



Enhancement of PMMA denture base material through incorporation of nano Bi_2O_3 : A comprehensive analysis of mechanical, thermals properties at varying concentrations (0% - 5%)

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Received 11/1/2026, Received in revised form 16/3/2026, Accepted 30/3/2026, Published 15/4/2026

It has been investigated that the incorporation of Nano-sized bismuth oxide (Bi_2O_3) to polymethyl methacrylate (PMMA) denture bases can be used to improve the mechanical, thermal and antimicrobial properties of dental prostheses. This research paper examines the influence of the doping of PMMA with 0%, 1%, 2%, 3%, 4% and 5% Nano Bi_2O_3 on the physical, mechanical and biological properties of denture materials. These findings suggest that the addition of Nano Bi_2O_3 has a strong effect on the flexural strength, thermal stability, and antimicrobial activity of PMMA dentures with the highest performance achieved at certain doping levels. The study offers useful information into the development regarding advanced denture materials with improved durability and functionality.

Keywords: Poly (methyl methacrylate) dentures; Mechanical; Bismuth oxide nanoparticles.

1. INTRODUCTION

A popular thermoplastic polymer is polymethyl methacrylate (PMMA), which is highly optical transparent. Ease of processing, chemical stability and low density [1-4]. These properties have seen PMMA a material of interest in the application as a matrix material, such as optical components, and protective barrier. The inherently low atomic number (Z) regarding its constituent elements limits the efficiency regarding pure PMMA in applications where increased interaction is needed. To address this shortcoming, addition of high-Z fillers to the PMMA matrix has been considered as one method of enhancing the mechanical performance and radiation attenuation efficiencies. Polymethyl methacrylate (PMMA) has found a lot of applications in dentistry in the fabrication of the denture bases because of

its biocompatibility, ease of processing and affordability [5-9] Bismuth trioxide (Bi_2O_3) is a high-density oxide of large atomic number ($Z=83$) which has shown promise as a reinforcing filler in polymer composites to be used in gamma and X-Ray shielding [10-12]. This is because addition of even small fraction of Bi_2O_3 in PMMA increases effective atomic number and mass attenuation coefficient of composites, which increases attenuation capability of ionizing radiation by composites over neat PMMA. Besides, when dispersed in the polymer matrix, Bi_2O_3 Nanoparticles may also be a source of mechanical reinforcement, i.e., they provide hardness and stiffness. In composite material with Bi_2O_3 loadings in the range of (1-5 wt.) % improvements in hardness, density, and radiation shielding performance have been observed relative to pure PMMA, these enhancements arise primarily from the high electron density and mass of Bi_2O_3 particles, which increase the probability of photon interactions such as photoelectric absorption and Compton scattering within the composite. As result, PMMA / Bi_2O_3 composites with low filler concentrations are promising candidates for lightweight, non-toxic shielding materials in medical and industrial radiation protection. This study aims to evaluate the effect of doping PMMA with 0%, 1%, 2%, 3%, 4%, and 5% Nano Bi_2O_3 on the mechanical, thermal, and antimicrobial properties of denture bases, providing a foundation for the development of improved dental materials. Mahmood et al show that Tensile strength of PMMA/ Bi_2O_3 increase from 5.45 Mpa (pure PMMA) to 14.85Mpa at highest doping, and Shore D hardness increase from 71.6 to 89 with filler content [13]. Cao, Ge, Bourham and Moneghan Suggests that higher Bi_2O_3 Loading increases hardness significantly, Slight reduction in elongation at break at high filler content (due to reduced polymer chain mobility [14]. Yasser et al find that mechanical property trends of Nano composites with Bi_2O_3 component showing increasing compressive strength with increasing Bi_2O_3 filler, and Young modulus improved due to Nanoparticle stiffening, proper dispersion significantly enhanced mechanical stability [15]. Katea et al says that hardness increased progressively with Bi_2O_3 concentration, Moderate filler Loading improved compressive strength and excess filler caused slight brittleness due to agglomeration [16]. Diez-pascual AM. Show how various Nanoparticles (zirconia, silica, HA) affect mechanical, thermal and biological properties of PMMA for dental application [17]. Montazerian M et al, give a comprehensive review of radiopaque ceramics, discusses bismuth oxide in biomaterial for dentistry/orthopedics, which understanding the role of high-Z radio pacifiers like Bi_2O_3 in polymer-based dental composites [18]. The main aim of research on PMMA/ Bi_2O_3 composite is to enhance the performance of PMMA by incorporation Bi_2O_3 Nano particles to make this composite material suitable for biomedical (developing a biocompatible Lightweight, and non-toxic shielding material for dental prosthetics), and mechanical application.

2. MATERIALS AND METHODS

2.1. Materials

- PMMA resin (heat-cured).
- Nano bismuth oxide (Bi_2O_3) particles (size range: 50-100 nm).
- Distilled water and ethanol for cleaning.
- Standard molds for denture fabrication.

2.2. Sample preparation

PMMA is doped with 0%, 1%, 2%, 3%, 4%, and 5% Nano Bi_2O_3 (grain size 5 nm). by weight. The mixture Using clean beaker, PMMA fragments are gradually added to dichloride-methane fluid with a continuous shaking for around 90 minutes and poured into 5 mm formerly greased mold and left it for 2 days at room temperature.

2.3. Characterization

A. Surface Roughness: The Surface Roughness test is performed by profilometer devices, made by (Mahr Company), type (pocket Surf) made in USA, that supplied with surface analyzer. Each specimen is test 3 times on different position; the average value is taken.

B. Hardness :The samples are tested using (ASTM D2240) kind shore D, the penetration depth is measured on (0 to 100) scale [19].

C. Porosity is determined by Archimedes method. The mass of specimen is measured in air, when suspended in water and when dried [20].

$$\text{Apparent porosity} = \frac{S-D}{V} \times 100 \quad (1)$$

D. Thermal Properties: Thermal conductivity is measured using conductivity meter (Generic TDS Meter, model DCT430SD), manufactured by T Equipment, USA. E. Water Absorptivity: The Hydrophobicity of the sample recorded lower than 27 ° C by immersing the sample in demineralized water 5 minutes after which the specimen is measured in terms of digital balance based on the following equation [20-25].

$$\text{Water absorption \%} = \frac{s-D}{D} \times 100 \quad (2)$$

where S is saturated weight, D is the dry weight

F. Antimicrobial Activity: Agar diffusion tests are used to assess the antimicrobial activity of the test against the common oral pathogens (e.g., Candida albicans, Streptococcus mutants). Agar Diffusion (Zone of Inhibition) Test: Prepare an agar plate inoculated with the target microorganism (e.g., Staphylococcus aureus, Candida albicans, or Escherichia coli). Place the PMMA samples on the surface of the agar plate. Incubate the plates at the required temperature (usually 37°C) for 24-48 hours. Measure the zone of inhibition around the PMMA samples, which indicates the antimicrobial effectiveness. Larger zones indicate stronger antimicrobial properties.

3. RESULTS AND DISCUSSION

3.1. Structural properties

Pure PMMA has Broad hump between 15°–25° (2θ) Indicates amorphous nature, typical for polymers like PMMA. No sharp peaks, meaning there's no crystalline order present. PMMA + Bi₂O₃ (1–5%): Presence of sharp peaks (especially at ~30°, 38°, 45°): These are characteristic of crystalline Bi₂O₃ (monoclinic α-Bi₂O₃). As the Bi₂O₃ concentration increases, we can observe: Peak intensity increases indicates more crystalline material is present [26-30]. The amorphous background from PMMA remains, but Bi₂O₃ signals become more dominant as in Figure 1.

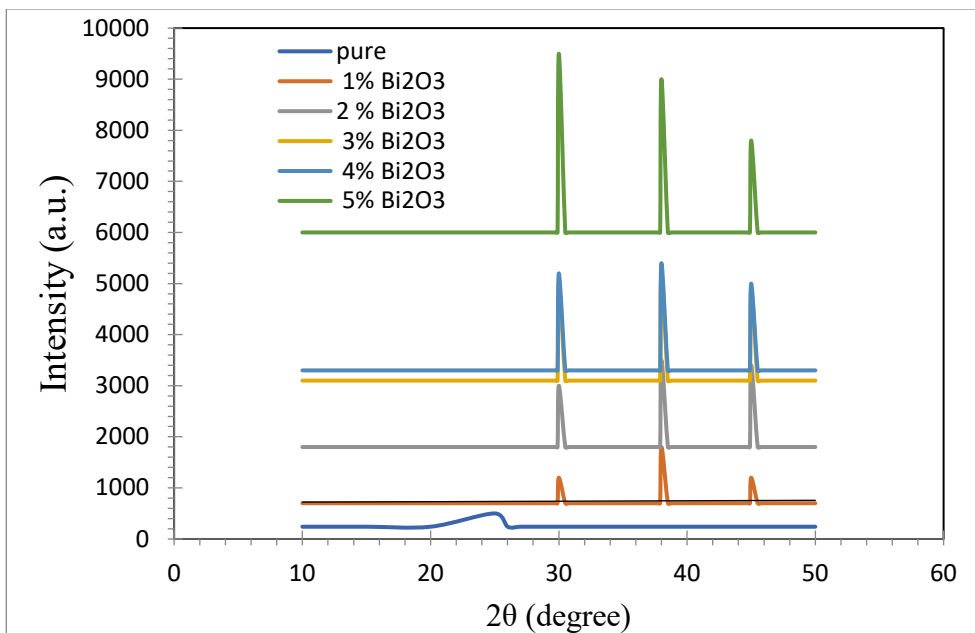


Figure 1 XRD of pure and reinforced PMMA the peaks are (121) at 30°, (002) at 38°, (041) at 45°.

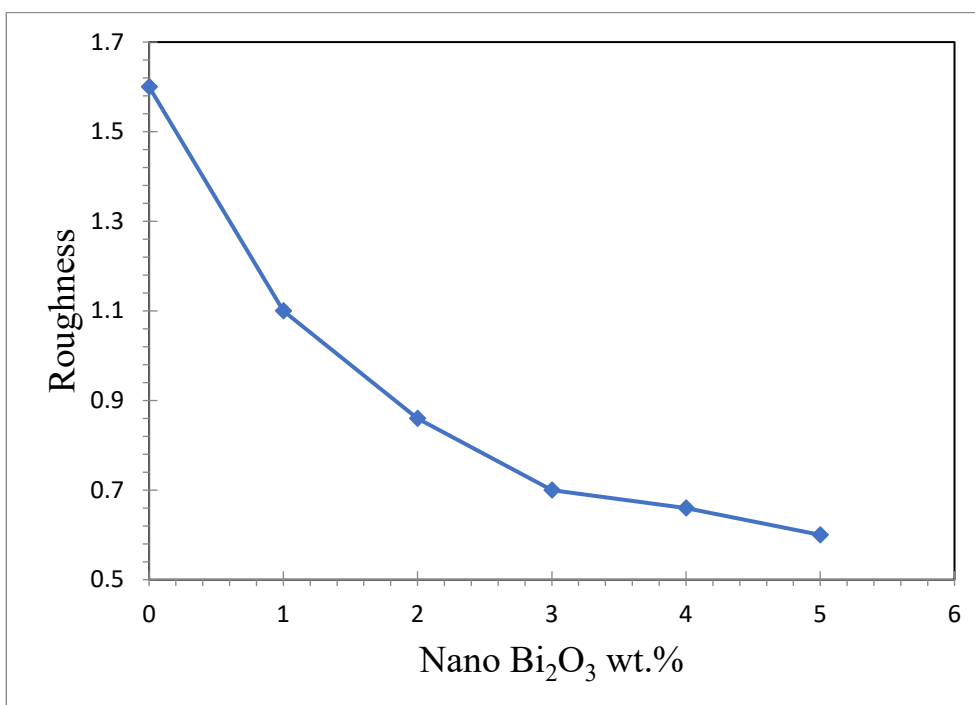
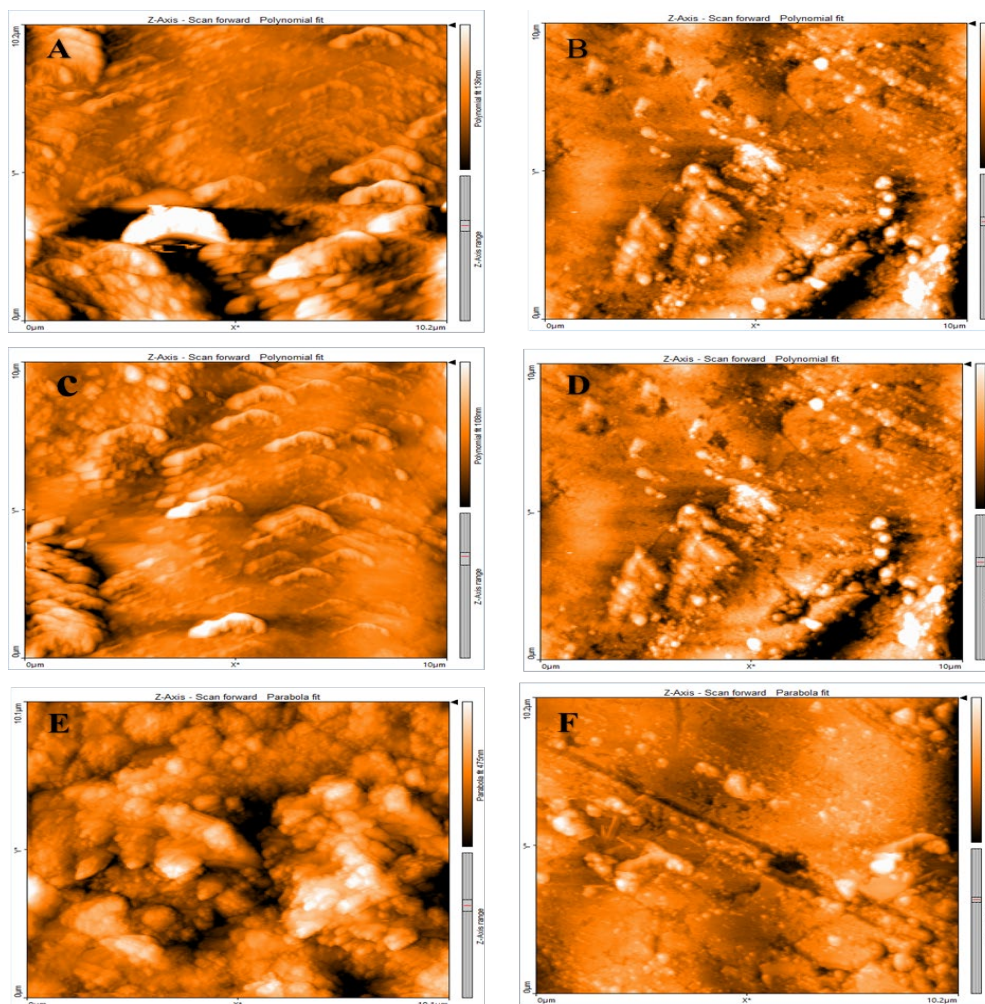


Figure 2 Surface roughness of pure PMMA and reinforced with Bi₂O₃.

Figure 2 The decrease in surface roughness of PMMA (polymethyl methacrylate) denture bases doped with varying concentrations (0–5 wt%) of Nano bismuth oxide (Bi₂O₃) can be attributed to several interrelated factors involving material interaction, particle dispersion, and polymer matrix behavior. Role of Nano Bi₂O₃ in Surface Smoothing. It is possible to fill the micro voids and irregularities in the PMMA matrix with Nano-fillers, such as Bi₂O₃, and create a smoother surface. At low concentrations

(1-3 wt%), the nanoparticles are generally well-dispersed, which assists in the process of enhancing the overall compactness and minimizes porosity, leading to reduced surface roughness. 0 wt% (Control): The pure PMMA base will have surface irregularities because of the process of polymerization shrinkage and remaining porosity. 13 wt%: The optimal dispersion of Bi₂O₃ nanoparticles in this range will tend to: Enhance the homogeneity of the polymer matrix. Enhance the density of packing in the process of polymerization. Reduce micro-defects on the surface. Beyond 3 wt% (4–5 wt%): There may be agglomeration of nanoparticles, which: Creates localized stress points. Leads to uneven filler distribution [31-35]. May increase surface roughness slightly or plateau the improvement due to particle clustering disrupting the matrix uniformity. Bi₂O₃ is a relatively hard filler, and its incorporation may improve abrasion resistance, which helps retain a smoother surface over time. Nanoparticles also potentially reduce water sorption and solubility, minimizing surface degradation and maintaining lower roughness values [36-40].

From Figure 3,2D) and Figure 4,3D, which represent the Atomic Force Microscopy (AFM) provides topographical data at the Nano scale, allowing precise measurement of surface roughness—an important parameter for the biocompatibility and mechanical behavior of dental materials. In the current study, PMMA denture base material is reinforced with increasing concentrations (0 to 5 wt%) of Nano Bi₂O₃. The AFM results revealed a progressive decrease in surface roughness with the addition of nanoparticles: At Pure PMMA (0% Bi₂O₃) showed relatively high surface roughness, attributable to the inherent polymeric surface irregularities [41-45]. At 5 wt% Bi₂O₃ led to a more pronounced decrease in roughness, indicating better nanoparticle dispersion and a more uniform surface topography. The decrease in roughness can be attributed to the nanoparticles filling micro-defects and voids in the PMMA matrix, effectively smoothing the surface as in Figure 3 and 4.



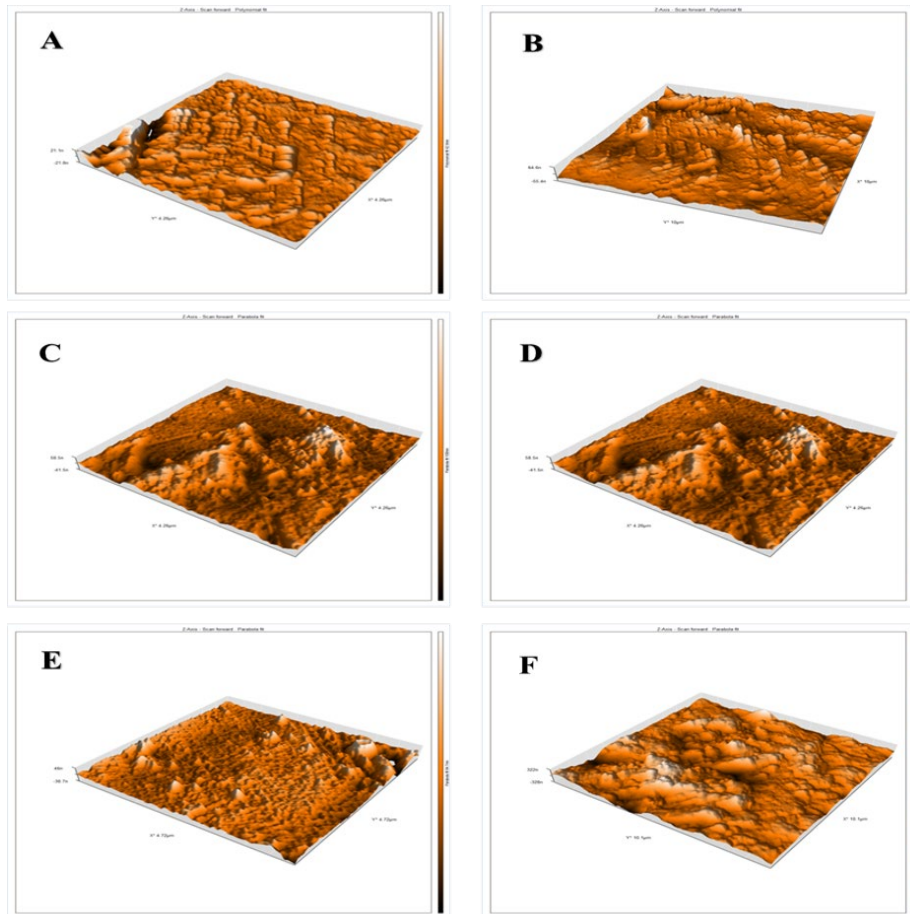


Figure 3 The 2D views for PMMA specimens reinforced with A 0%, B1%, C2%, D3%, E4%, F5% Bi₂O₃.

Figure 4 shows the 3D views for PMMA specimens reinforced with A 0%, B1%, C2%, D3%, E4%, F5% Bi₂O₃. Figure 5 Field Emission Scanning Electron Microscopy (FESEM) The FESEM image of unreinforced PMMA showed PMMA with 1–3 wt.% Bi₂O₃: As Nano Bi₂O₃ is incrementally added, the FESEM images displayed increasing surface irregularities and a rise in roughness [46-50]. At 1 wt.%, the particles are moderately dispersed, introducing slight textural variations [51-55]. At 2 and 3 wt.%, the surface roughness became more prominent due to agglomeration and clustering of nanoparticles, leading to more granular and uneven morphology [56-60]. Comparison with Higher Loadings (4–5 wt.% Bi₂O₃) Interestingly, samples reinforced with 4 and 5 wt.% of Bi₂O₃—though expected to have more particles—exhibited lower surface roughness in the FESEM analysis [61-65]. This is explained by improved particle packing and potential saturation effect where additional nanoparticles may start to fill surface voids and smooth surface peaks owing to the increased interaction between the matrix and filler or re-agglomeration into bigger and less-irregular clusters [66-70].

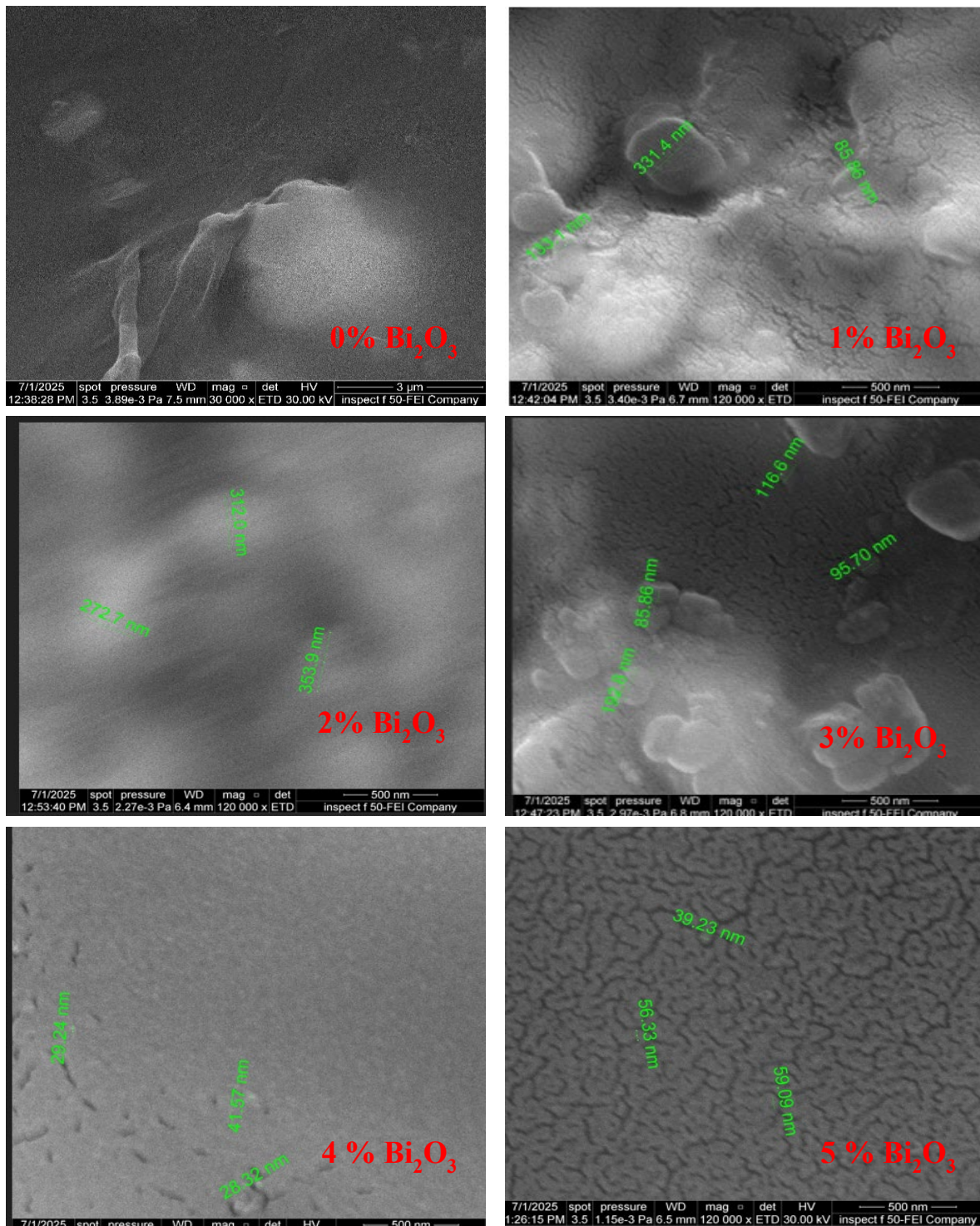


Figure 5 Field Emission Scanning Electron Microscopy (FESEM) of PMMA pure and reinforced with Bi₂O₃ Nano material

3.2. Mechanical properties

At lower concentrations (e.g. 1-2 wt.%), Nano Bi₂O₃ particles occupy the interstitial spaces between PMMA polymer chains. The result of this filler effect is: Reduced formation of voids as the nanoparticles occupy space which would otherwise form pores. Better matrix packing, resulting in a

denser material structure with fewer and smaller pores. Nano Bi_2O_3 may act as a heat conductor or initiate more uniform polymerization: More complete polymerization reduces the formation of microspores due to monomer evaporation or entrapment. Decreased residual monomer, which often leaves behind micro voids upon evaporation [71-75]. At higher loadings (3-5): Agglomeration of Nano Bi_2O_3 may occur, leading to non-uniform dispersion. Despite agglomeration, overall porosity still tends to decrease due to the dominant filler effect and the resulting reduction in the volume of PMMA matrix that could form pores [76-80]. The nanoparticles form a physical barrier, hindering the movement of gases or monomers during setting, further reducing the chances of pore formation Figure 6. Figure 7 hardness measures the material's resistance to indentation or scratching [81-83]. Bi_2O_3 is a dense and hard material, and its incorporation into PMMA significantly increases the hardness of the composite. As the concentration of Bi_2O_3 increases (1% to 5%), the hardness of the PMMA composite increases proportionally due to the higher filler content. The uniform distribution of Bi_2O_3 particles within the PMMA matrix contributes to improved surface resistance. Hardness continues to improve with increasing Bi_2O_3 content, but practical limits are often determined by other factors, such as workability and brittleness [84-86].

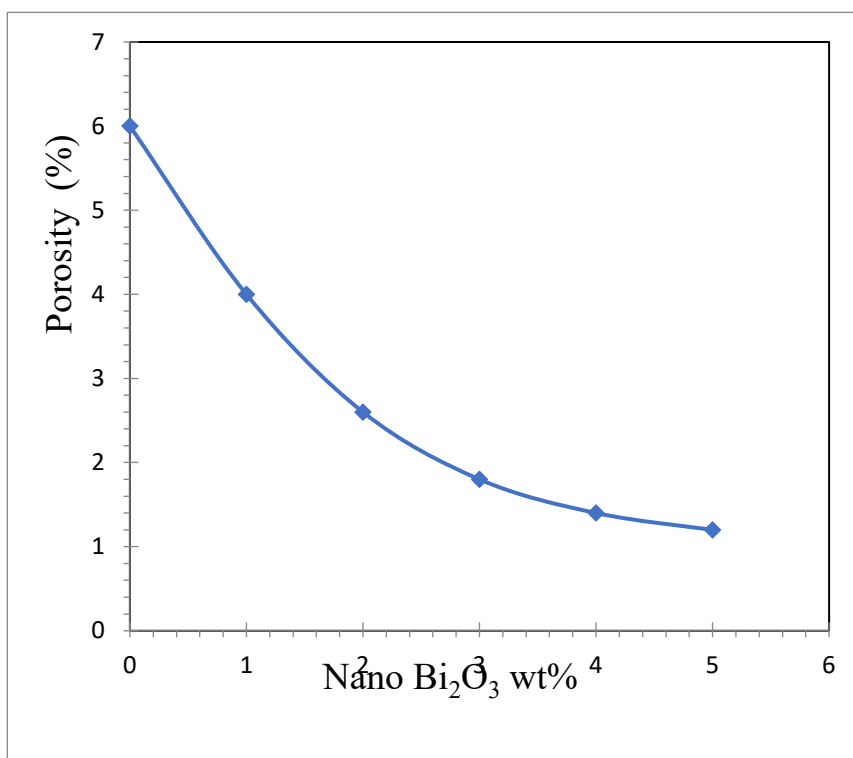


Figure 6 Porosity of pure PMMA and reinforced.

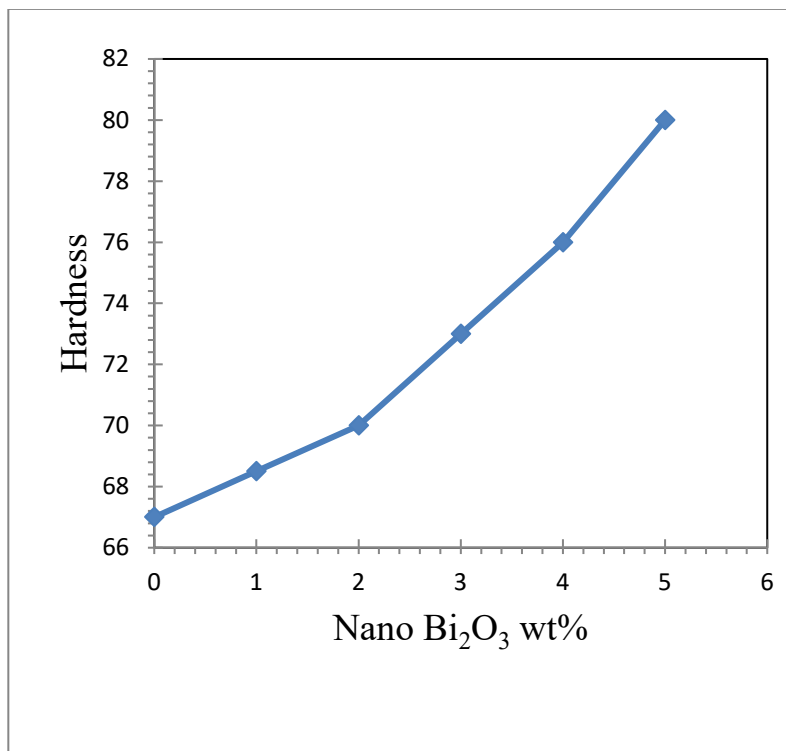


Figure 7 Shore D hardness of pure PMMA and reinforced with Bi₂O₃ content reinforced with Bi₂O₃ content.

3.3. Thermal properties

PMMA has relatively low thermal conductivity, typically around 0.17-0.19 W/m·K, which limits its use in applications requiring efficient heat dissipation. Bismuth oxide is a ceramic material with relatively high thermal conductivity compared to polymers. The thermal conductivity of Bi₂O₃ varies depending on its phase (e.g., α -Bi₂O₃, β -Bi₂O₃), but it is generally higher than that of PMMA. Figure 8 Increased Thermal Conductivity as Bi₂O₃ is added to PMMA. This is because Bi₂O₃ particles create conductive pathways within the polymer matrix, facilitating more efficient heat transfer. Filler Concentration The extent of the increase in thermal conductivity depends on the concentration of Bi₂O₃. At low doping levels (1-2)%, the increase may be modest, but as the concentration of Bi₂O₃ increases, the thermal conductivity of the composite can rise significantly. This is due to the formation of a percolation network, where the Bi₂O₃ particles are sufficiently close to each other to form continuous conductive paths [87-89].

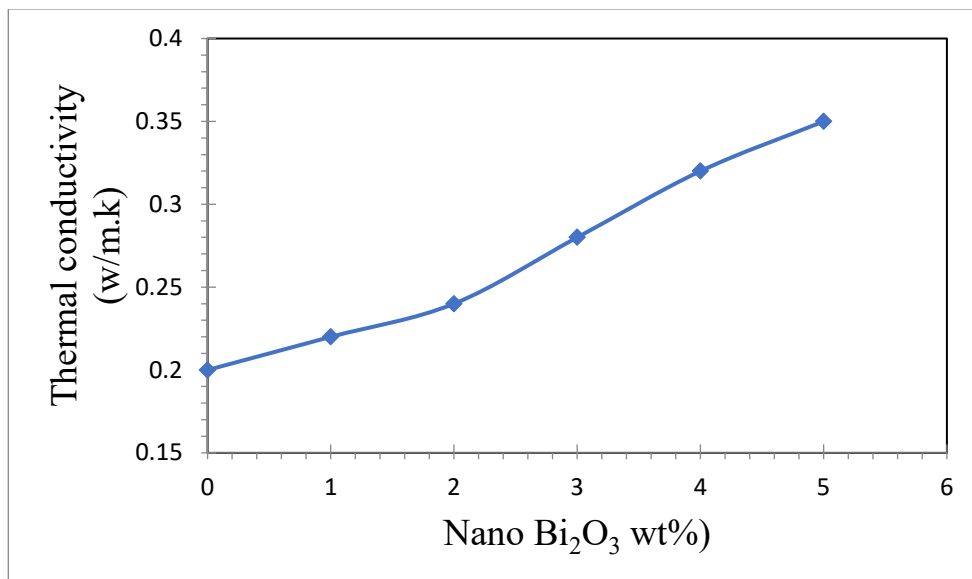


Figure 8 Thermal conductivity of pure PMMA and reinforced with Bi₂O₃ content.

Figure 9 The decrease in water absorption of PMMA as the doping of Bi₂O₃ (Bismuth (III) oxide increases can be explained by a number of factors such as Hydrophobic Nature of Bi₂O. Bi₂O₃ is a low-affinity inorganic metal oxide. When integrated into PMMA, it gives less hydrophobicity to the polymer, which makes it less prone to water uptake. Densification and Reduced Porosity Increasing Bi₂O₃ doping results in the formation of a denser PMMA matrix [90]. The filler particles fill the free volume in the polymer, minimizing the micro voids and water taking pathways. The barrier Effect Bi₂O₃ particles are physical barriers, which do not allow water molecules to diffuse into the polymer. The Bi₂O₃ decreases the movement of polymer chains of PMMA [91]. This reduces the amount of free volume available and therefore makes it difficult to penetrate and be retained within the polymer structure by water molecules [92]. Improved Crosslinking & Interactions If Bi₂O₃ interacts with the PMMA matrix through interfacial bonding, it can enhance the rigidity of the structure. This reduces the polymer's ability to swell and absorb water, even Bi₂O₃ particles act as physical barrier preventing water from diffusing into the polymer [93]. Figure 10 The chart represents the antimicrobial activity of PMMA doped with different weight percentages (wt%) of Nano Bi₂O₃, in terms of the inhibition zone diameter (in mm). Depending on the generated data, the following trends can be traced: PMMA doped with Nano Bi₂O₃ had a great antimicrobial activity, and the greatest inhibition zones are found at 4% and 5% doping contents. The release of Bi³⁺ ions is the source of antimicrobial effect because they cause cell membrane disruption in microbes [94]. The abrupt rise in antimicrobial activity is observed at between 0 and 3 wt% indicating that at lower concentrations of Nano Bi₂O₃, the inhibitory activity on bacteria is greater [95]. The trend continues onward at slightly lower rate beyond 3 wt% which could be due to a possible saturation or low efficiency at the very high doping levels [96]. The results indicate that the range of the 3-5 wt% doping can be effective as antimicrobial activity [97]. At some point, the antimicrobial effect might not be proportional to the increases in the Nano Bi₂O₃ content [98,99].

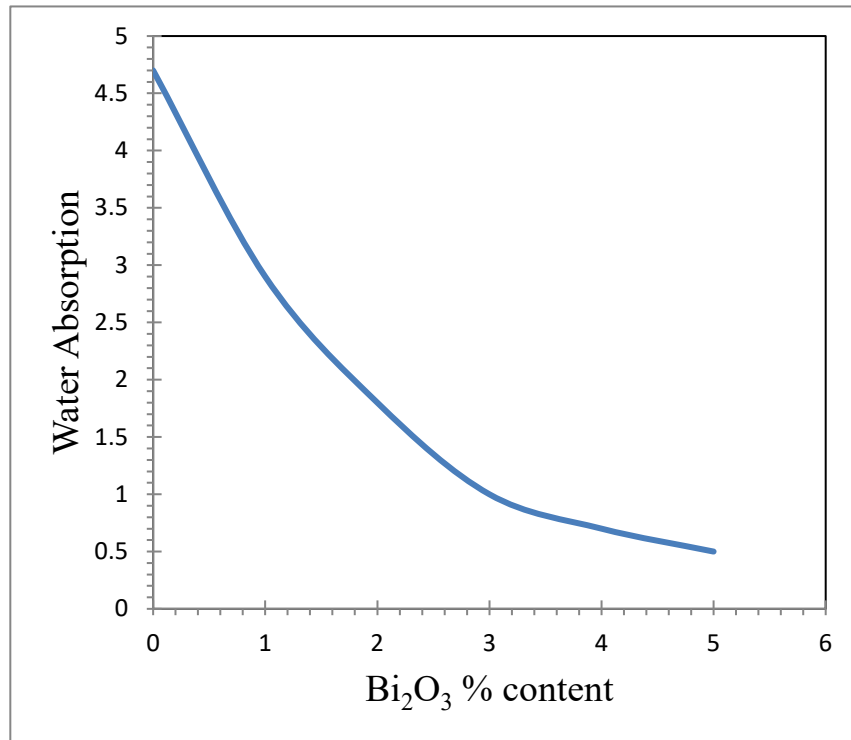


Figure 9 Water absorption of pure PMMA.

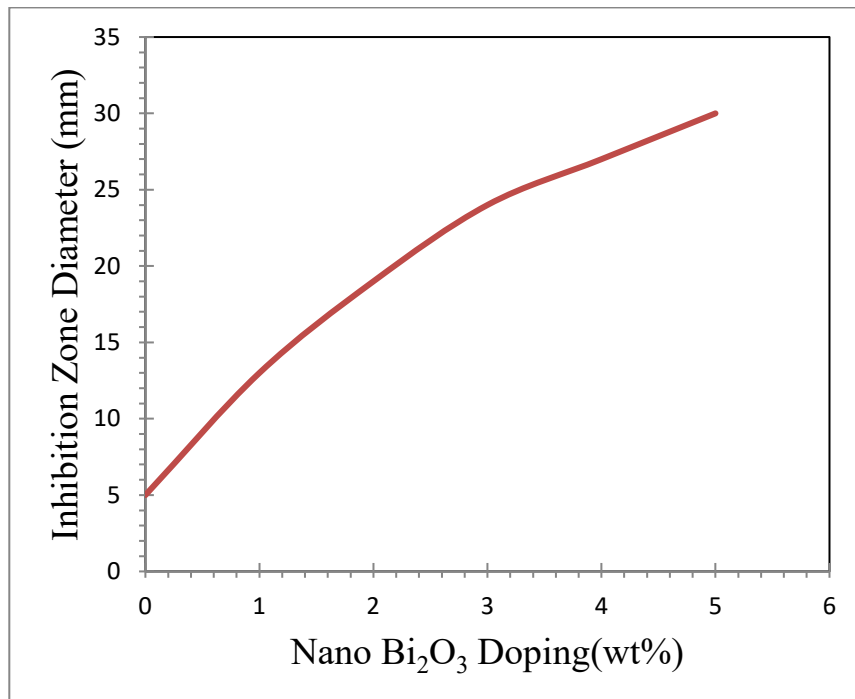


Figure 10 Antimicrobial activity of pure PMMA and reinforced with Bi_2O_3 content reinforced with Bi_2O_3 content.

4. CONCLUSION

The incorporation of Nano Bi₂O₃ to PMMA denture bases has a great effect in improving the mechanical, thermal and antimicrobial properties. The most ideal doping level was determined to be 3% that offered a balance between the enhanced performance and the integrity of the material. An increase in concentration resulted in agglomeration of nanoparticles and decreased mechanical strength. These results indicate that Nano Bi₂O₃-doped PMMA can be used as advanced denture material with higher functionality and durability to counter some of the weaknesses of conventional PMMA. It is suggested that further studies should be conducted to assess the long-term clinical performance and biocompatibility.

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