Bulgarian Chemical Communications, Volume 57, Special Issue E (pp. 40-51) 2025 DOI: 10.34049/bcc.57.E.SIMONS07

Nanofiller concentration in PMMA-nanocomposites for preliminary dental restorations

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Received: May 30, 2025; Revised: June 17, 2025

Digital dentistry has significantly transformed patient perceptions regarding various dental procedures by emphasizing high precision, enhanced comfort, personalized treatment plans, and reduced treatment times. This systematic review aims to identify and categorize the most commonly used nanocomposites in the 3D printing of provisional restorations, based on representative results from tests such as flexural strength and elastic modulus measurements. An English-language literature search was conducted using keywords including nanocomposites, provisionals, safe load, 3D printing, and geometry across multiple databases: PubMed, Google Scholar, ScienceDirect, and Scopus. The selection and categorization of relevant studies were carried out in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. A total of 231 articles were initially identified based on their titles. Selected articles were then analyzed according to the following criteria: historical developments in dental materials; applications of nanotechnology in dentistry; and the use of polymethyl methacrylate (PMMA) in the fabrication of provisional and preliminary fixed restorations. In conclusion, while the full potential of nanomaterials in dentistry is still being uncovered, ongoing advancements are expected to further enhance their properties and applications.

Keywords: nanocomposites, provisional restorations, PMMA, 3D printing, digital dentistry

INTRODUCTION

One of the major branches of contemporary dentistry is digital dentistry which involves the integration of digital technologies into routine clinical practice. This includes tools such as intraoral scanners, Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) systems, three-dimensional (3D) printing, and digital radiographic imaging [1]. Digital dentistry has significantly shifted patient perceptions of dental procedures by emphasizing high precision, increased comfort, case-specific customization, and expedited treatment timelines [1].

CAD/CAM technology involves milling preformed blocks of material into desired forms such as veneers, crowns, bridges, and other restorations. This approach enables high precision in the planning and fabrication of provisional restorations, largely due to the seamless connection between the digital impression and the restoration design. Consequently, this minimizes processing and fabrication time [2]. 3D printing represents another vital component of digital dentistry. This technique employs additive manufacturing to construct objects layer by layer, offering high precision, reduced material waste, and rapid production times [2, 3]. Both CAD/CAM and 3D printing provide several advantages, including shorter times for diagnosis, planning, and restoration fabrication; seamless integration of various tools (e.g., scanners, printers, milling units); and enhanced patient comfort and involvement [4].

Despite these advantages, digital dentistry also presents challenges. These include high initial costs, the need for frequent technological updates, and the requirement for specialized training of personnel [4]. Furthermore, the materials used in digital workflows often differ from those in conventional methods, necessitating specific handling protocols and testing procedures [4].

Digital dentistry is closely associated with the fabrication of provisional restorations, which require exceptional precision, particularly in marginal fit. Technologies such as CAD/CAM and 3D printing are well-suited to meet these requirements, though the cost of production and implementation remains a limitation. Within the Bulgarian scientific community, various authors have investigated the integration of digital technologies and materials in the fabrication of provisional restorations. Notably, Dimova *et al.* (1998) explored patient perspectives on preliminary restorations [5]. Additional studies have highlighted pediatric cases where treatment

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with crowns presents unique challenges due to age-related factors. In such situations, digital dentistry can facilitate more efficient treatment planning and execution, ultimately improving outcomes and reducing patient stress [6, 7].

Dental materials used in digital workflows differ significantly from their analog counterparts, requiring specialized testing and performance characteristics for each application. Composites are among the most commonly used materials for provisional restorations. These materials vary in their polymerization behavior and in the exothermic reactions they produce during curing [8]. Digital dentistry enables the effective incorporation of CAD/CAM technologies in the fabrication process, offering consistent quality and reproducibility [9].

An important contemporary development in dental materials is nanodentistry. Nanotechnology—or molecular engineering—focuses on the design and production of materials and structures with particle dimensions ranging from 0.1 to 100 nanometers. Nanocomposites are created by embedding nanoscale inorganic filler particles into an organic or hybrid matrix, often using a coupling agent to enhance adhesion between the matrix and the filler phase [10, 11].

Nanocomposites have a wide range of applications in dentistry, including caries-preventive restorative materials, reinforced resin bases for dentures, and provisional restorations [10, 12]. In Bulgaria, several authors have explored the properties of these materials. Ivanova *et al.* examined the delamination tendencies at the interface of bi-layered materials, identifying potential weaknesses in such structures [13]. Other research teams have analyzed the structural characteristics and mechanical parameters of nanocomposites, contributing to a deeper understanding of their performance [14–20].

Polymethyl methacrylate (PMMA) is one of the most widely used matrix materials in nanocomposites. PMMA is a hard, thermoplastic polymer known for its high Young's modulus and excellent scratch resistance [21]. Its flexural strength exceeds that of polyethyl methacrylate, making it a preferred choice for provisional and long-term restorations [22].

AIM

The aim of this systematic review is to identify and categorize the most commonly used nanocomposites in the 3D printing of provisional dental restorations, based on representative data from mechanical tests such as flexural strength and elastic modulus measurements.

MATERIALS AND METHODS

A survey was conducted in English based on keywords such as nanocomposites, provisionals, safe load, 3D print, and geometry, in different articles in the following databases: PubMed, Google Scholar, Science Direct, and Scopus. To select and categorize the collected information followed the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 guidelines.

Study selection

A survey was conducted in English based on keywords such as nanocomposites, provisionals, safe load, and geometry, in different articles in the following databases: PubMed, Google Scholar, Science Direct, and Scopus. Inclusion criteria consist of full-text articles, systematic reviews, and meta-analyses. Abstracts, patents, and short communications were excluded. Of 231 scientific research articles, 103 meet the inclusion criteria and are included in this article.

Analysis

A specific form in Microsoft Office Excel was used to systematize the extracted data and analysis. Duplicates were eliminated.

RESULTS

Initially, 231 articles were identified based on their titles in the database mentioned. The articles were published up to December 2024. Duplicate entries were removed. 192 articles remained. Therefore, an abstract review was made. Out of the 192 studies mentioned, 103 met the inclusion criteria. 89 were excluded from the survey due to insufficient data or different tests used. Figure 1 depicts the selection process using the PRISMA flow chart as a graphical representation of the evaluation process.

DISCUSSION

Historical review

The conceptual origins of nanotechnology can be traced back to 1960, when physicist Richard Feynman delivered his now-famous lecture, “There's Plenty of Room at the Bottom.”

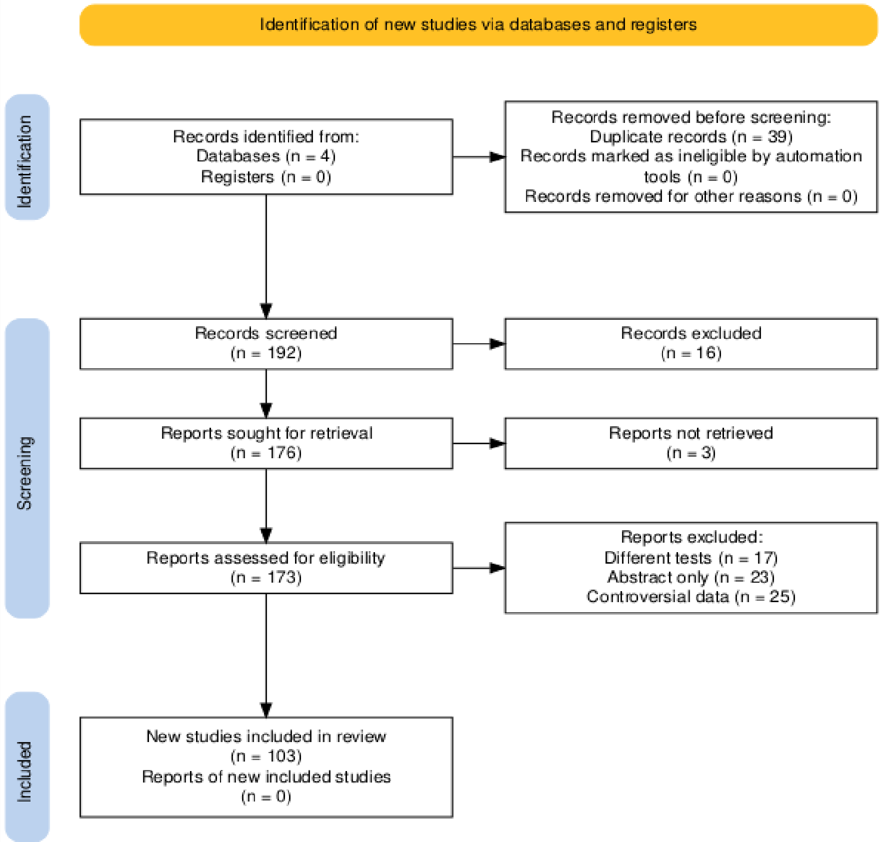

Figure 1. PRISMA flow chart.

In his visionary address, Feynman outlined a future in which scientists could manipulate individual atoms and molecules to create materials with unprecedented properties and performance [23]. Although the technical feasibility of such manipulation was purely theoretical at the time, Feynman is now recognized as one of the foundational thinkers behind the atomic theories that underpin modern nanomaterial science.

It would take several decades for these ideas to evolve into tangible scientific progress. By the early 2000s, the rapid advancement of molecular engineering and nanofabrication technologies had brought many of Feynman's predictions closer to reality. Notably, in the year 2000, Robert A. Freitas Jr. expanded upon Feynman's vision in an article published in the Journal of the American Dental Association, where he introduced the concept of nanodentistry [24]. Freitas proposed futuristic applications of nanotechnology in dental care, such as the use of dental nanorobots for targeted anesthesia, reduction of dentin hypersensitivity, and other microscale therapeutic interventions. At the time, these suggestions seemed far-fetched—much like Feynman's did in the 1960s—but they foreshadowed innovations that are now being actively explored or developed.

Today, nanotechnology is recognized as a cornerstone of innovation across multiple scientific disciplines, including medicine and dentistry. It plays a vital role in the design and fabrication of nanomaterials, which are now widely used in dental composites, coatings, drug delivery systems, and tissue regeneration. Nanodentistry, once a theoretical field, has grown into a distinct and impactful area of dental research and clinical application. The ongoing integration of nanotechnology into digital workflows, such as 3D printing and CAD/CAM fabrication, further solidifies its relevance in modern dental practice.

Nanotechnology in dentistry

In 2003, Ure *et al.* noted that while nanotechnology was largely regarded as a scientific discipline, its practical applications in dentistry—collectively termed nanodentistry—were still in their early stages of development [25]. Since then, the field has experienced significant growth, and various nanostructures are now being explored and implemented in dental applications. These include nanoparticles (ranging in size from 0.1 to 100 nanometers), as well as nanorods, nanospheres, nanotubes, nanofibers, dendrimers, and dendritic copolymers [12].

The fabrication of these nanostructures typically follows one of two primary methods: the bottom-up or top-down approach. The bottom-up approach involves constructing nanoparticles from atomic or molecular units through techniques such as desolvation, emulsification, spray drying, and freeze drying [26]. This method allows for precise control over particle size, distribution, surface characteristics, and overall purity. For example, Mitra *et al*. developed a synthetic chemical process in which molecules are assembled in a stepwise fashion to form nanoscale filler particles suitable for dental applications [27]. In contrast, the top-down approach starts with bulk materials that are subsequently broken down into nanosized particles using mechanical or physical methods, including etching, homogenization, milling, and ultrasonication [28]. While this method is more straightforward and often less expensive, it generally results in lower control over particle size and uniformity, and can compromise the surface integrity and mechanical properties of the nanoparticles [12, 29, 30].

In the context of dentistry, the bottom-up approach is generally preferred for the synthesis of nanocomposites due to its superior control over morphology and enhanced mechanical and optical properties of the final product. These characteristics are critical in achieving high-performance materials for restorative and prosthetic dentistry.

Beyond restorative materials, nanotechnology is also being extensively researched for other dental applications. For instance, nanoengineered coatings for dental implants have shown promise in promoting osseointegration, while nanoscale bone graft materials are being investigated for their potential to accelerate bone regeneration [31–33].

Figure 2. Applications of nanotechnology in dentistry (Shalini *et al*., 2020 [33]).

Furthermore, nanotechnology is playing a transformative role in drug delivery systems, periodontal therapy, caries prevention, and tissue engineering. An overview of current and potential applications of nanoengineering in dentistry is provided in Figure 2 illustrating the breadth and future direction of the field.

Nanocomposites in dentistry

Nanocomposites are a primary nanotechnological application in dentistry, used for provisional restorations and definitive restorative materials [33, 34]. They comprise nanosized inorganic fillers dispersed in organic or inorganic matrices, connected *via* coupling agents that reduce nanocluster formation and enhance mechanical properties [10, 11, 35].

PMMA for provisional restorations

Provisional restorations are vital for maintaining vertical occlusion, preventing tooth migration, and ensuring temporomandibular joint and muscular stability during treatment [36]. Polymethyl methacrylate (PMMA) is commonly used due to affordability, aesthetic acceptability, ease of manipulation, and polishability. However, PMMA exhibits high polymerization shrinkage, causing marginal inaccuracies that risk periodontal disease and restoration failure [38–43]. PMMA is also durable and widely employed in denture bases [39, 43–45]. The requirements and desired characteristics of PMMA are summarized in Fig. 3. Balkenhol *et al.* compared self-curing PMMA (Trim) with dual-curing composites, showing superior flexural strength and modulus in composites over time [46]. Similarly, Barqawi *et al.* (2024) reported that light-cured urethane dimethacrylate (UDMA) outperforms chemically activated PMMA in chair time and periodontal outcomes [47]. These findings highlight the need to improve PMMA-based materials, notably *via* nanoparticle incorporation [48].

PMMA nanocomposites for provisional fixed restorations

Nanocomposites enable enhanced control over physical, mechanical, thermal, and biological properties compared to conventional materials lacking fillers (e.g., polymers, ceramics, metal alloys). PMMA's poor impact and fracture toughness necessitate reinforcement with synthetic or natural fillers like fibers, ceramics, and metal particles [49, 50]. Chen *et al.* (2010) suggested that increasing nanofiller concentration reduces resin matrix content, thereby decreasing shrinkage and improving mechanical properties [10]. Recent improvements in PMMA-based nanocomposites have broadened their clinical applications [51].

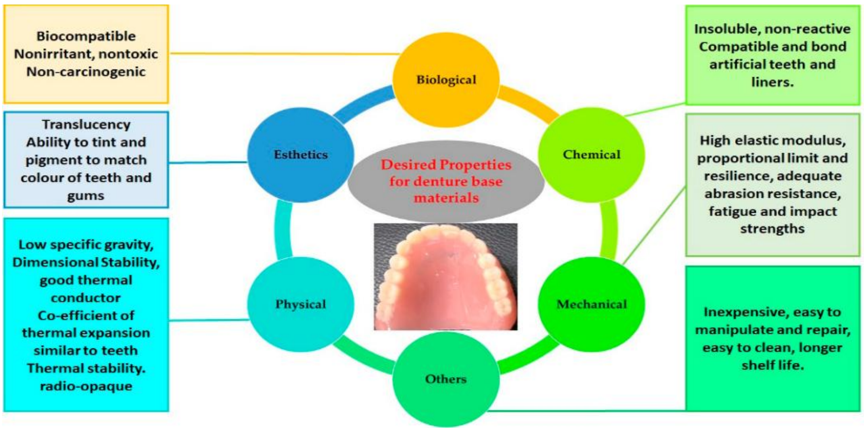

Figure 3. Desired characteristics of PMMA (Zafar, 2020 [45]).

Standardized tests to evaluate these materials include:

✓ *Flexural strength* (FS) is a critical parameter in determining the longevity of prosthodontic appliances and their resistance to masticatory forces. It characterizes the performance of dental materials when subjected to bending forces. The International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM International) have established guidelines for testing materials used in everyday dentistry. Among the essential parameters assessed is flexural strength [52–54]. Although alternative methods, such as biaxial testing, have been proposed, the ISO-approved three-point bending test remains the standard due to its reliability and widespread adoption [55, 56]. Table 1 summarizes findings from various studies that explore the relationship between nanoparticle concentration and flexural strength [55, 63–73]. Most studies indicate that increasing nanoparticle concentration enhances flexural strength up to an optimal threshold, beyond which a slight decline is observed. Nevertheless, all modified specimens demonstrate superior FS compared to their unmodified counterparts.

This decrease at higher concentrations is likely attributed to nanoparticle agglomeration, forming larger clusters that reduce the material's efficiency. Surface modification of nanoparticles—such as silanization—can mitigate this effect by preventing excessive agglomeration. The extent of required surface treatment, such as silane application, is influenced by the nanoparticles' size and surface area. Jasim *et al.* (2014) [75] concluded that a direct correlation exists: larger surface areas demand higher silane concentrations to ensure adequate coverage and performance.

Gad *et al.* (2019) [76] conducted a systematic review on PMMA denture base materials modified with TiO_2 nanoparticles. Their findings underscore the need for further *in vivo* research to validate the promising mechanical and clinical properties observed *in vitro*. These results align with earlier conclusions made by Gad *et al*. in 2017 [77].

Coupling agents such as silanes significantly enhance the bond between the polymer matrix and fillers, improving overall mechanical performance. However, some studies present differing views. Leão *et al*. (2019) [78] reported that silanization had no statistically significant effect on the mechanical properties of ZrO_2-filled composites, although they acknowledged improvements in flexural strength from nanoparticle incorporation.

Lohbauer *et al.* (2013) [79] suggested that limitations in mechanical properties often stem from deficiencies within the matrix itself, which can potentially be addressed through chemical modification of the composite. Akova *et al.* (2006) [80] investigated the impact of food-simulating solutions on provisional materials, finding that ethanol exposure significantly reduced flexural strength. These results highlight the influence of the oral environment and its dynamic conditions—such as dietary and masticatory functions—on the performance of provisional dental materials.

✓ *Hardness and microhardness* (MH) assess resistance to plastic deformation, critical for clinical wear resistance [81]. The Vickers microhardness test is widely used, following ISO and ASTM protocols [82, 83]. Most studies (Table 2) demonstrate that nanoparticle incorporation improves MH [57, 58, 63, 65, 66, 70, 73, 84–87]. Akova *et al.*'s findings on ethanol's deleterious effect on hardness further underline oral environment impacts [80].

✓ *Fracture toughness* (FT) indicates resistance to crack propagation under stress, essential for prosthesis durability [81]. Testing standards align with those for FS, with limited alternative method use [54-56, 88, 89]. Table 3 compiles data showing nanoparticle-enhanced FT in PMMA nanocomposites [66, 70, 72, 84, 90–93].

Table 1. Studies comparing flexural strength of nanocomposites.

Author	Test	Materials tested	Key findings
Rodrigues et al 2008a [55]	3 - point bending test	Specimens of the composites Filtek Z250™ and Filtek Supreme™ are light-cured.	Flexural strength of the microfilled composite Filtek Z250™ showed higher values than the one of the nanofilled composite Filtek Supreme™ .
Hata et al 2022 [57]	3 - point bending test	PMMA-based resin with nanoporous silica filler particles. Specimens were obtained after light-curing in sizes 14 x 4 x 2 mm.	The specimens with added nanoporous silica filler have improved flexural strength property.
Kim et al 2002 [58]	3 - point bending test	Different direct composites with varying morphologies of fillers were put in metal molds. Specimens were obtained after light-curing in sizes 2 x 2 x 25 mm.	Polymerized fillers lead to the lowest mechanical properties. Round fillers presented the highest flexural strength. However, increasing the filler concentration does not improve the mechanical properties.
Orsi et al 2010 [59]	3 - point load test	Different PMMA-based composites were used in the study: Dencor, Duralay, and Trim Plus II. Specimens were obtained in sizes 65 x 10 x 3 mm. Sixty were loaded with glass fibers, and sixty were used as a control group.	The flexural strength of the specimens was not improved by adding glass filler fibers.
Rodrigues et al 2008b [60]	4 - point bending test	Filtek Z250ᵗᵐ-Z2 (microhybrid) and Filtek Supreme™-SU (nanofill) composite specimens were compared.	The flexural strength of the specimens showed similar results - the nanofil composite presented a slightly lower result.
Kumari et al 2024 [61]	3 - point bending test	PMMA with MgO nanoparticles with different particle concentrations is compared to non-modified PMMA. Specimens are in dimensions 1.3 cm (diameter) x 9 cm (length).	Nanofilled composite specimens showed improvement in the fracture toughness compared to the non-modified PMMA. The highest result was presented by 5 wt% MgO.
Saen et al 2016 [62]	3 - point bending test 4 - point bending test	Bis-GMA/TEGDMA (70/30 wt%/wt%) and the corresponding nanocomposite containing 50 wt% of silanized Aerosil OX-50 silica. Nanosilica particles were silanised with γ-MPS.	Flexural strength is generally improved in the modified specimens. Another parameter was added in the testing technique speeding up of the test. A critical value is presented, after which flexural strength decreases.
Jamel et al 2023 [63]	3 - point bending test	PMMA non-modified and modified with glass fibers (GF) and ZrO_2 nanoparticles specimens are prepared in sizes 2 x 2 x 25 mm. The concentration of the different groups is as follows: group 1 (0% GF + 0% ZrO_2), group 2 (0% GF + 5% ZrO_2), group 3 (1% GF + 4% ZrO_2), group 4 (2% GF + 3% ZrO_2), group 5 (2.5% GF + 2.5% ZrO_2), group 6 (3% GF + 2% ZrO_2), group 7 (4% GF + 1% ZrO_2), group 8 (5% GF + 0% ZrO_2).	Flexural strength is generally improved in the modified specimens. The highest values are recorded in group 8 (5% GF + 0% ZrO_2). A correlation between the increase in GF concentration and improvement of mechanical properties is observed.
Balos et al 2020 [64]	3 - point bending test	PMMA non-modified and modified with nanosilica specimens are prepared in 0, 0.02, 0.05, 0.1, 0.2, 0.5, 0.7, 1, 1.5, 2, 2.5, 3, 5 wt%	Flexural strength is improved in the modified specimens, A peak mechanical performance is presented in the 0.05 and 2 wt%. An increase in nanoparticle concentration leads to a decrease in flexural strength. Therefore, the lowest mechanical properties are in the non-modified and the 5 wt% group.
Alshahrani et al 2024 [65]	3 - point bending test	Auto-polymerizing acrylic resin is mixed with nano-SiO_2 and nano-TiO_2 with concentrations of 0, 1, 2.5 wt%.	Low nano-SiO_2 addition shows improvement in the flexural strength. However, the 2.5 wt% of nano-SiO_2 and both 1 and 2.5 wt% nano-TiO_2 did not improve nor deprove the mechanical propertis.
Zidan et al 2019 [66]	3 - point bending test	PMMA modified with ZrO_2 specimens are prepared in a concentration of 0, 1.5, 3, 5, 7, 10 wt%.	An improvement in the flexural strength is presented in 1.5, 3, and 5 wt% groups, with a peak performance in the 3 wt% group. By increasing the concentration of the nanoparticles further a decrease in the mechanical property is presented.
Barapatre et al 2022 [67]	3 - point bending test	PMMA modified with 3 wt% ZrO_2, 3 wt% Polyetheretherketone (PEEK), or 1.5 wt% ZrO_2 and 1.5 wt% PEEK specimens are prepared in sizes 65 x 10 x 2.5 mm.	The flexural strength improved in all modified specimens. The highest performance is shown in the hybrid group of 1.5 wt% ZrO_2 and 1.5 wt% PEEK.
Gad et al 2016 [68]	3 - point bending test	Repair resin is modified with nanoparticles of ZrO_2 with 2.5, 5, 7.5 wt% concentration.	The addition of ZrO_2 nanoparticles improved the flexural strength of the repair resin. The peak performance value is found in 7.5 wt% ZrO_2 .
Ai et al 2016 [69]	3 - point bending test	Bis-GMA/TEGDMA composite is modified with 4-10 wt% of polydopamine (PDA) - coated hydroxyapatite (HA) and added Ag nanoparticles (HA-PDA-Ag)	A significant improvement of the flexural strength is presented in the modified group.
Thomaidis et al 2013 [70]	3 - point bending test	Specimens of the composites Filtek Z250, Filtek Ultimate, Admira and Majesty Posterior are compared.	Filtek Z-250 is presented with the highest flexural strength
Kumar et al 2013 [71]	biaxial flexural strength	Different composites are compared after 1-week dry, 1-week wet, and 13-week wet storage. The specimens are in sizes 12 mm (diameter) and 1 mm (thickness).	Flexural strength declined in the modified nanocomposites after 1-week dry storage. Higher deformation is connected to the addition of nanofiller.
Atai et al 2011 [72]	3 - point bending test	Microfilled, sintered nanosilica composite and Filtek Supreme composite are compared. Specimens are in sizes 2 x 2 x 25 mm and light-cured.	Both Filtek Supreme and nanosilica composite showed improved flexural strength compared to the microfilled composite.
Alhavaz et al 2017 [73]	3 - point bending test	PMMA is reinforced with untreated Zr nanoparticles. Specimens are divided into groups of 0, 1, 2.5, 5 wt% Zr nanofiller.	Flexural strength is generally improved by adding untreated zirconia. It reaches a maximum at 2.5 wt% and a slight decline is visible in the 5 wt% group.

Abbreviations: wt% - weight percentage; Bis-GMA - Bis-[4-(methacryloxypropoxy)-phenyl]-propane, TEGMA - triethyleneglycoldimethacrylate, γ-MPS - 3- Methacryloxypropyltrimethoxy-silane

Table 2. Studies comparing hardness and microhardness of nanocomposites.

Author	Test	Materials tested	Key findings
Hata et al 2022 [57]	Vickers microhardness tester	PMMA-based resin with nanoporous silica filler particles. Specimens were obtained after light-curing in sizes 14 x 4 x 2 mm.	Microhardness in the modified specimens is improved compared to the non - modified ones.
Kim et al 2002 [58]	Vickers microhardness tester	Different direct composites with varying morphologies of fillers were put in metal molds. Specimens were obtained after light-curing in sizes 5 x 1 mm.	Polymerized fillers lead to the lowest mechanical properties. Round fillers presented the highest flexural strength. However, increasing the filler concentration does not improve the mechanical properties.
Jamel et al 2023 [63]	Vickers microhardness tester	PMMA non-modified and modified with glass fibers (GF) and ZrO_2 nanoparticles specimens are prepared in sizes 9 (diameter) x 3 mm (thickness). The concentration of the different groups is as follows: group 1 (0% GF+ 0% ZrO_2), group 2 (0% GF + 5% ZrO_2), group 3 (1% GF + 4% ZrO_2), group 4 (2% GF + 3% ZrO_2), group 5 (2.5% GF + 2.5% ZrO_2), group 6 (3% GF+ 2% ZrO_2), group 7 (4% GF + 1% ZrO_2), group 8 (5% GF + 0% ZrO_2).	Microhardness is generally improved in the modified specimens. The highest values are recorded in group 8 (5% GF + 0% ZrO_2). A correlation between the increase in GF concentration and improvement of mechanical properties is observed.
Alshahrani et al 2024 [65]	Vickers hardness tester	Auto-polymerizing acrylic resin is mixed with nano-SiO_2 and nano-TiO_2 with concentrations of 0, 1, 2.5 wt%. Specimes are molded in sizes of 10 x 10 x 3.4 mm.	Hardness is improved in all modified groups compared to non-modified resin.
Zidan et al 2019 [66]	Vickers microhardness tester	PMMA modified with ZrO_2 specimens are prepared in a concentration of 0, 1.5, 3, 5, 7, 10 wt%. Specimens are divided into two groups: 0-day dried, 7-day water immersion, and 45-day water immersion.	A direct correlation of the increase of the mechanical properties and the concentration of nanoparticles is found in the 0-day group. After water immersion a decrease in the hardness is found.
Thomaidis et al 2013 [70]	Brinell hardness test	Specimens of the composites Filtek Z250, Filtek Ultimate, Admira and Majesty Posterior are compared.	Majesty Posterior is presented with the highest Brinell hardness.
Alhavaz et al 2017 [73]	Vickers microhardness tester	PMMA is reinforced with untreated Zr nanoparticles. Specimens are divided into groups of 0, 1, 2.5, 5 wt% Zr nanofiller.	Microhardness is improved by adding nanofiller reinforcement in the PMMA base material.
Balos et al 2014 [84]	Vickers microhardness tester	PMMA-based materials (Triplex Hot, Plyhot, Biocryl) with different dispersions of nanoparticles (0.023%, 0.046%, 0.091%, 0.23%, 0.46%, 0.92%). Specimens were cut in sizes 50 x 50 x 4 mm, using metalographic abrasive cutting machine and silicone carbide paper. A micrometer with an accuracy of 0.01 mm confirmed the sizing.	Microhardness has two peaks of performance at 0.023% and 0.91%. Overall, all modified specimens have improved microhardness compared to the original non-modified. The authors concluded that the results are obtained due to nanoparticle agglomeration formation, which increases the risk of cracks.
Raj et al 2018 [85]	Durometer (ASTM)	PMMA/ZnO composite specimens were obtained in sizes 60 x 10 mm. The specimens have different concentrations of ZnO particles: 0, 1, 2, 5, 10, 15 wt %.	Hardness was improved in the 1 wt %, however, there was a slight decrease in the mechanical property for the others. In general, 2, 5 wt% groups showed improvements, 10 wt% - similar results to the control group and 15 wt% presented a decrease in the hardnes compared to the control group.
Ayad et al 2008 [86]	Vickers microhardness tester	PMMA modified with ZrO_2 rectangular models are prepared in sizes 30 x 10 x 2.5 mm.	The results of this study show similar statistical valueas of microhardness for non-modified and modified specimens.
Elkhouly et al 2022 [87]	Vickers microhardness tester	PMMA reinforced nanocomposites with date seed nanoparticles (DSNP) and TiO_2 nanoparticles are compared. The fillers are divided into groups with different concentrations of nanoparticles: 0, 0.3, 0.6, 0.9, 1.2 and 1.5 wt%.	1.2 wt% DSNP PMMA nanocomposite showed the highest mechanical properties compared to the TiO_2 .

Abbreviations: wt% - weight percentage

Table 3. Studies comparing fracture toughness of nanocomposites.

Author	Test	Materials tested	Key findings
Zidan et al 2019 [66]	Single-edge-notched bending method	PMMA modified with ZrO_2 specimens are prepared in a concentration of 0, 1.5, 3, 5, 7, 10 wt%.	A decrease in the fracture toughness is presented in almost all groups is presented compared to the non-modified group. The 5 wt% group shows similar result as the control group.
Thomaidis et al 2013 [70]	Single-edge-notched bending method	Specimens of the composites Filtek Z250, Filtek Ultimate, Admira and Majesty Posterior are compared.	Filtek Z-250 is presented with the highest fracture toughness.
Atai et al 2011 [72]	Single-edge-notched bending method	Microfilled, sintered nanosilica composite and Filtek Supreme composite are compared. Specimens are in sizes 5 x 2 x 25 mm and light-cured.	Sintered nanosilica composite showed improved fracture toughness compared to the microfilled and Filtek Supreme composites.
Balos et al 2014 [84]	4 - point bending test	PMMA-based materials (Triplex Hot, Plyhot, Biocryl) with different dispersions of nanoparticles (0.023%, 0.046%, 0.091%, 0.23%, 0.46%, 0.92%). Specimens were cut in sizes 50 x 50 x 4 mm, using metalographic abrasive cutting machine and silicone carbide paper. A micrometer with an accuracy of 0.01 mm confirmed the sizing.	Fracture toughness improved with 0.023% addition of nanosilica particles compared to the initial non - modified material. The three different PMMA - based materials showed simillar results. By increasing the value of nanoparticles the fracture toughness decreases. The authors conclude that the main reason for the results of the study is the particle agglomeration which leads to crack formation. Alverall, all modified specimens have improved their fracture toughness compared to the non-modified one.
Topouzi et al 2017 [90]	3 - point bending test (single-edge notched method)	PMMA modified with silica nanoparticles samples are prepared with size 3 x 6 x 25 mm with a pre-crack perpendicular to the length and depth of 3 mm. Silica nanoparticles are devided into non-modified (SIL) and modified with trietoxyvinylsilane (T-SIL). Each group consists of specimens with 0.25%, 0.50%, 0.75% and 1 wt%.	An improvement in fracture toughness is recorded in the modified PMMA. PMMA/T-SIL with 0.25% nanoparticles presented the highest mechanical properties.
Xu et al 2002 [91]	Single-edge-V-notched beam method	Seven silica powders with ratio of whiskers:silica mass 0:1, 1:5, 1:2, 1:1, 2:1, 5:1, 1:0 are silanised. They are mixed manually with Bis-GMA, TEGDMA and others	An improvement in fracture toughness is recorded in the specimens. The increase reached a constant plateau when the whiskers:silica ratio reached 1:0. It is deduced that this phenomenon is due to the agglomeration of whiskers. This can lead to a need for the prevention of the entanglement of the nanoparticles.
Protopapa et al 2011 [92]	3 - point bending test (single-edge notched method)	PMMA reinforced with nanodiamonds specimens with concentrations of 0.10, 0.38, 0.50, 0.83% wt are tested.	An improvement in fracture toughness is recorded in the modified specimens. The highest results are shown in the 0.1 %wt group. Therefore, a lower nanodiamonds concentration leads to higher mechanical properties of PMMA-composites.
Alhotan et al 2021 [93]	3 - point bending test (single-edge notched method)	PMMA reinforced with TiO_2 and ZrO_2 nanoparticles, and E-glass-fibres specimens with concentrations of 1.5, 3, 5, 7 wt % are tested. The sizes of the specimens were 40 x 8 x 4 mm	An improvement in fracture toughness is recorded in the modified specimens.

Abbreviations: wt% - weight percentage

✓ *Biological characteristics.* Nanocomposites affect oral microenvironment homeostasis and must exhibit biocompatibility, measured *via* cytotoxicity tests. Higher residual monomer correlates with increased cytotoxicity [54, 95]. Maintaining healthy gingiva and marginal integrity is critical for periodontal health and treatment success [96, 97]. Balos *et al.* observed decreased cell viability at higher nanoparticle concentrations, indicating potential inflammation risks [64]. Conversely, modifications with antibacterial agents (e.g., silver nanoparticles) can enhance antimicrobial effects while maintaining low cytotoxicity [69]. Zhang *et al.* demonstrated that silanized nano-hydroxyapatite improves PMMA biocompatibility and osteointegration stimulation [98, 99]. De Castro *et al*. reported ion release proportional to $AgVO_3$ concentration, suggesting controlled filler levels reduce cytotoxicity [100]. Surface protein adsorption modulates cellular response; nano-hydroxyapatite doping improves surface texture and adhesion, favoring periodontal health [99, 101]. Nanocomposites also display antimicrobial activity against cariogenic bacteria (*S. mutans, L. acidophilus*), though simultaneous cytotoxicity evaluation remains essential [102]. Hydrophobic glass nanofillers reduce water sorption, influencing aesthetics and material longevity [103].

✓ *Digital technologies.* Additive manufacturing (3D printing) and subtractive CAD/CAM technologies enable rapid, precise fabrication of provisional restorations [2]. Some 3D-printed resins (e.g., Saremco print - CROWNTEC, Temp PRINT) exhibit superior mechanical properties over conventional analog materials, though variations exist [104]. Nanoparticle reinforcement, such as

ZrO_2 doping, improves microhardness and flexural modulus but may alter aesthetics [105–107]. Mechanical performance depends on base resin and filler characteristics [108, 109]. Production methods affect mechanical properties; digital light processing (DLP) and stereolithography (SLA) yield improved flexural strength compared to conventional or subtractive methods [110, 111]. Build orientation influences strength and elastic modulus, with 0° preferred for flexural strength and 90° for elasticity [111]. Food-simulating solutions impact 3D-printed resin properties, necessitating further study [112]. Compared to milled CAD/CAM restorations, 3D-printed materials often show superior wear resistance and surface smoothness, though findings are inconclusive overall [113–116]. Milled restorations typically offer better marginal fit, essential to periodontal health, which can be optimized by adjusting layer thickness in 3D printing [117–120].

CONCLUSIONS

Based on the comprehensive review and analysis of the current scientific literature, several essential conclusions can be drawn regarding the role of PMMA-based and other nanocomposites in contemporary dentistry, particularly in the fabrication of preliminary restorations.

Firstly, PMMA-based nanocomposites are fundamental to modern dental materials science. Their widespread application in prosthodontics, especially in temporary restorations, is attributed to their favorable handling properties, aesthetics, and cost-effectiveness. However, pure PMMA presents notable limitations, including poor mechanical performance, high polymerization shrinkage, and suboptimal biological compatibility. The incorporation of nanoparticles addresses many of these shortcomings, providing a viable pathway for performance enhancement.

Secondly, nanoengineering has emerged as a transformative approach in the development of dental materials. The addition of various nanofillers—such as TiO_2, ZrO_2, silver, hydroxyapatite, and glass can significantly improve mechanical properties like flexural strength, hardness, and fracture toughness. Furthermore, biological behaviors such as cytocompatibility and antibacterial activity can be tailored by modifying the filler composition and surface characteristics. Nevertheless, the optimization of filler concentration and surface treatment (e.g., silanization) is critical to avoid issues like agglomeration and increased cytotoxicity.

Thirdly, the exploration of nanotechnology's full potential in dentistry is still ongoing. While promising results have been observed *in vitro*, there remains a need for more *in vivo* and clinical studies to validate the long-term effectiveness and safety of these materials. Digital manufacturing technologies, including CAD/CAM and 3D printing, further expand the application of nanocomposites by improving production accuracy, reducing clinical chair time, and enhancing patient outcomes.

In conclusion, PMMA-based nanocomposites represent a dynamic and evolving area of dental materials research. Their continued development, driven by advancements in nanoscience and digital fabrication, holds significant potential for improving the quality, durability, and biological performance of provisional restorations. As new discoveries emerge, these materials are likely to become even more integral to personalized, efficient, and patient-centered dental care.

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