OPEN ACCESS
Global Journal of Research in Dental Sciences
ISSN: 2583-2840 (Online)
Volume 05 | Issue 05 | Sept. – Oct. | 2025
Journal homepage: https://gjrpublication.com/gjrds/
Review Article

Titanium dioxide (TiO_2)-Modified Poly (methyl methacrylate) for Stereolithographic Complete Dentures - A Review

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DOI: 10.5281/zenodo.17380945 **Submission Date:** 02 Sept. 2025 | **Published Date:** 17 Oct. 2025

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Abstract
Poly (methyl methacrylate) (PMMA) continues to be the most frequently used denture base material owing to its low cost, ease of fabrication, and acceptable esthetics. However, its application is restricted by inherent shortcomings such as limited mechanical strength, polymerization shrinkage, and susceptibility to microbial growth, which often compromise its long-term performance. To overcome these challenges, reinforcement with titanium dioxide (TiO_2) nanoparticles has gained significant attention. Owing to their unique physical and biological properties, TiO_2 enhances the flexural, tensile, and impact strength of PMMA while also imparting antibacterial and antifungal effects. At appropriate concentrations, these benefits can be achieved without affecting the material's optical qualities or biocompatibility. With the increasing use of digital workflows, particularly computer-aided design and stereolithographic (SLA) manufacturing, the need for denture base materials with improved stability and fracture resistance has become more pronounced. TiO_2-modified PMMA addresses these requirements by offering enhanced reliability and durability in digitally fabricated prostheses. This review consolidates the available evidence on the mechanical, antimicrobial, and biological advantages of TiO_2-reinforced PMMA and highlights future directions, including hybrid nanocomposites and clinical validation, to support its wider application in prosthodontic practice.

Keywords: *Titaniumdioxide (TiO_2), Polymethyl methacrylate (PMMA), Stereolithography (SLA), Nanocomposites, Antibacterial and Antifungal activity, Denture base material.*

INTRODUCTION
Polymethyl methacrylate known as (PMMA) is the go to choice for denture base since over a century. The overall adoption originates from favorable esthetics, chemical stability, ease of processing, and low budget [1]. Even though its years of clinical successes, it still suffers from various drawbacks which hinders the long-term performance. Like low flexural and impact strength, fracturability, polymerization shrink, porosity, water absorption, and strong microbial colonization attraction [2,3]. In elderly individuals, these deficiencies might lead to recurrent prosthesis fracture, infection like denture stomatitis, and lowers the quality of life. The experiments are focused on overcoming the limitations which have usually included reinforcement of the resin matrix. The old methods used glass or polyethylene fibers, metal inserts, or high-impact monomers. New age methods like nanotechnology have opened avenues toward improvement in mechanical, antimicrobial, and esthetic properties of PMMA [4]. Titanium dioxide (TiO_2), being

distinctive physio-chemical and biological characteristics stands as one of the best options among the various nanoparticles investigated for reinforcement [5-7].

Hence TiO_2 is present in many crystalline phases from which the most prominent are Rutile and Anatase. While also on the nanosize scale it is seen to have higher, surface energy and photocatalytic activity. While possing the antibacterial activities [8]. If we add TiO_2 into PMMA, the nanoparticles enhance strength of the polymer matrix which adds on to antimicrobial and antifungal properties needed for denture base materials [5,6,9]. Poles apart to some metallic filler.s the TiO_2 is biocompatible with being chemically inert under physiological conditions. Finally leaves the optical translucency of the material virtually unchanged [10]. Zirconia (ZrO_2), Silica (SiO_2), and Alumina (Al_2O_3) and likes of these nanoparticles have been added to PMMA to carry out studies. All of these have been seemed to increase some property but TiO_2 has many advantages. Wear resistance and surface smoothness have been improved by nano particles like Zirconia and Silica. In other hand its clearly evident that TiO_2 has much better antimicrobial activity [1,11]. The previous reinforcement studies have found that alumina improves in flexural strength and thermal diffusivity [12]. These studies brokethrough to the systematic imbibement of TiO_2 nanoparticles which merges reinforcement and biological activity. When TiO_2 is added to PMMA its Flexural strength, fracture toughness and microhardness, i.e found out by Virto studies [6,7].

An example to not is, when 2.5–5 wt% TiO_2 nanotube modified the denture bases which showed a great resistance to fracture than its counterparts' resins [6]. The Tensile and impact strength, viscoelastic stability [5], lower dimension changes on processing [2]. Thin and sophisticated geometries are resulted in stereolithographic production in reinforced PMMA backed by other reports [13]. On the other hand, unreinforced PMMA can be fragile to fracture the mechanical improvements which are highly valued as critical is the antimicrobial property of TiO_2 modified PMMA [14,15]. Wearers of dentures are vurnable to microbial infection caused by Candidas albicans, where it highlights the implications of a case of denture stomatitis. TiO_2-nanoparticles where photocatalytic antibacterial with antifungal activity destroy microbial membranes and produce reactive oxygen species under UV or visible light [9,16]. When TiO_2 infused in PMMA matrices have prevented cariogenic bacteria [17] and also inhibited growth of Candida [9], and from biofilm deposition [16]. The latest methods where TiO_2 integrated into hydroxyapatite shows increased antifungal activities with photodynamic support [9].

TiO_2 is promising when it comes to biocompatibility. Low in cytotoxicity and promotes tissue cell viability on being incorporated into PMMA, vitro studies confirm these [9,18]. The clinical problem such as color stability is retained with TiO_2 reinforcing at proper levels while translucency is reduced by excess of the filler [19]. The newest techniques such as Nano ceramic coatings and TiO_2 content make the esthetic stability even more improved [19]. The shift in paradigm to computer dentistry particularly towards CAD, CAM and SLA prosthesis preparation of dentures the alteration of the material becomes vital. Workflows supported by the computer attains excellent accuracy and minimal adjustments with quick fabrication. However, the resins instilled will exhibit some strength along with stability and good resolution.

When TiO_2 is added to SLA-compatible PMMA, the resins are found to achieve good outcomes. These add mechanical improvements as well as microbial resistance [14, 20]. From here on, it binds itself to future prosthodontics by infusing mechanical strength, biological coverage, and compatibility with newest manufacturing. This review assesses the literature on TiO_2 modified PMMA for denture bases but has more in accordance with stereolithographic complete dentures, and it addresses Mechanical and thermochemical properties. It examines mechanical and thermomechanical characteristics as well as esthetic stability, antimicrobial activity, antifungal activity, biocompatibility, and finally, digital fabrication processes, hence making general conclusions and determining future research avenues.

METHODS OF LITERATURE SEARCH

This paper is a narrative review that was built from the references provided to it, that is, articles published between the years 2008 and 2025. The references comprised original studies of in vitro experimental design, systematic reviews, narrative reviews, and application-based investigations of TiO_2-modified PMMA and composites thereof.

Search topics were:

- Mechanical and thermomechanical properties of TiO_2-modified PMMA.
- Antimicrobial and antifungal efficacy against oral pathogens.
- Biocompatibility and esthetic results.
- Application of TiO_2-modified PMMA in CAD/CAM and stereolithography techniques.Only studies explicitly listed in the curated bibliography were included.

MECHANICAL AND THERMOMECHANICAL PROPERTY

Such reinforcements resulted in relatively uniform improvements in the mechanical properties of PMMA base denture formulations. Injection molding has been shown to cause linear and volumetric changes in PMMA resins upon processing, thereby influencing their dimensional accuracies [2]. TiO_2 modification would maintain such instabilities at a minimum level, hence improved expenditure for fit in denture fabrication. Many studies have demonstrated that the addition of 2.5-5 wt% TiO_2 nanotubes will improve the flexural strength, fracture toughness, and microhardness substantially [6]. A number of authors have documented improved flexural strength from the addition of TiO_2 nanoparticles, with optimal improvement being achieved at intermediate levels [7]. Similarly, the same gains in tensile strength and impact strength have also been observed using TiO_2, thereby improving fracture resistance under force gripping [13]. A viscoelastic study gave clues that, with an increase in TiO_2, modulus and creep resistances increase against [5]. These results relate to SLA dentures, which have thin cross-sections and hence require resistance against stress concentrations. While the reinforced TiO_2 improves the short-term handling and long-term service of the prosthesis (Table 1).

Table 1. Mechanical and thermomechanical performance of modified PMMA- TiO_2

Reference	Modification	Property Improved	Outcome
[2] El Bahra, S., Ludwig, K.	Injection-molded PMMA	Dimensional stability	Reduced linear/volumetric changes
[6] Abdulrazzaq Naji	2.5–5 wt% TiO_2 nanotubes	Flexural strength, toughness, hardness	Significant increases across properties
[7] Nazirkar,G., Bhanushali, S	Anatase TiO_2 NPs	Flexural strength	Optimal improvement at ~3 wt%
[13] Ghahremani, L., Shirkavand, S	TiO_2-modified PMMA	Tensile/impact strength	Enhanced resistance to fracture
[5] Alrahlah, A., Fouad, H	TiO_2 nanoparticles	Viscoelastic properties	Improved modulus and creep stability

ANTIMICROBIAL AND ANTIFUNGAL ACTIVITY

Microbial colonization is the absoulte cauation of denture realted infections which includes denture stomatitis. Therefore, TiO_2 incorporation renders PMMA with antibacterial and antifungal properties. One study demonstrated the ability of TiO_2-modified PMMA to inhibit the growth of oral bacterial strains, thus reducing biofilm formation (Figure 1) [3]. Conversely, a different study with SiO_2 and TiO_2 nanoparticles revealed strong antimicrobial effects against cariogenic bacteria [17]. More recently, photodynamic-assisted antifungal action of TiO_2-hydroxyapatite nanocomposites modified PMMA against Candida albicans was reported [9]. In another study, antibacterial action together with improvement in mechanical properties was reported for the TiO_2-modified PMMA (Table 2) [5]. Such information validates that TiO_2 can decrease colonization without adversely affecting the aesthetics of dentures. TiO_2 nanoparticles generate reactive oxygen species in presence of visible or UV light, and these reactive oxygen species attack microbial cell membranes. This added feature of photoactivation may be especially useful against fungi that occur in large numbers or in cases of recurrent denture stomatitis.

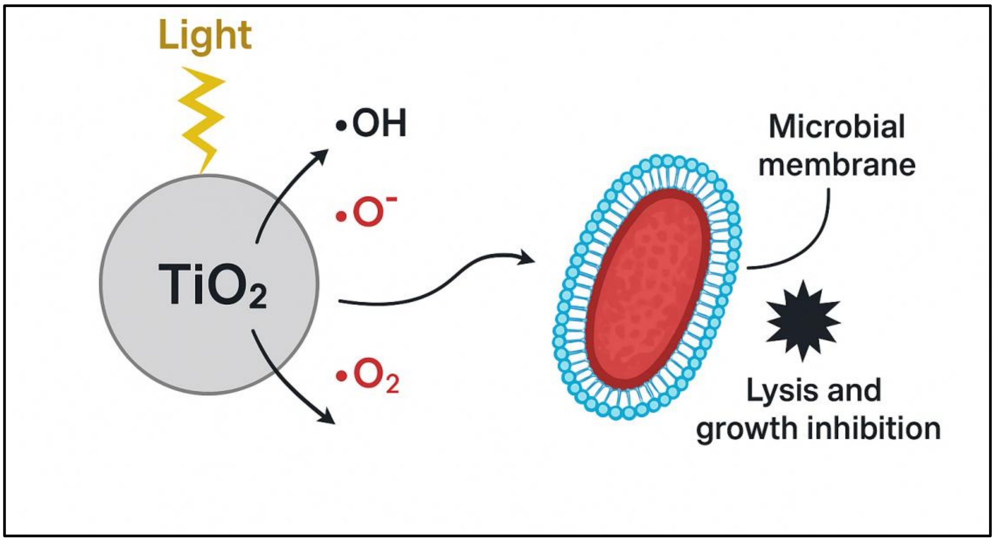

Figure 1. Photocatalytic antimicrobial mechanism of TiO2 under Light Activation

Table 2. Antimicrobial and antifungal performance of TiO_2-modified PMMA

Reference	Pathogen Targeted	Method	Outcome
[3] Zore, A., Abram, A., Učaka	Oral bacteria	In vitro	Demonstrated antibacterial activity
[17] Rao S, Nandish BT, Ginjupalli K	Cariogenic bacteria	In vitro	Strong antimicrobial effect with SiO_2/TiO_2
[9] Liu, Y., Wang, Z., Liu	Candida albicans	In vitro + photodynamic	Significant antifungal effect
[5] Alrahlah, A., Fouad, H	Oral bacteria	Mechanical + antibacterial	Dual property improvement

BIOCOMPATABILITY AND ESTHETIC STABILITY

The primary clinical requirements for denture base materials will be aesthetics, safety, microbial resistance, and strength. The TiO_2 modified PMMA possess a bearable level of cytotoxicity with no effect on cell viability backed by the biocompatibility studies [9,18]. So, it is safe to be used for intraoral applications. However, this is evident that it is not enough because the esthetic performance is equally important. The addition of TiO_2 at apt fille levels it does not hinder the color or the translucency and stability. Only when the filler is excessive it can cause variations to the esthetics. The nano ceramic coatings and TiO_2-based modifications leads developments in color stability and stain resistance. which is a good advantage for long term use of prosthesis [19]. Whereas the addition of TiO_2 effectively leads to result in the denture bases that are durable and aesthetically appealing.

STEREOLITHOGRAPHY AND CAD/CAM APPLICATION

The prosthodontics processes aided by computer have sped up the useage of CAM/CAD and stereolithography (SLA) processes for denture construction.These process needs the materials which are good in precision with minimal polymerization shrinkage and long-term performance reliability which is obvious with the TiO_2-modified PMMA. Many experiments and findings have shown that the addition of the TiO_2 with the advantages as mentioned above for typical of SLA manufacturing [14]. Attributes of being antibacterial and mechanical while being consistent is what is required for digital denture manufacturing. Further to this the TiO_2 and PEEK modified SLA resins have also been shown to exhibit the same [20],Rigorus reviews have shown the restorative 3D printing materials shedding light on the importance of further optimization of nanocomposite based SLA resins [15]. However, the fact is that TiO_2 remains a reliable additive by balancing between conventional PMMA and the latest digital materials.

BROADER PERSPECTIVES AND REVIEWS

Many reviews show us a broader picture with regards to modifying PMMA. The enhancement of Mechanical, Biological and surface properties, applying the nanofillers like TiO_2, ZrO_2, and SiO_2 has been elucidated by a review of material science [1]. Similarly, such a review shows us the versatility of PMMA being a prosthodontic material and flexible to the requirement for nanomodification [4]. Likewise, a systematic review of PMMA denture base advancements by the addition of nanoparticles reverifies the improvements [10,17,18].

FUTURE DIRECTIONS

There should be a focus on Hybrid nanocomposites such as TiO_2 hydroxyapatite blends. Which are known to offer good mechanical reinforcement and Photodynamic antimicrobial actions [9]. The balance of strength, translucency and cytocompatibility should be reached by optimizing the concentrations. Clinical investigations which compare the SLA Fabricated TiO_2 modified dentures with controls are needed to check within the in vitro findings. such studies shall facilitate the integration with CAD workflows and long-term microbial resistance studies thereby elucidating the clinical potential.

CONCLUSION

TiO_2-modified PMMA is a pioneering structure modification of denture bases. Introduction of TiO_2 nanoparticles always enhances flexural, tensile, and impact strength, impart a robust antimicrobial, and antifungal protection. In contrast, biocompatibility and esthetic stability are clinically feasible, particularly at optimized levels. More significantly, TiO_2 is digitally fabricable, particularly stereolithographic dentures that are mechanically robust, stable, and biologically shielded.

ACKOWNLODGEMENT

Nil.

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CITATION

Babu, A. T., Kalyan, A. V., & Nandini, V. V. (2025). Titanium dioxide (TiO_2)-Modified Poly (methyl methacrylate) for Stereolithographic Complete Dentures - A Review. In Global Journal of Research in Dental Sciences (Vol. 5, Number 5, pp. 57–62). https://doi.org/10.5281/zenodo.17380945