dawood, Z. H., Alshaikhnesser, F. Y., Alboryh, S. Y., Khan, S. Q., Abualsaud, R., & Gad, M. M. (2024).

3D-Printed Resins + ZrO ₂ NP	For NEXTDENT and ASIGA resins, Flexural Strength was enhanced by 47.6% and 38.5 %, respectively.	Alshaikh, A. A., Khattar, A., Almindil, I. A., Alsaif, M. H., Akhtar, S., Khan, S. Q., & Gad, M. M. (2022).
PMMA + h-BN + ZrO ₂ NP	550% and 240% enhancement in Flexural Strength and Elastic Modulus, respectively, using 5 wt. % Boron Nitride. 400% increase in Vickers Hardness using ZrO ₂ NP	Alqahtani, M. (2020a)
PMMA+ Electrospun PVP+ZrO ₂ -Composite Nanofiber	Flexural strength increased by 83% and 67% for PMMA/PVP/ ZrO ₂ -10s and PMMA/PVP/ ZrO ₂ -20d samples, respectively. Flexural toughness increased by 169% and 153% for PMMA/PVP/ ZrO ₂ -5s and PMMA/PVP/ ZrO ₂ -10s composite samples, respectively.	Akkoyun, S., & Özdoğan, M. (2022).

C. Carbonate Ceramic Reinforced Polymethyl Methacrylate

1) Calcium carbonate nanoparticles (CaCO₃-NP)

Using the in-situ polymerization method, PMMA polymer was reinforced for use in denture applications, leveraging the strengthening properties of calcium carbonate nanoparticles (CaCO₃-NP) (Sharafeddin et al., 2025). This innovative approach led to an increase in Young's modulus without compromising the impact strength of the reinforced composites (Chatterjee & Mishra, 2013). In addition, PMMA grafts were made using treated CaCO₃ nanoparticles produced through stable emulsion polymerization (Jian-ming et al., 2004). To improve the interfacial bond between PMMA and CaCO₃, the nanoparticle surfaces were treated with gamma methacryloxypropyltrimethoxysilane during the fabrication of the PMMA/CaCO₃ nanoparticles composite. The research showed that the grafting efficiency, including the grafting ratio of PMMA to CaCO₃ nanoparticles treated with gamma-methacryloxypropyltrimethoxysilane, exceeded that of CaCO₃-NP modified with stearic acid.

Jagger et al. (1999) modified CaCO₃ nanoparticles with polybutyl acrylate chains grafted onto their surfaces, which were used to reinforce PMMA. This procedure was done to strengthen the interfacial bonds between PMMA and the inorganic nanofillers. The results showed that the CaCO₃ treatment produced good nanoparticle dispersion into PMMA and a robust interfacial adhesion between the fillers and the matrix (Jagger et al., 1999). Interestingly, adding CaCO₃ nanoparticles may increase the wear resistance of PMMA dentures while altering their abrasion mechanism. This development creates new opportunities to enhance PMMA's mechanical qualities in denture applications.

D. Bio-Ceramic Reinforced Polymethyl Methacrylate

1) Hydroxyapatite nanoparticles (HA-NP)

Hydroxyapatite is a material that is frequently studied for use in dentistry and medical applications due to its well-known biocompatibility (Akhtar et al., 2021; Hameed et al., 2024).

Studies on the impacts of hydroxyapatite addition to PMMA for bone replacement have been done (Balhuc et al., 2021). The mechanical properties of PMMA reinforced with nano-hydroxyapatite have been studied using compressive, abrasion, and bending tests (Akhlaghi-Fard et al., 2024; Fouly et al., 2021; Kaloka et al., 2024). Additional study has shown that applying a silane coupling agent to the surface of hydroxyapatite enhanced its mechanical properties, which include elasticity and flexural moduli, with 26% and 27.3% increment, respectively, by adding 15 wt. % nanocomposite reinforcement to hydroxyapatite (Aldabib & Ishak, 2020). However, after adding HA at 5 wt. % of filler loading, only a 1.6% and a 3% increase in tensile and flexural strength, respectively, were observed (Aldabib & Ishak, 2020). The surface hardness increased by 8% when 15 wt. % HA was used. On the other hand, increased hydroxyapatite wt. % reduced fracture toughness because of nanoparticle aggregation in the polymer matrix, which hindered chain mobility and produced stress concentration spots that caused stress-induced failure.

Additional research showed that using HA as a reinforcement material increased the flexural modulus and flexural strength of PMMA dentures by 42% and 45%, respectively (Shahkar et al., 2024). Methacryloxypropyltrimethoxysilane surface treatment of hydroxyapatite enhanced the hydroxyapatite fillers' interfacial bond with the PMMA matrix (Pan et al., 2013; Tham et al., 2010). Adversely, the water plasticizing process caused the development of weak spots in the PMMA and HA bonding regions, thereby decreasing flexural strength (Tham et al., 2010).

Compared to unreinforced PMMA, PMMA/HA nanocomposites demonstrated improvement in fatigue, compression, and thermal conductivity (Kul et al., 2016). Increased wt. % of hydroxyapatite filler reduced the wear rate, according to studies on the effects of hydroxyapatite nanoparticles on the compression and wear resistance of PMMA nanocomposites. According to compression testing, PMMA's ultimate compressive and yield strengths improved

with the addition of 2.5 wt. % hydroxyapatite nanofiller, while the elongation at break was reduced. Nonetheless, there was a reduction in ultimate and yield compressive strengths, with an increase in elongation at break when more than 2.5 wt. % hydroxyapatite was added.

Additional research examined the impact of salinized HA-NP on the properties of heat-cured PMMA dentures. The study discovered that adding 2 wt. % HA-NP reinforcement filler greatly improved impact strength, surface roughness, and surface hardness. This beneficial effect also extended to water sorption and solubility, although transverse strength decreased by 10.8% at the same wt. %. (Karadi & Hussein, 2017).

The setup for comparing the friction properties of PMMA/HA nanocomposites with those of a stainless-steel

counterpart is shown in the finite element analysis model (Figure 7a). A drop in the maximum stress values is observed in the corresponding stress distribution (Figure 7b) across the surfaces of nanocomposites with different HA weight ratios, suggesting better stress distribution and possibly lower material failure risk. Increasing the HA concentration in PMMA reduces the friction coefficient across various normal loads, indicating improved wear resistance, as shown in the friction coefficient graph (Figure 7c). These enhancements are due to the reinforcing effect of HA nanoparticles, which enhance the load-bearing capacity and rigidity of the composite (Fouly et al., 2021).

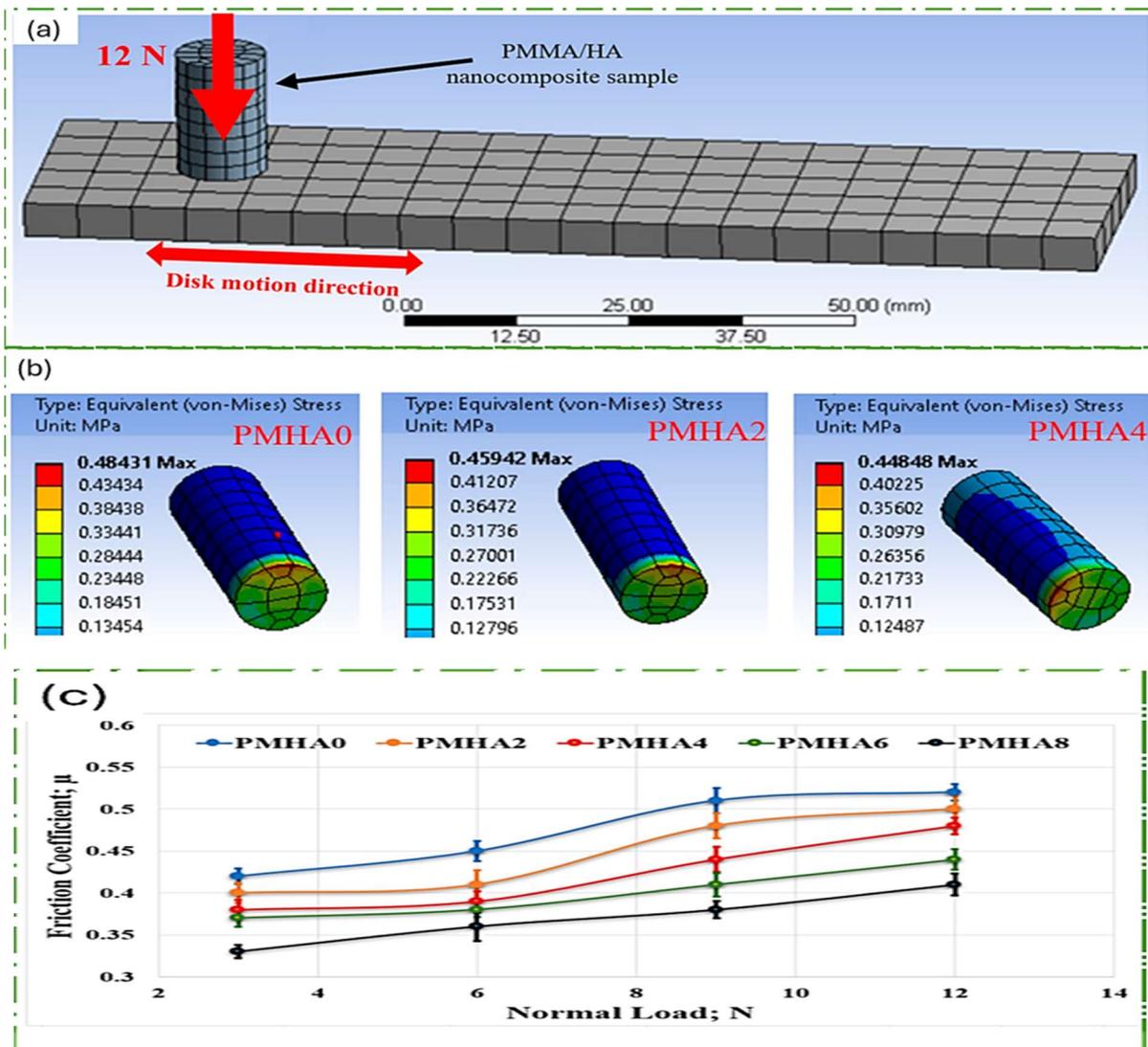


Figure 7(a) Finite element model of the friction test configuration of a PMMA/HA nanocomposite sample. (b) Simulated equivalent stress distributions on the PMMA/HA nanocomposite surface. (c) Variations in the friction coefficient of PMMA/HA nanocomposites and PMMA surface under varied applied normal loads, Reproduced under the terms of the CC-BY 4.0 license, (Fouly et al., 2021) Copyright 2021, The Authors, published by MDPI.

2) Other bio-ceramic Polymethyl Methacrylate composites for dental applications.

Mechanical properties of PMMA-based denture composites' enhancement led to research focused on utilizing unconventional reinforcements, such as seashell, rice husk, peanut, *Vaccinium macrocarpon* (cranberry) extract, cinnamon particles, and egg shell (hydroxyapatite) nanopowder (Fouly et al., 2024; Monem et al., 2021; Viswanathan & Krishnan, 2025; Wijaya & Chairunnisa, 2024). A comprehensive research intended to assess the tribological characteristics and hardness of a PMMA denture composite reinforced using seashell nano-powder was conducted (Karthick et al., 2014). The findings revealed that bio-composites of PMMA demonstrated significant improvements in microhardness when seashell nanopowder was used as a reinforcement, with the optimum characteristics at 12 wt.%. This concentration exhibited the highest microhardness (25.12 HV), outperforming that of the 8 wt.% reinforced composites. However, a notable decrease in microhardness was observed when the concentration exceeded 12 wt.%. Superior wear resistance was evident in both 12% and 8% seashell nanopowder-reinforced composites. Eggshell waste products were used to synthesize HAP nanopowder to improve the mechanical properties of PMMA dentures, with improved thermal stability and tensile strength observed at 10 wt. % reinforcement filler (Yerou et al., 2026). Cellulose nanocrystals extracted from rice husks were used to enhance the wear resistance, while reducing the coefficient of friction of the PMMA denture composite, as the wt. % of the nanocrystals were increased (Fouly et al., 2024).

The impact of PMMA and double-treated organoclay nanocomposites, subjected to a salinization procedure with the coupling agent 3-trimethoxysilylpropyl methacrylate, on the PMMA denture's mechanical properties was researched (Shakeri et al., 2019). Findings showed enhanced mechanical properties in both reinforced samples compared to the control matrix. Remarkably, fracture toughness, flexural modulus, and flexural strength increased by approximately 32%, 65.8%, and 30%, respectively.

E. Hybrid Ceramic

In lieu of individually incorporating fillers into the matrix, researchers have been developing hybrid reinforcement systems that combine various fillers and fibers to enhance the mechanical properties of PMMA denture composites (Aldwimi et al., 2024, 2025; Bharvada et al., 2025; Elhmali et al., 2024). Various methods have been employed for hybrid reinforcement, including grafting with multiple fiber types (Yu et al., 2012), combining different ceramics and metal oxides (Aljafery & Hussain, 2015), simultaneous grafts using oxides of fibers and fillers (Ahmed & Zainal, 2011), and utilizing a combination of ceramic fillers (Gad et al., 2019).

The flexural and impact strengths of high-impact acrylic resin reinforced using 1 wt.% of salinized TiO₂ and 5 wt. % of ZrO₂ NP, including their hybrid mixture with 2, and 1-wt.% of the additive mixture of 1% zirconia oxide and 1% titanium oxide, respectively, were investigated (Lilda G. et al., 2020). Zirconia, Titania-NP, and E-glass fibers reinforced PMMA were investigated for their surface hardness and flexural strength (Alhotan et al., 2021a). Compared to the control samples, flexural strength was considerably greater in samples reinforced using 3 wt. % zirconia; 5 and 7 wt. % E-glass fiber.

Innovative systems incorporating nano-fillers with different shapes, such as gelatin-treated halloysite nanotubes and silane-coupled aluminum trihydrate, were devised to explore the enhancement of acrylic material (Gawdzinska et al., 2019). The optimal operational characteristics were observed for a 2.5 wt.% hybrid nanocomposite of treated halloysite nanotubes and 2.5 wt.% silane-treated aluminum trihydrate. Adding treated nanofillers improved mechanical properties, including stress break, flexural strength, and impact resistance, albeit at the expense of a decrease in tensile modulus. At 5 wt.% of HNTs-g, tensile strength reduced by 50%, whereas elongation at break increased by 91%.

Additionally, radiopacity increased by up to 25% with the addition of 7.5 wt.% nitrile butadiene rubber, along with 1 wt.% alumina/yttrium-stabilized zirconia (Al₂O₃/1% Y-TSZ), in comparison to the control PMMA (Alhareb et al., 2016). These hybrid combinations also contributed to decreased shrinkage (Han et al., 2015). Studies by Han et al. (2015) revealed a 44% increase in flexural strength when 4 wt.% of silver-supported material (Novaron) was added to nano-ZrO₂-ABW/PMMA composites (Han et al., 2015). The impact and flexural strengths of reinforced polymethyl methacrylate were examined by Gad et al. (2019), using glass fibers and ZrO₂ nanoparticles in different weight percentages. When compared to control samples, hybrid reinforced composites showed noticeably greater impact and flexural strengths (Gad et al., 2019). For instance, the flexural strength of 5% nano-ZrO₂ + 0% GFs nanocomposites improved by 21% in comparison to control samples. Conversely, the (0% nano-ZrO₂ + 5% GFs) nanocomposites saw a 6% increase. Furthermore, 2.5 wt. % nano-ZrO₂ + 2.5 wt. % glass fiber nanocomposites demonstrated the highest impact strength, with a 51% improvement over the control PMMA group.

Therefore, hybrid ceramic reinforcing systems have demonstrated encouraging improvements in the mechanical properties of PMMA denture bases. Surface hardness, impact resistance, and flexural strength have been improved because of the synergistic effects of combining various fillers, fibers, and nanoparticles. In general, Table 3 summarizes the mechanical property enhancements observed in PMMA composites when reinforced with various nanofillers, highlighting specific improvements and corresponding references.

Table 3 Overview of the mechanical property enhancements in Polymethyl Methacrylate composite dentures with various reinforcement fillers

Matrix + reinforcement fillers	Mechanical properties enhanced compared to the control PMMA	References
PMMA + hydroxyapatite NP + alumina nanoparticles.	Fracture resistance in mode I increased by 70%.	Mousavi, A., Aliha, M. R. M., & Imani, D. M. (2020)
PMMA + ZnO	Flexural strength had its highest value exhibited in 1.4 wt. % zinc oxide NP, which increased by 48.8%.	Vikram, S., & Chander, N. G. (2020).
PMMA + multi-walled carbon nanotubes	The 1 and 2 wt.% carbon nanotube groups significantly increased total fracture work (-40%).	Kim, K.-I., Kim, D.-A., Patel, K. D., Shin, U. S., Kim, H.-W., Lee, J.-H., & Lee, H.-H. (2019).
PMMA + Nanodiamond	0.1 wt.% nano-diamond led to a more than 20% increase in flexural strength	Mangal, U., Kim, J.-Y., Seo, J.-Y., Kwon, J.-S., & Choi, S.-H. (2019).
PMMA + SrTiO ₃ /Y ₂ O ₃ -NP	Hybrid nanoparticles had 135.4% enhancement in impact resistance and 218.4% in Microhardness.	Elhmali, H. T., Radojevic, V., Stajcic, A., Petrovic, M., Stojanovic, D. B., Vlahovic, B., & Stajcic, I. (2025).
PMMA + coated glass flakes	21% in flexural strength at 1 w% of acrylic-coated glass flakes. Flexural Strength decreased by 12.4% with the addition of 5 wt. %.	Nejatian, T., Nathwani, N., Taylor, L., & Sefat, F. (2020)
PMMA + Double-treated organoclay nanoparticles.	Flexural strength, flexural modulus, and fracture toughness all showed average increments of around 30%, 65.8%, and 32%, respectively.	Shakeri, F., Nodehi, A., & Atai, M. (2019)
3D-Printed PMMA + Nanozeolite particles	Nanozeolite particles enhanced surface roughness, flexural strength, and fracture toughness of the 3D-Printed denture composite	Mohamed, P. A., Ghabour, O., Ibrahim, Y., & Eldokmak, M. M. (2025).
PMMA + Silver-doped CNT	Silver-doped CNT significantly enhanced the Impact Strength (37.5%) and Micro Hardness (171.6%) of the PMMA denture composite.	Alhotan, A., Abdelraouf, R. M., El-Korashy, S. A., Labban, N., Alotaibi, H., Matinlinna, J. P., & Hamdy, T. M. (2023b)
PMMA +h-BN Nano powder	Enhanced Flexural Strength and Vickers numbers by 300% and 550%, respectively.	Alqahtani, M. (2020b)
PMMA + Low Hydroxyapatite NP	At 0.8 wt. %, Hardness increased 9%, Young's Modulus increased 70.8%, and Fracture toughness by 9%.	Fouly, A., Ibrahim, A. M. M., Sherif, E.-S. M., FathEl-Bab, A. M. R., & Badran, A. H. (2021).
PMMA + AgNPs.	At 0.5 wt. % and 5 wt. %, AgNPs enhanced the Compressive strength by 5.3% and 8.3%, respectively.	Jain, S. K., Ila, A., Palaniswamy, A., Saini, R. S., Ahmed, H., Singh, G., Babu, J. S., Swarnalatha, C., & Nayyar, A. S. (2024).

PMMA + TiO ₂ -NP	At 5 wt. %, TiO ₂ -NP enhanced Flexural Strength by 82.5%. No significant changes in Surface Roughness and Micro hardness.	Abdelraouf, R. M., Bayoumi, R. E., & Hamdy, T. M. (2022).
PMMA + Nanoparticles of SrTiO ₃ /MnO ₂	Hybrid SrTiO ₃ /MnO ₂ NP enhanced Microhardness and Impact Energy by 89.9% and 145.4%, respectively.	Elhmali, H. T., Stajcic, I., Stajcic, A., Pesic, I., Jovanovic, M., Petrovic, M., & Radojevic, V. (2024).
PMMA + Silver-doped CNT	Enhanced Flexural Strength by 109.5%, Flexural Modulus by 108.6%, and Impact Strength by 386.9%.	Hamdy, T. M. (2024).
PMMA + Polyimide (PI)	The flexural strength of PMMA increased by 13.5% by adding 0.6% of PI	Yang, A., Zhao, D., Wu, Y., & Xu, C. (2017)

IV. CHALLENGES AND FUTURE TRENDS

While advancements in incorporating ceramic nanoparticles have undeniably enhanced the mechanical properties of Polymethyl Methacrylate (PMMA) in denture applications, several challenges persist, suggesting potential avenues for future research and innovation. Filler agglomeration is a serious issue, particularly evident in studies that used silica (SiO₂) and titanium dioxide (TiO₂) reinforcements. To achieve steady improvement in mechanical properties, the dispersion of the filler in the PMMA matrix remains a crucial factor that must be controlled. Moreover, the impact of increased filler content on some properties, including elongation at break and fracture toughness, exhibits complex trade-offs that demand careful consideration when designing materials.

Further work in this field may involve a more in-depth study of hybrid reinforcement systems. It is also possible to synergistically enhance the efficacy of PMMA denture materials by combining different ceramic fillers, fibers, and other nanoparticles. Future studies should focus on how such problems with filler agglomeration can be corrected and on the subsequent effects on mechanical properties. In addition, enhanced interfacial attachment between the PMMA and ceramic nanoparticles can be achieved using the latest surface treatments and novel coupling agents, thereby eliminating issues with the composite's strength and durability.

Creative solutions are possible through interdisciplinary collaboration among material scientists, dentists, and biomedical engineers to develop improved denture materials. Research on the effects of ceramic reinforcements on mechanical, biological, and thermal properties may yield new insights in the quest for superior denture materials. Lastly, overcoming some barriers and improving PMMA by strengthening it with ceramic nanoparticles is a promising avenue for the development of denture applications and can have a significant impact on the prosthodontics industry. Translating new denture base material, from laboratory innovation to routine clinical practice involves several major challenges:

a) Cost: Advanced materials and digital manufacturing technologies can be expensive, particularly during early adoption. The need for specialized equipment, training, and proprietary materials may increase expenses for dental practices and patients. To make these solutions widely accessible and affordable, costs must decrease over time through streamlined workflows and economies of scale.

b) Regulatory Approval: Before new dental materials can be used clinically, they must meet strict regulatory standards for safety and effectiveness. This involves extensive testing for biocompatibility, toxicity, and performance. The approval process is often time-consuming and costly, with varying requirements across different countries, which can complicate market entry.

c) Long-term Durability In-vivo: Laboratory tests provide initial performance data, but the true test of a material's durability comes from long-term clinical use. Denture base materials must withstand years of mechanical stress, temperature changes, and exposure to oral fluids. Unanticipated problems—such as wear, staining, or microbial buildup—may only become evident after prolonged use, requiring continuous evaluation.

d) Patient Acceptance: Technical excellence alone does not guarantee success; patient acceptance is crucial. Comfort, aesthetics, taste, and perceived value all influence whether patients are willing to use new dentures. Some patients may be hesitant about unfamiliar materials or concerned about higher costs. Clear communication and education about the advantages are essential to encourage adoption and build trust.

V. CONCLUSION

This paper reviews the various areas of ceramic nanoparticle reinforcements of PMMA in dentures. The research covers most types of ceramics, including titanium dioxide (TiO₂), zinc oxide (ZnO), silica (SiO₂), Zirconia Nanoparticles (ZrO₂), calcium carbonate (CaCO₃), and hydroxyapatite (HA). It has selected and critically examined papers that examined the influence of these reinforcements on key mechanical properties, such as flexural strength, hardness,

fracture toughness, compressive strength, elastic modulus, and impact resistance. The investigation also includes hybrid reinforcement systems, explaining the synergistic impact of using fillers of different types and shedding light on the potential for better denture performance. CAD/ 3D-printed dentures which demonstrate the use of digital technology for denture base fabrication has transformed, personalized, and enhanced patient outcomes. This list serves as a valuable source of knowledge about the complex relationships between PMMA and other ceramic reinforcements, based on an in-depth review of multiple studies. The trends in mechanical characteristics, including flexural strength and fracture toughness, provide a basis on which the well-informed material design strategies can be based. Such an extensive review not only expands our understanding of the mechanical enhancement of the material enabled by the reinforcements in the form of ceramic nanoparticles but also suggests the avenues of future research and development in the optimization of PMMA denture materials to reach higher durability and functionality in the dental context.

AUTHOR CONTRIBUTIONS

I. V Diwe: Conceptualization, Methodology, writing original draft manuscript, **O. A. Adeleye:** editing manuscript, preparing final manuscript, **H. E. Mgbemere:** Conceptualization, plotting graphs, preparing final manuscript, **B. O. Akinboboye:** methodology, editing original manuscript.

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