ISSN 2706-6819 Vol.8, Issue 3: 21-28, DOI: 10.25236/IJFM.2026.080303

Research Progress on the Mechanical Properties and Antibacterial Activity of Denture Base Resins Modified with Nano-Silver-Loaded Titanium Dioxide

Ruyu Yang[1,a], Xin Li[2,b], Yuanzhu Long[2,c], Jun Li[3,d], Chengxue Yang[3,e,*]

[1]Nanming District People's Hospital, Guiyang, 550002, Guizhou, China
[2]School of Stomatology, Zunyi Medical University, Zunyi, 563000, Guizhou, China
[3]Hospital of Stomatology, Zunyi Medical University, Zunyi, 563000, Guizhou, China
[a]1731850728@qq.com, [b]zxcvbnm13595786881@163.com, [c]135682383@qq.com,
[d]lijun5573@zmu.edu.cn, [e]chengxueyang1017@163.com
** Corresponding author*

Abstract: *The denture base constitutes a fundamental component of removable partial denture prostheses. Polymethyl methacrylate (PMMA) remains the predominant material for this application owing to its cost-effectiveness, favorable biocompatibility, and ease of processing. Nevertheless, PMMA-based denture bases exhibit inherent shortcomings, including susceptibility to aging, mechanical fracture, and bacterial adhesion, which predispose patients to secondary caries, periodontal pathologies, and denture stomatitis. Accumulating evidence indicates that the incorporation of nano-silver-loaded titanium dioxide (Ag-TiO_2) can substantially enhance both the mechanical integrity and antimicrobial efficacy of PMMA. However, the practical utility of Ag-TiO_2 in PMMA modification is considerably constrained by its pronounced tendency toward agglomeration, attributable to its large specific surface area and high polarity. To circumvent this obstacle, investigators have explored various preparative strategies to mitigate nanoparticle aggregation. The present review systematically synthesizes the current literature concerning the agglomeration issue of nano-Ag-TiO_2 and its impact on augmenting the mechanical strength and antibacterial performance of denture base resins.*

Keywords: *Nano-silver-loaded titanium dioxide, Modification, Denture base resin*

1. Introduction

Against the backdrop of an aging global demographic, partial and complete edentulism persist as one of the most frequently encountered oral disorders. Removable partial dentures continue to serve as one of the principal therapeutic alternatives for tooth defects and tooth loss [1]. Polymethyl methacrylate (PMMA) has gained widespread acceptance as the preferred denture base resin, primarily attributed to its reparability, excellent biocompatibility, and low manufacturing cost [1]. Nonetheless, a notable drawback of PMMA resides in its inherent microporous architecture. An elevated porosity level fosters high internal stress concentrations, predisposing the material to deformation and warpage [2], thereby adversely affecting its mechanical performance. Concurrently, this porous surface topography facilitates the colonization of oral microorganisms [3], encompassing both bacterial and fungal adhesion, which subsequently promotes biofilm and dental plaque formation [4], and potentiates substance retention and calculus deposition, culminating in discoloration and aesthetic compromise [5]. Conventional cleansing modalities prove inadequate in preventing short-term microbial biofilm recolonization [6]. Consequently, there exists a compelling impetus to identify a material capable of concurrently reinforcing PMMA's antibacterial capacity and mechanical resilience.

Concurrent with advances in materials science, nanomaterials have garnered attention within the purview of prosthodontics. Nanoparticulate agents, particularly silver ions (Ag^+) and titanium dioxide (TiO_2), have been validated to suppress surface biofilm formation [7-8]. Zhao et al. (original Chinese reference [10]) documented that the addition of nano-Ag-TiO_2 to denture base resins markedly potentiated antibacterial activity and diminished the incidence of denture stomatitis. Gad et al. [9] observed that incorporating 0.5%–3% nano-Ag-TiO_2 into PMMA led to increments in both flexural strength and flexural modulus. Furthermore, multi-criteria decision-making (MCDM) analyses have corroborated that nano-TiO_2 confers favorable improvements in PMMA properties [10].

ISSN 2706-6819 Vol.8, Issue 3: 21-28, DOI: 10.25236/IJFM.2026.080303

Nevertheless, nanomaterials are intrinsically prone to agglomeration owing to their diminished particle size, elevated specific surface area, and substantial surface polarity [11]. Optimal dispersion of nanoparticles within the PMMA matrix is a prerequisite for harnessing their beneficial effects. Inadequate dispersion culminating in agglomerates creates mechanical weak points and crack initiation sites, significantly degrading the composite's performance—not only nullifying the advantages of nanoscale incorporation but occasionally even diminishing mechanical parameters [12-13]. Hence, the modification of nanoparticles within PMMA remains a persistent research hotspot in this field (original Chinese reference [16]).

Of particular interest is the recent rapid evolution of three-dimensional (3D) printing technology, which has inaugurated novel avenues for the application of nano-modified denture base resins. Altarazi et al. [14] integrated silanized TiO_2 nanoparticles at varying concentrations (0.10, 0.25, 0.50, 0.75 wt%) into 3D-printed (stereolithography, SLA) denture base resin, and established that the 0.10 wt% addition level yielded the most favorable overall performance; furthermore, after artificial saliva aging, the nanocomposite retained superior properties relative to the unmodified counterpart. Abo Salh et al. [15] corroborated these findings, demonstrating that the addition of ZrO_2NPs, AgNPs, and TiO_2NPs to 3D-printed denture resin evoked marked reductions in bacterial counts compared to pristine resin, with antimicrobial efficacy escalating proportionally with nanoparticulate concentration. Collectively, these observations underscore that the convergence of nanomodification and digital manufacturing technologies holds substantial promise as a trajectory for future denture base material development.

2. Advances in the Modification of Nano-Silver-Loaded Titanium Dioxide Materials

To achieve favorable nanoparticle dispersion within PMMA, current methodologies are broadly classified into physical strategies (e.g., high-energy particle treatment, ultrasonication, mechanical dispersion) and chemical approaches (e.g., dispersant addition, esterification, coupling agents) (original Chinese reference [19]). Although physical methods enable nanoparticle dispersion, cessation of mechanical force permits re-agglomeration under van der Waals interactions. Furthermore, nanoparticle aggregation stems not exclusively from high surface polarity but also from the absence of stable chemical linkages with the PMMA matrix (original Chinese reference [20]). Silane coupling agents have emerged as pivotal mediators in reinforcing the interfacial bonding between nanoparticles and PMMA [9], and nanoparticles pretreated with such agents have been shown to enhance surface hardness, flexural strength, and impact resistance of PMMA [16]. Moreover, concurrent utilization of appropriate concentrations of nanomaterials and silane coupling agents synergistically promotes interfacial adhesion and augments surface hardness [17].

Recent investigations have further refined our mechanistic understanding and optimized protocols regarding the application of silane coupling agents. For instance, γ-methacryloxypropyltrimethoxysilane (γ-MPS) functions as a "molecular bridge" interconnecting organic and inorganic phases, forming covalent bonds on nanoparticle surfaces and effectively improving nanofiller distribution within the polymeric substrate [18].In one study, KH-570 silane coupling agent was employed to modify Ag-TiO_2, and 3% of the resultant modified particles were introduced into PMMA; the outcomes revealed substantially enhanced dispersion stability of the nanofiller (original Chinese reference [24]). Additionally, covalent linkage between silane-modified nanoparticles and PMMA facilitates robust interfacial integration [19]. Although no universal consensus currently exists regarding the optimal strategy for mitigating nanoparticle agglomeration (original Chinese reference [19]), the aggregate evidence intimates that silane coupling agent-mediated surface modification constitutes a viable and efficacious option.

3. Influence of Nano-Ag-TiO_2 on the Mechanical Properties of Modified Denture Base Resins

Nano-silver-loaded formulations, representing composites of silver ions with inorganic nanocarriers, not only exhibit broad-spectrum antibacterial characteristics [8] but also confer improvements in the mechanical attributes of PMMA, encompassing thermal conductivity and compressive strength [20]. Supplementation of PMMA with nano-Ag-TiO_2 enhances surface hardness, wear resistance, and flexural strength.

3.1 Surface Hardness

Augmented surface hardness is instrumental in prolonging the service life of denture bases, as it mitigates abrasive wear attributable to masticatory forces and routine function. Multiple investigations

ISSN 2706-6819 Vol.8, Issue 3: 21-28, DOI: 10.25236/IJFM.2026.080303

have affirmed that the introduction of nano-Ag-TiO_2 into PMMA elevates its overall mechanical profile [16]. Lung et al. [21] assessed both unmodified and functionalized nanoparticles in dental resin matrices, discerning that modified nanofillers particularly improved surface hardness. Xia et al. [22] ascribed this hardening effect to two determinants: optimal filler (nanoparticle) loading and the employment of silane coupling agents. This is rationalized by the coupling agent simultaneously reinforcing interfacial adhesion and fostering improved nanoparticle dispersion; conversely, excessive filler content exacerbates agglomeration within the matrix. Notably, the inclusion of 3% nano-Ag-TiO_2 was demonstrated to augment surface hardness by 35%, representing the optimal threshold [23].

In a more recent systematic evaluation, Erhim et al. [24] investigated the surface hardness and impact strength of self-cured denture base resins fortified with Ag-TiO_2 and Ag-ZrO_2 nanoparticles. Their results indicated that all nanoparticle-modified cohorts manifested significantly elevated surface hardness relative to controls, with the 0.3% Ag-0.3% TiO_2 group achieving the maximal values for both parameters. Furthermore, the mechanical outcomes exhibited a conspicuous concentration-dependent pattern—0.3% addition yielded optimal results across most metrics, whereas further increments in nanofiller loading elicited performance decrements [24].

3.2 Flexural and Tensile Strengths

When performing intraoral functions, denture resin bases must effectively resist deformation forces generated by mastication; consequently, flexural and tensile strengths constitute critical parameters for clinical performance. Evidence suggests that nano-Ag-TiO_2 incorporation augments the hardness, flexural strength, fracture toughness, and thermal conductivity of PMMA [25]. Gad et al. [9] reported that 0.5% – 3% nano-Ag-TiO_2 addition proportionally increased both flexural strength and modulus. In a separate dosage-response assessment, nano-TiO_2 was incorporated at 1%, 3%, and 5% ratios; flexural strength improved at 1%, remained unaltered at 3%, but declined at 5% [26]. This deterioration at higher percentages is presumably attributable to intensified nanoparticle agglomeration, engendering stress concentrators. Tensile testing has further revealed that nano-TiO_2-reinforced PMMA displays up to a 35% increment in tensile strength relative to neat PMMA [27-28]. This enhancement likely stems from load transfer to the rigid nanoparticles. Thus, uniform nanoparticle distribution is of paramount importance in upgrading the mechanical behavior of denture base resins.

The concentration-dependent influence on flexural strength has also been validated in 3D-printed denture base resins, wherein TiO_2 nanoparticles at 0.5, 1.0, and 1.5 wt% concentrations all improved flexural strength, yet the 2 wt% formulation exhibited reduced strength compared to the 1.5 wt% group [29]. Another investigation of Ag: TiO_2 and Ag: ZrO_2 nanoparticles in self-cured denture resins identified the maximal flexural strength in the 0.3 wt% Ag-0.15 wt% TiO_2-15 wt% ZrO_2 cohort, whereas the 0.3 wt% Ag-0.5 wt% TiO_2 group displayed the minimal value [30]. These findings collectively substantiate the existence of an "optimal window" for nanoparticle loading, beyond which agglomeration effects precipitate mechanical compromise.

3.3 Color Stability and Thermal Stability

Color stability is of paramount importance for all dental materials, as clinical chromatic alterations diminish patient acceptance. Color stability denotes the capacity of a material to preserve its intrinsic hue despite environmental challenges. Discoloration of dental polymers may arise from the interplay of intrinsic and extrinsic variables; therefore, nanomaterials should ideally reinforce mechanical properties without prejudicing esthetics. Since the human eye exhibits differential sensitivity, color shifts are objectively quantified via spectrophotometric light absorption measurements. Aziz [31] evaluated chromatic changes after 3% TiO_2 incorporation and observed increased opacity relative to neat PMMA, likely attributable to heightened light absorption by the nano-Ag-TiO_2 compared to the polymer matrix. Given that nano-Ag-TiO_2 manifests a white appearance, it is essential to establish an appropriate percentage of TiO_2 that confers superior mechanical performance, antibacterial action, and acceptable esthetic outcomes, especially for anterior aesthetic zones. Prior reports have indicated that nano-TiO_2 addition not only restrains resin degradation but also elevates the thermal stability of the composite [10], plausibly due to reduced interchain distances, diminished interactions, and stabilized bond formation between nanoparticles and polymer chains.

Recent evidence has furnished more nuanced insights into color stability. AlGhamdi et al. [32] scrutinized the influence of varying TiO_2 nanoparticle concentrations on the color stability and surface characteristics of 3D-printed denture base resins. Following thermocycling, the nanocomposite resins

ISSN 2706-6819 Vol.8, Issue 3: 21-28, DOI: 10.25236/IJFM.2026.080303

exhibited increased color change and surface roughness without significant hardness alterations. Notably, the chromatic response to TiO_2 addition diverged across resin substrates: NextDent resin with 1 wt% and 2 wt% TiO_2 displayed unacceptable color deviations (NBS values of 8.84 and 8.28, respectively), whereas ASIGA resin maintained clinically acceptable color parameters [32]. This disparity underscores that the choice of resin matrix exerts a substantial influence on color stability, advocating for material-specific considerations in clinical implementation.

4. Antibacterial Properties of Nanomaterial-Modified Denture Base Resins

The propensity for biofilm formation on denture base resin surfaces is exacerbated by robust microbial adhesion to biomaterials and the permeation of microorganisms into superficial micropores [33-34]. Conventional cleansing regimens, including mechanical brushing, are frequently inadequate in eliminating these biofilms, which pose long-term periodontal risks, particularly in geriatric populations [35]. Nano-inorganic antimicrobial agents have attracted considerable interest owing to their broad-spectrum activity and superior biosafety profiles. In this context, nano-Ag-TiO_2 has demonstrated pronounced inhibitory effects, effectively preventing biofilm establishment [36].

4.1 Antibacterial Mechanism of Nano-Ag-TiO_2

Beyond the inherent antibacterial properties of silver ions, TiO_2 concomitantly generates electron/hole pairs, yielding reactive oxygen species (ROS) [37]. The photocatalytic reaction of silver ions additionally alleviates the ultraviolet irradiation limitation of TiO_2, thereby enhancing the overall photocatalytic activity of the composite while facilitating sustained silver release and prolonging bactericidal efficacy [38].

4.2 Antibacterial Activity of Nano-Ag-TiO_2-Modified Denture Base Resins

Zhao et al. [39] demonstrated that nanocomposites incorporating nano-Ag-TiO_2 exerted evident inhibitory activity against Staphylococcus aureus. A dose-dependent investigation using 0.4%, 1%, and 3% nano-Ag-TiO_2 in PMMA revealed progressively augmented suppression of Candida growth with increasing nanofiller content [36]. Furthermore, 48-hour Candida albicans colonization rates were reduced by 22% and 26% with 1% and 3% nano-Ag-TiO_2 supplementation, respectively [16]. Ren et al. (original Chinese reference [48]) reported escalating antibacterial efficacy against Streptococcus mutans when nano-Ag-TiO_2 was introduced at concentrations of 1.25, 2.5, 5.0, and 10.0 g/L. Conventional antimicrobial agents are notably inferior to nano-silver particles, which operate via two distinct mechanisms: disruption of cell membrane permeability and respiration, and generation of hydrogen peroxide culminating in bacterial cell death [40]. Consequently, it is reasonable to postulate that modified nano-Ag-TiO_2 manifests superior antibacterial efficacy relative to its unmodified counterpart.

Pertaining to 3D-printed resins, Abo Salh et al. [15] furnished key data demonstrating that ZrO_2NPs, AgNPs, and TiO_2NPs at 0.5%, 1%, and 1.5% concentrations exhibited significant antimicrobial activity against Streptococcus pyogenes, S. aureus, and C. albicans, with effectiveness intensifying proportionally with concentration. In parallel, an evaluation of silver-doped TiO_2 nanoparticle-infused PMMA denture base resins substantiated effective antibacterial and antifungal action against cariogenic bacteria and C. albicans [41]. The dual antibacterial repertoire of nano-Ag-TiO_2—encompassing contact-mediated disruption of cell membranes/enzymatic systems and photocatalytic ROS generation—confers a distinct advantage over single-mechanism conventional antimicrobials.

5. Cytotoxicity of Nanomaterial-Modified Denture Base Resins

5.1 Cytotoxicity of Nanoparticles

Nanoparticle size constitutes a critical physicochemical determinant of cytotoxic potential. Smaller nanomaterials exhibit heightened cell membrane permeability and increased interaction with organelles such as mitochondria, lysosomes, and nuclei, culminating in cellular injury; however, larger agglomerates do not necessarily equate to diminished toxicity [42-43]. Nanoparticle toxicity is fundamentally linked to ROS overproduction and consequent oxidative stress. ROS species—comprising hydrogen peroxide, hydroxyl radicals, singlet oxygen, hypochlorous acid, and superoxide anions—serve as pivotal triggers of oxidative imbalance. Under physiological conditions, ROS generation and

ISSN 2706-6819 Vol.8, Issue 3: 21-28, DOI: 10.25236/IJFM.2026.080303

elimination remain equilibrated, and ROS participate in vital regulatory roles in cell proliferation, differentiation, and apoptosis. Nevertheless, disruption of redox equilibrium, evoked by elevated ROS generation or compromised antioxidant defenses, induces macromolecular oxidation (proteins, lipids, nucleic acids), thereby instigating DNA impairment, aberrant signal transduction, cytotoxicity, and cell death [44]. Nanoparticle-induced oxidative stress is categorized into direct and indirect forms. Direct oxidative stress arises from the expansive nanoparticle surface area, which furnishes abundant reactive sites, amplifying chemical reactivity and ROS production; surfaces reacting with oxidants and free radicals additionally accelerate ROS formation. Indirect oxidative stress involves mitochondrial participation—mitochondria are essential organelles in this cascade. Nano-metal particles, such as nano-silver, release Ag^+ that depolarizes mitochondrial membranes, disrupts electron transfer chains, and impairs the mitochondrial electron transport chain (METC), consequently elevating intracellular ROS and magnifying oxidative disequilibrium (termed ROS-induced ROS release), ultimately provoking mitochondrial dysfunction [45].

Of particular relevance, the agglomeration state of nanoparticles exerts a marked influence on cytotoxic outcomes. Murugadoss et al. [46] established that TiO_2 nanoparticle agglomeration potentiates in vitro and in vivo toxic responses, intimating that dispersion status is not only instrumental to mechanical integrity but also constitutes a pivotal determinant of biosafety. Hence, surface modification strategies that ameliorate nanoparticle dispersion may concurrently improve mechanical/antibacterial performance and attenuate potential cytotoxic hazards.

5.2 Cytotoxicity of Nano-Ag-TiO_2-Modified Denture Base Resins

Chen et al. [40] documented that denture base resins incorporating 3% nano-TiO_2 attained antibacterial efficacy without eliciting cytotoxicity within an appropriate dosage range. Although nano-Ag-TiO_2 manifests mild cytotoxic effects, experimental outcomes remain compliant with the International Standard ISO 10993-5:2009 for biological evaluation of medical devices [47]. Surface chemical functionalization, through covalent conjugation of anionic, non-ionic, zwitterionic, and cationic groups, has been reported to mitigate the toxicity of nano-Ag-TiO_2 [48-49].

With respect to the protracted safety of silver nanoparticles, a systematic review has cautioned that their long-term deployment in dental restorative materials may confer potential neurotoxic risks to the central nervous system [50]. This observation underscores that, despite acceptable short-term cytotoxicity profiles, the chronic repercussions of sustained silver ion release on human health necessitate further longitudinal and systematic investigation.

6. Conclusions and Future Perspectives

In summary, nano-Ag-TiO_2 possesses considerable potential to augment the antibacterial and mechanical performance of denture base resins, contingent upon the attainment of favorable and uniform nanoparticle dispersion. Although no universal consensus has been reached regarding the optimal approach to counteract nanoparticle agglomeration, silane coupling agent modification has consistently proven to be a feasible and effective strategy.

Looking forward, future research on nano-Ag-TiO_2-modified denture base resins should concentrate on the following domains: (1) further optimization of nanoparticle surface functionalization protocols to achieve more homogeneous dispersion and robust interfacial bonding; (2) systematic investigation of the implications of nanoparticle incorporation on curing kinetics, interlayer adhesion, and long-term service performance of 3D-printed resins, as the confluence of digital manufacturing and nanomodification offers novel prospects for customized denture fabrication; (3) development of material-specific nanomodification regimens, recognizing the differential responses of various resin matrices to nanoparticle loading; and (4) comprehensive examination of silver ion release kinetics and the protracted impact of nano-Ag-TiO_2 on the oral microecology, an area currently lacking exhaustive data. Addressing these unresolved questions will furnish a more robust theoretical and empirical foundation for the clinical translation of nanomaterial-reinforced denture base resins.

Acknowledgements

This work was supported by the Science and Technology Program Fund of Guizhou Province (Grant No. ZK[2022]636) and the Natural Science Foundation of Guizhou Province (Grant No. QKHJC-

ISSN 2706-6819 Vol.8, Issue 3: 21-28, DOI: 10.25236/IJFM.2026.080303

ZK[2023]YB536).

References

[1] Wolfaardt JF, Cleaton-Jones P, Fatti P. The occurrence of porosity in a heat-cured poly (methyl methacrylate) denture base resin[J]. J Prosthet Dent, 1986, 55(3): 393-400.
[2] Kattadiyil MT, Jekki R, Goodacre CJ, et al. Comparison of treatment outcomes in digital and conventional complete removable dental prosthesis fabrications in a predoctoral setting[J]. J Prosthet Dent, 2015, 114(6): 818-825.
[3] Takahashi N, Iwasa F, Inoue Y, et al. Evaluation of the durability and antiadhesive action of 2-methacryloyloxyethyl phosphorylcholine grafting on an acrylic resin denture base material[J]. J Prosthet Dent, 2014, 112(2): 194-203.
[4] Yannikakis S, Zissis A, Polyzois G, et al. Evaluation of porosity in microwave-processed acrylic resin using a photographic method[J]. J Prosthet Dent, 2002, 87(6): 613-619.
[5] Faot F, Cavalcanti YW, Mendonça e Bertolini M, et al. Efficacy of citric acid denture cleanser on the Candida albicans biofilm formed on poly(methyl methacrylate): effects on residual biofilm and recolonization process[J]. BMC Oral Health, 2014, 14: 77.
[6] Pokrowiecki R, Wojnarowicz J, Zareba T, et al. Nanoparticles and human saliva: a step towards drug delivery systems for dental and craniofacial biomaterials[J]. Int J Nanomedicine, 2019, 14: 9235-9257.
[7] Makvandi P, Gu JT, Zare EN, et al. Polymeric and inorganic nanoscopical antimicrobial fillers in dentistry[J]. Acta Biomater, 2020, 101: 69-101.
[8] Wang Y, Zhang X, Bai Y, et al. Anticancer and antibacterial activities of silver nanoparticles (AgNPs) synthesized from Cucumis melo L[J]. J Nanosci Nanotechnol, 2020, 20(7): 4143-4151.
[9] Gad MM, Fouda SM, Al-Harbi FA, et al. PMMA denture base material enhancement: a review of fiber, filler, and nanofiller addition[J]. Int J Nanomedicine, 2017, 12: 3801-3812.
[10] Gad MM, Abualsaud R. Behavior of PMMA denture base materials containing titanium dioxide nanoparticles: a literature review[J]. Int J Biomater, 2019, 2019: 6190610.
[11] Zhu X, Guo A, Yan Z, et al. PET/Ag NW/PMMA transparent electromagnetic interference shielding films with high stability and flexibility[J]. Nanoscale, 2021, 13(17): 8067-8076.
[12] Gad MM, Abualsaud R, Rahoma A, et al. Effect of zirconium oxide nanoparticles addition on the optical and tensile properties of polymethyl methacrylate denture base material[J]. Int J Nanomedicine, 2018, 13: 283-292.
[13] Ai M, Du Z, Zhu S, et al. Composite resin reinforced with silver nanoparticles-laden hydroxyapatite nanowires for dental application[J]. Dent Mater, 2017, 33(1): 12-22.
[14] Altarazi A, Haider J, Alhotan A, et al. 3D printed denture base material: the effect of incorporating TiO_2 nanoparticles and artificial ageing on the physical and mechanical properties[J]. Dent Mater, 2023, 39(12): 1122-1136.
[15] Abo Salh IBE, Add El-Salam EB, Ezzat AA, et al. Antimicrobial effect of three different nanoparticles-modified 3D-printed denture resin: an in vitro study[J]. J Int Soc Prev Community Dent, 2025, 15(1): 42-49.
[16] Cascione M, De Matteis V, Pellegrino P, et al. Improvement of PMMA dental matrix performance by addition of titanium dioxide nanoparticles and clay nanotubes[J]. Nanomaterials (Basel), 2021, 11(8): 2027.
[17] Cheng Y, Sakai T, Moroi R, et al. Self-cleaning ability of a photocatalyst-containing denture base material[J]. Dent Mater J, 2008, 27(2): 179-186.
[18] Mohamed SH. Reinforced filler in denture base materials[M]//Ardelean LC, Rusu LC, eds. Advances in Dentures: Prosthetic Solutions, Materials and Technologies. London: IntechOpen, 2024.
[19] Syahida A, Widodo TT, Hadianto E. Ikatan polimer PMMA dengan titanium dioksida[J]. MEDALI Jurnal: Media Dental Intelektual, 2024, 6(2): 103-112.
[20] Kul E, Aladağ Lİ, Yesildal R. Evaluation of thermal conductivity and flexural strength properties of poly(methyl methacrylate) denture base material reinforced with different fillers[J]. J Prosthet Dent, 2016, 116(5): 803-810.
[21] Lung CY, Sarfraz Z, Habib A, et al. Effect of silanization of hydroxyapatite fillers on physical and mechanical properties of a bis-GMA based resin composite[J]. J Mech Behav Biomed Mater, 2016, 54: 283-294.
[22] Xia Y, Zhang F, Xie H, et al. Nanoparticle-reinforced resin-based dental composites[J]. J Dent, 2008, 36(6): 450-455.
[23] Totu EE, Nechifor AC, Nechifor G, et al. Poly(methyl methacrylate) with TiO_2 nanoparticles inclusion for stereolitographic complete denture manufacturing - the future in dental care for elderly edentulous patients?[J]. J Dent, 2017, 59: 68-77.

ISSN 2706-6819 Vol.8, Issue 3: 21-28, DOI: 10.25236/IJFM.2026.080303

[24] Erhim EA, Abbood MA, Halbos HT. Assessment of surface hardness and impact strength of denture base resins reinforced with silver-titanium dioxide and silver-zirconium dioxide nanoparticles: in vitro study[J]. Open Engineering, 2024, 14(1).
[25] Asar NV, Albayrak H, Korkmaz T, et al. Influence of various metal oxides on mechanical and physical properties of heat-cured polymethyl methacrylate denture base resins[J]. J Adv Prosthodont, 2013, 5(3): 241-247.
[26] Karci M, Demir N, Yazman S. Evaluation of flexural strength of different denture base materials reinforced with different nanoparticles[J]. J Prosthodont, 2019, 28(5): 572-579.
[27] Shirkavand S, Moslehifard E. Effect of TiO_2 nanoparticles on tensile strength of dental acrylic resins[J]. J Dent Res Dent Clin Dent Prospects, 2014, 8(4): 197-203.
[28] Cierech M, Wojnarowicz J, Kolenda A, et al. Zinc oxide nanoparticles cytotoxicity and release from newly formed PMMA-ZnO nanocomposites designed for denture bases[J]. Nanomaterials (Basel), 2019, 9(9): 1318.
[29] Yoon SW, Cho YE. A study of the antifungal properties and flexural strength of 3D printed denture base resin containing titanium dioxide nanoparticles[J]. J Korean Acad Prosthodont, 2024, 62(2): 95-103.
[30] Erhim EA, Abbood MA, Halbos HT. Assessing the impact of Ag: TiO_2 and Ag: ZrO_2 nanoparticles on the flexural strength of self-cured denture base resin[J]. J Phys Conf Ser, 2024, 2857(1): 012056.
[31] Aziz HK. TiO_2-nanofillers effects on some properties of highly-impact resin using different processing techniques[J]. Open Dent J, 2018, 12: 202-212.
[32] AlGhamdi MA, Fouda SM, Al-Dulaijan YA, et al. Nanocomposite 3D printed resins containing titanium dioxide (TiO_2) nanoparticles: an in vitro analysis of color, hardness, and surface roughness properties[J]. Front Dent Med, 2025, 6: 1581461.
[33] Chladek G, Basa K, Mertas A, et al. Effect of storage in distilled water for three months on the antimicrobial properties of poly(methyl methacrylate) denture base material doped with inorganic filler[J]. Materials (Basel), 2016, 9(5): 328.
[34] Song R, Zhong Z, Lin L. Evaluation of chitosan quaternary ammonium salt-modified resin denture base material[J]. Int J Biol Macromol, 2016, 85: 102-110.
[35] Dalwai S, Rodrigues SJ, Baliga S, et al. Comparative evaluation of antifungal action of tea tree oil, chlorhexidine gluconate and fluconazole on heat polymerized acrylic denture base resin - an in vitro study[J]. Gerodontology, 2016, 33(3): 402-409.
[36] Anehosur GV, Kulkarni R, Naik MG, et al. Synthesis and determination of antimicrobial activity of visible light activated TiO_2 nanoparticles with polymethyl methacrylate denture base resin against Staphylococcus aureus[J]. J Gerontol Geriat Res, 2012, 1: 103-111.
[37] Dědková K, Lang J, Matějová K, et al. Nanostructured composite material graphite/TiO_2 and its antibacterial activity under visible light irradiation[J]. J Photochem Photobiol B, 2015, 149: 265-271.
[38] Goei R, Lim TT. Ag-decorated TiO_2 photocatalytic membrane with hierarchical architecture: photocatalytic and anti-bacterial activities[J]. Water Res, 2014, 59: 207-218.
[39] Zhao L, Wang H, Huo K, et al. Antibacterial nano-structured titania coating incorporated with silver nanoparticles[J]. Biomaterials, 2011, 32(24): 5706-5716.
[40] Chen R, Han Z, Huang Z, et al. Antibacterial activity, cytotoxicity and mechanical behavior of nano-enhanced denture base resin with different kinds of inorganic antibacterial agents[J]. Dent Mater J, 2017, 36(6): 693-699.
[41] Savitha PN, Dayalan M, Choudhary VT. Evaluation of antimicrobial properties of conventional poly methyl methacrylate denture base resin materials containing silver doped titanium dioxide nanoparticles against cariogenic bacteria and Candida albicans[J]. IP Ann Prosthodont Restor Dent, 2023, 9(4):206-213.
[42] Saifi MA, Khan W, Godugu C. Cytotoxicity of nanomaterials: using nanotoxicology to address the safety concerns of nanoparticles[J]. Pharm Nanotechnol, 2018, 6(1): 3-16.
[43] Wang J, Wang J, Liu Y, et al. Aging-independent and size-dependent genotoxic response induced by titanium dioxide nanoparticles in mammalian cells[J]. J Environ Sci (China), 2019, 85: 94-106.
[44] Angelé-Martínez C, Ameer FS, Raval YS, et al. Polyphenol effects on CuO-nanoparticle-mediated DNA damage, reactive oxygen species generation, and fibroblast cell death[J]. Toxicol In Vitro, 2022, 78: 105252.
[45] Zhang N, Xiong G, Liu Z. Toxicity of metal-based nanoparticles: challenges in the nano era[J]. Front Bioeng Biotechnol, 2022, 10: 1001572.
[46] Murugadoss S, Brassinne F, Sebaihi N, et al. Agglomeration of titanium dioxide nanoparticles increases toxicological responses in vitro and in vivo[J]. Part Fibre Toxicol, 2020, 17(1): 10.
[47] Prucek R, Tuček J, Kilianová M, et al. The targeted antibacterial and antifungal properties of magnetic nanocomposite of iron oxide and silver nanoparticles[J]. Biomaterials, 2011, 32(21): 4704-

ISSN 2706-6819 Vol.8, Issue 3: 21-28, DOI: 10.25236/IJFM.2026.080303

4713.
[48] Amin ML, Joo JY, Yi DK, et al. Surface modification and local orientations of surface molecules in nanotherapeutics[J]. J Control Release, 2015, 207: 131-142.
[49] Han Z, Sarkar S, Smith AM. Zwitterion and oligo(ethylene glycol) synergy minimizes nonspecific binding of compact quantum dots[J]. ACS Nano, 2020, 14(3): 3227-3241.
[50] Wang K, Wang S, Yin J, Yang Q, Yu Y, Chen L. Long-term application of silver nanoparticles in dental restoration materials: potential toxic injury to the CNS[J]. J Mater Sci Mater Med,2023,34(11): 52.