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# A COMPARATIVE INVESTIGATION INTO ENHANCING THE MECHANICAL PROPERTIES OF COLD-CURE PMMA DENTURE BASE RESIN USING NATURAL NANOPARTICLES DERIVED FROM ALMOND AND WALNUT SHELLS

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**Abstract**

*The present study proposes a sustainable approach to improve the mechanical performance of cold cure polymethyl methacrylate (PMMA) denture base resin using natural bio-based nanoparticles. The work aims to synthesize and compare the mechanical properties of cold cure PMMA nanocomposites reinforced with two bio-based nanofillers derived from walnut shell nanoparticles (WSP) and almond shell nanoparticles (ASP). The novelty of this study lies in the direct comparison of these two natural bio-based nanofillers as sustainable reinforcements for cold cure PMMA denture base resin. The WSP and ASP nanoparticles were independently integrated into PMMA matrix at concentrations of (0, 0.5, 1.0, 1.5 and 2.0 wt%).The mechanical performance was evaluated by tensile, flexural, impact strength and fracture toughness tests, and atomic force microscopy (AFM) was utilized to analyze particle size and dispersion. AFM analysis revealed average particle sizes of 78.20 nm and 91.93 nm for WSP and ASP, respectively, and uniform distribution of nanoparticles in PMMA matrix. The best mechanical performance was achieved at 2 wt.% reinforcement. The tensile strength of nanocomposite specimens reinforcement with walnut shell nano-powder (WSP) was increased from 44 MPa to 77 MPa at the ratio of (75%) , flexural strength from 78 MPa to 92 MPa (17.9%), impact strength from 5 to 7.5 kJ/m² (50%), and fracture toughness from 6.1 to 9.26 MPa·m½ (51.8%). Similarly, the incorporation of ASP increased the tensile strength to 73 MPa (66%), flexural strength to 93 MPa (19.2%), impact strength to 7.3 kJ/m² (46%), and fracture toughness to 8.38 MPa·m½ (37.4%) as compared to the unreinforced PMMA. These results enhance the feasibility of use this bio-based nanoparticles as sustainable dental biomaterials and provide a feasible approach to fabricate mechanically enhanced denture base resins with lower environmental impact.*

Keywords: *Cold-cured PMMA, biopolymers, Acrylics toughened with natural particles, nut shell and Walnut shell nanofillers.*

## Introduction

Trauma, dental disease or other illnesses that result in loss of teeth can affect patients' psychological well-being, esthetics, speech, and functional occlusion. Therefore, replacing missing teeth is crucial to restoring normal dental function. In dental applications, polymethyl methacrylate (PMMA) has long been used to produce removable dentures that replace missing teeth and associated tissues, but acrylic dentures have both advantages and disadvantages. Among the important problems with dentures is the fragility of methyl methacrylate, which makes them prone to breakage during use due to incorrect occlusion or accidental damage [1].

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This experimental research focuses on improving the performance of dentures made of polymethyl methacrylate (PMMA) by incorporating environmentally friendly and biocompatible nanoparticles.

Among the previous research conducted in this field is a study investigating the effect of adding nanoparticles of the clove powder (CP) nanoparticles in a polymer blend matrix of (PMMA) and 2% natural rubber (NR) at various weights fractions (0%, 0.1%, 0.3%, 0.5% and 0.7%) has been investigated to improve the mechanical properties such as tensile strength and hardness for dental applications [2]. In the same context, promising results have been obtained in the addition of natural nanofillers such as pomegranate peel powder (PPP) and clove powder (CP) into the same matrix (PMMA:2% NR); especially, in the increase of the fracture toughness and impact resistance of the material making it more suitable for denture base applications [3].

Particles of diameters in the range of 1 to 100 nm are generally referred to as nanoparticles. They can be derived from a number of sources including metals, ceramics and polymers. The unique physicochemical properties of these nanomaterials have attracted much interest in the field of dentistry. Many studies have proved that the addition of nanoparticles to dental materials, especially denture base materials can improve their mechanical properties, thermal properties and biocompatibility significantly [4].

The selection of (WSP) as a reinforcing particle was based on its agricultural byproduct origin, its inherent hardness, its good mechanical properties, its wide availability, its low cost, its environmental sustainability and its capacity to form strong interfacial adhesion with the acrylic resin matrix [5]. In a study by Foley et al. (2022), the mechanical and tribological properties of PMMA reinforced with two different natural fillers corn cob and miswak powders were examined at different weight percentages 2%, 4%, 6%, 8% and 10 wt.%. The results of mechanical properties showed improved in properties of composite compared with the unmodified PMMA by increasing the content of either filler [6]. In 2023, composite samples were developed using a mixture of PMMA (heat cure) with different weight fractions (0%, 2%, 4% and 6%) of polyamide and polyvinylpyrrolidone separately as matrix material reinforced with two types of powders (Sisal powder and coconut fillers) with different weight fractions (2%, 4%, and 6%) to obtain improved impact properties for denture applications [7].

And in the year 2024, the incorporation of walnut shell micro-powder (25 and 150μm) significantly improved the mechanical properties, including compressive strength and hardness, of the developed bio composites compared with neat PMMA [8]. In the same year, PMMA matrices were reinforced with nano-hydroxyapatite and carbon nanotubes and showed an increase in tensile strength up to 30% and good adhesion to acrylic denture teeth [9].

Although early investigations have been focused on synthetic reinforcements, in the last years, research trends have been gradually moving towards sustainable and bio-based nanofillers, due to the growing concern for environmental and biocompatibility challenges.

Wally *et al.*, in 2025 they study the effect of MgO and ZrO2 nanoparticles on the properties of PMMA was investigated. Their comparative study showed that nanofillers enhanced the mechanical properties of PMMA but the degree of enhancement depended on the filler type. The study emphasized the important role of direct comparative evaluations to identify the most effective reinforcing nanoparticles and improve denture base properties [10]. In another investigation, the addition of zirconium dioxide ($ZrO_2$), silicon dioxide ($SiO_2$) and diamond nanoparticles (DNPs) was studied in concentrations ranging from 0.5 to 5 wt.%. The results showed improvement of some mechanical properties of PMMA. The maximum hardness value of 21.4 ± 0.8 VHN is achieved at 1 wt.% nanoparticle loading with acceptable surface roughness [11].

And from recent studies, in 2026, Yerou, et al, they study examined the addition of Salvadora persica (miswak) powder into PMMA-based dental composites and reported that the mechanical and thermal properties of the produced biocomposites were significantly improved. The improvements were attributed by the authors to the good interfacial bonding between the natural

filler and the polymer matrix. In addition, the study emphasized the environmental impact and biocompatibility of natural reinforcements, which are a promising alternative to conventional synthetic fillers [12].

In another recent study, Farajpour and Akbardoost in 2026, they show that the addition of nano-clay and acrylic impact modifiers to the PMMA denture base resin showed significant improvement in fracture toughness, impact resistance and mechanical behavior. On the other hand, the authors mentioned that a high filler loading could have a negative impact on the homogeneity of the materials and processing properties. The results indicated that nanoparticle reinforcement is a viable strategy to overcome the inherent brittleness of PMMA denture base resins [13].

A recent study, Mohamed et al. they improved hybrid PMMA nanocomposites containing bio-based organic nanoparticles and inorganic nanofillers, resulting in improved tribological and mechanical properties, including enhanced wear resistance and strength [14].

Despite tremendous progress made in strengthening of the PMMA denture base materials using synthetic as well as natural nanoparticles, some obstacles still exist. Synthetic nanofillers such as zirconia, silica, hydroxyapatite and carbon nanotubes have been demonstrated to be very successful in increasing mechanical qualities, but their relatively expensive cost, inclination to agglomerate and complex processing may limit their practical applicability. On the other hand, bio-based nanofillers have the advantages of being sustainable, biodegradable, low-cost, and biocompatible. However, the reinforcing efficacy of diverse natural nanoparticles strongly relies on their composition, shape, particle size and concentrate.

In addition, most of the previous experiments have been based on a single natural filler system, which makes it difficult to compare the relative efficiency of different bio-based reinforcements. Walnut and almond shells are common agricultural by-products characterized by low density, good hardness, renewability, and the existence of lignocellulosic ingredients that may give rise to effective stress transfer inside polymer matrices. These characteristics make them promising candidates for sustainable reinforcement of PMMA denture base materials.

To the best of our knowledge as researchers in this field, we believe no previous study has been conducted comparing walnut shell nanoparticles (WSP) and almond shell nanoparticles (ASP) as sustainable nano-reinforcements for cold-cured PMMA denture base resin under identical fabrication and testing conditions. Hence a thorough comparison under similar production and testing conditions is necessary to determine the most efficient sustainable reinforcing method.

Therefore, the present work aims to comparatively evaluate the effect of incorporating almond shell nanoparticles (ASP) and walnut shell nanoparticles (WSP) into cold-cured PMMA denture base resin in terms of tensile strength, elastic modulus, flexural strength, impact strength, and fracture toughness.

## Materials and Methods

The samples were made with a polymeric matrix, the cold-cured PMMA, which is utilized as a base material in dental applications. The powders of ASP and WSP were used as reinforcing agents individually. Both ASP and WSP were processed to nanoscale. The PMMA resin (Spofa Dental, Czech Republic) was used as the control formulation. The natural fillers underwent milling followed by sieving through a 100 nm mesh to ensure nanoscale uniformity. Atomic Force Microscopy (AFM) analysis was performed to confirm their particle size and the average diameters were found to be 91.93 and 78.20 nm for almond shell powder (ASP) and walnut shell powder (WSP), respectively which confirmed their nanometric range. The reinforcement content for PMMA was introduced at varying weight fractions of (0%, 0.5%, 1.0%, 1.5%, and 2.0%), respectively. Summary of samples of the two composite groups prepared containing on the nano-sized ASP and WSP fillers is presented in Table 1.

**Table 1.** Composition of PMMA composites reinforced with natural nanoparticles (ASP and WSP)

| Group Code | Reinforcement Type | Weight Fraction (%) | Filler Weight (g) | PMMA Powder (g) | Monomer (ml) |
|---|---|---|---|---|---|
| C | None (Neat) | 0% | 0 | 22.00 | 11.00 |
| A0.5 | ASP | 0.5% | 0.11 | 21.89 | 11.00 |
| A1.0 | ASP | 1.0% | 0.22 | 21.78 | 11.00 |
| A1.5 | ASP | 1.5% | 0.33 | 21.67 | 11.00 |
| A2.0 | ASP | 2.0% | 0.44 | 21.56 | 11.00 |
| W0.5 | WSP | 0.5% | 0.11 | 21.89 | 11.00 |
| W1.0 | WSP | 1.0% | 0.22 | 21.78 | 11.00 |
| W1.5 | WSP | 1.5% | 0.33 | 21.67 | 11.00 |
| W2.0 | WSP | 2.0% | 0.44 | 21.56 | 11.00 |

## Preparation of Specimens

The natural almond and walnut shells were individually subjected to thorough cleaning using detergent powder and distilled water. then wash it well with hot distilled water at temperature at (30°C) to remove all clay and dust particles from it. Oven dried at 80°C for 4 hours to eliminate residual moisture. The dried shells were first mechanically ground to obtain extremely fine granules and then ground in a porcelain mill for four hours. And this process was done over and over. Then, the almond and walnut shell powders were sieved through a series of sieves (300, 150, 75, 53 and 25) in decreasing order of size. The powders that passed through the 25-micron sieve were selected. In this step, the powders were ground one more time with a porcelain mill grinder to obtain nano-scale particle sizes. In this study, the cold-cured acrylic resin was mixed according to the manufacturer's recommendation of a standard volume ratio (2:1), equivalent to 22 grams of PMMA powder and 11 milliliters of liquid methyl methacrylate (MMA) monomer per sample.

In order to achieve a homogeneous distribution of the mixture, the nano-reinforcement powders (ASP or WSP) were separately and manually mixed with the PMMA powder by continuous mechanical stirring for 10 min. The powder mixture was then slowly added to the liquid MMA monomer. The mixture passed through distinct phases sandy, sticky, dough-like, rubbery, and eventually hard indicating progressive polymerization. The resulting paste was then poured into metallic molds, subjected to room temperature curing under a pressure of 2.5 bar for 30 minutes, and subsequently post-cured for 24 hours to ensure full setting. The polymerized samples were immersed in distilled water at (37 °C for 48 h) prior to mechanical tests to simulate intraoral conditions and reduce the content of residual monomer or internal stresses [15].

### Physical and Mechanical Tests

#### *The Atomic Force Microscopy*

The nanometric properties of almond shell powder (ASP) and walnut shell powder (WSP) were studied by atomic force microscopy (AFM). The measurements were carried out in the tapping mode using a Bruker Dimension Icon AFM system (Bruker Optics GmbH, Germany), suitable for the analysis of soft, organic based particles by reducing the deformation of the sample during scanning. For sample preparation, firstly, the powders were dispersed in ethanol and kept for 10 min to get homogeneous distribution. A small drop of suspension was placed on freshly cleaved mica substrates and air-dried in a clean and dust-free environment.

#### *Mechanical Tests*

To investigate the fracture resistance and mechanical performance of the fabricated polymer composite samples, a series of mechanical tests were conducted, including tensile, flexural, and impact evaluations.

***Tensile Test***

The tensile properties were tested using the Universal Testing Machine (UTM), model WDW-200E manufactured by Jinan Shijin Group Co., Ltd., China. Testing was performed according to the standard ASTM D638 for thermoset polymer substances [16]. The test was performed at room temperature (~23°C) and constant crosshead speed of 5 mm/min until failure of the specimen. During the test the system monitored the following key mechanical parameters:

(1) Tensile strength (MPa).
(2) Elongation at break (%).
(3)Stress-Strain.

All measurements were performed in triplicate to ensure the reproducibility and credibility of the reported values.

***Flexural test***

The flexural properties of the manufactured composite specimens were tested on a Universal Testing Machine (model WDW-200E) as per ASTM D790-78 [17]. A 50 mm support span three-point bending design was developed. The test was conducted under standard laboratory conditions (23 °C) with a constant crosshead velocity of 5 mm/min. Each sample was loaded to failure by applying a load to the center of the sample. The flexural strength and modulus were calculated from the force-deflection data obtained. For each composition, average values were used for comparison analysis to guarantee the reliability of results; at least three specimens were examined.

***Impact strength test***

The impact resistance of the prepared composite samples was determined using the Charpy impact tester (Model N 43-1, New York, USA) as per the ISO 179, the standard for plastics impact testing [18]. Test specimens were prepared as rectangular bars of approximately 80 mm length, 10 mm width and 4 mm thickness. Prior to testing these were conditioned at ambient temperature (~23 °C) to ensure consistent conditions. Each specimen was subjected to one pendulum impact and the fracture energy was computed. This energy was used to normalize the impact strength by the cross-sectional area of specimens in ($kJ/m^2$). To improve the accuracy and consistency, the average values of three specimens for each model were reported.

## Results and Discussions

***AFM Test Results***

Atomic Force Microscope imaging showed that both WSP and ASP particles are nanoscale and relatively smooth Fig. 1 and Fig. 2. The prepared partials were analyzed by size analysis by AFM scanning probe microscopy (CSPM) to confirm that the partials are on the nanometer scale and to verify the mean diameter and distribution of the walnut shell WSP and almond ASP powders. Table. 2 describes the average dimensions diameter of 78.20 nm for walnut shell powder (WSP) as obtained by AFM test and the average diameter is 91.93 nm for almond shell powder (ASP) that is illustrated in Table 3.

**Table 2.** The AFM test of walnut shell powder particle size study indicates an average diameter of 78.20 nm

| Diameter (nm)< | Volume (%) | Cumulation (%) | Diameter (nm)< | Volume (%) | Cumulation (%) | Diameter (nm)< | Volume (%) | Cumulation (%) |
|---|---|---|---|---|---|---|---|---|
| 65.00 | 16.23 | 16.23 | 80.00 | 17.28 | 71.73 | 95.00 | 7.85 | 96.86 |
| 70.00 | 21.99 | 38.22 | 85.00 | 6.28 | 78.01 | 100.00 | 3.14 | 100.00 |
| 75.00 | 16.23 | 54.45 | 90.00 | 10.99 | 89.01 | | | |

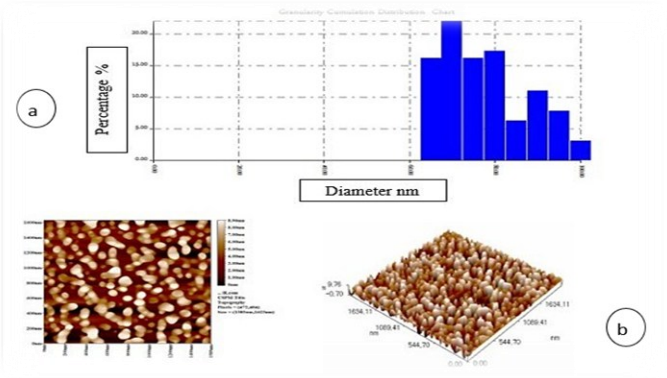


**Fig. 1.** AFM test of WSP fillers nanoparticles with an average diameter of 78.20 nm. (a) WSP fillers granularity cumulative distribution chart, (b) Three-dimensional (XYZ) picture for WSP particles

WSP which have smaller particles, provide better dispersion and improved interfacial area for stress transfer, that supports their mechanical performance. These observations are consistent with those reported by another st [19], when they used the atomic force microscopy (AFM) to characterize clove and pomegranate peel powders that was used as reinforcement material for polymethyl methacrylate, and they found that finer particle sizes enhanced both surface homogeneity and mechanical integration [3].

**Table 3.** The AFM test on the almond shell powder particle size study showed that the average diameter was 91.93 nm

| Diameter (nm)< | Volume (%) | Cumulation (%) | Diameter (nm)< | Volume (%) | Cumulation (%) | Diameter (nm)< | Volume (%) | Cumulation (%) |
|---|---|---|---|---|---|---|---|---|
| 40.00 | 4.55 | 4.55 | 75.00 | 4.55 | 20.45 | 105.00 | 7.58 | 73.48 |
| 45.00 | 1.52 | 6.06 | 80.00 | 9.85 | 30.30 | 110.00 | 8.33 | 81.82 |
| 50.00 | 1.52 | 7.58 | 85.00 | 8.33 | 38.64 | 115.00 | 12.12 | 93.94 |
| 55.00 | 2.27 | 9.85 | 90.00 | 6.06 | 44.70 | 120 | 6.06 | 100 |
| 60 | 1.52 | 11.36 | 95 | 10.61 | 55.30 | | | |
| 65 | 4.55 | 15.91 | 100 | 10.61 | 65.91 | | | |

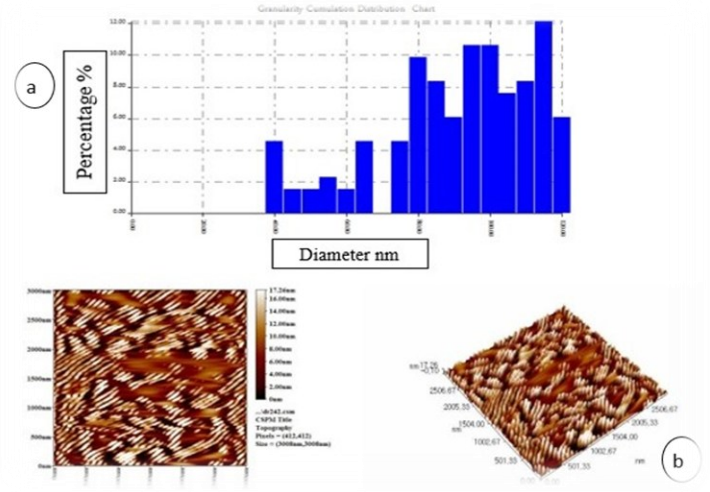


**Fig. 2.** AFM test of ASP fillers nanoparticles with an average diameter of 91.93 nm. (a) ASP fillers granularity cumulative distribution chart, (b) Three-dimensional (XYZ) picture for ASP particles.

***Results of FTIR Test***

Fourier transform infrared spectroscopy (FTIR) fully characterized the bands of the neat PMMA and nanocomposite specimens (PMMA: 2% ASP and PMMA: 2% WSP). The test of neat PMMA somewhat equal to the reported one [20] and is based on the group frequencies of the backbone chain, (C–C) and (C–H) groups, the ester group, (C–C), (C=O), and (C–O) units, and the methyl substituent, C–H units. Infrared spectra of neat PMMA and nanocomposite samples (PMMA: 2% ASP) are shown in Fig. 3. The asymmetric and symmetric peaks at 2954.7 and 2850.59 $cm^{-1}$, respectively, correspond to the (C–H) stretching of the methyl group ($CH_3$). Additionally, the range of (C=O and C-O) bands is 1500-2000 $cm^{-1}$ and 1000-1400 $cm^{-1}$, respectively [21]. The bands at (1447.57) and (1384.79) $cm^{-1}$ are assigned to (C–H) symmetric and asymmetric stretching modes, respectively. The strength of C=O stretching is assigned at 1731.96 $cm^{-1}$. Torsion of the $CH_2$ group is ascribed to 1240.45 $cm^{-1}$ band, ester group (C–O) vibration is represented by the band's peak at 1193.85 $cm^{-1}$, while the (C–C) bands are situated at (991.34 and 836.98) $cm^{-1}$ [20], [21]. The C=O bending medium strength in this spectrum is 750.26 $cm^{-1}$. As well as, an FTIR spectrum of nanocomposite specimen (PMMA: 2% ASP) that reinforced by 2% almond shell nano powder, reveals key functional groups such as O-H, C-H, and C=O (hydroxyl, methyl/methylene, and carbonyl groups). The peaks indicate that almond shell is a lignocellulosic material, offering insight into its potential application as a biosorbent or a precursor for biocarbon substances. The presence of these functional groups can be utilized to describe the chemical structure of the material and to monitor its changes after processes like pyrolysis or adsorption. Moreover, the infrared spectrum of the composite specimen (Fig. 3) shows that no new peaks or shifts of peaks were observed for the nanocomposite specimens (PMMA: 2% ASP) upon the addition of almond shell nano-powder. As previously mentioned in the references [20], by Rosemal, et al, these results related to the absence of cross ginking and presence of physical bonds in these prepared nano comosite samples.

Figure. 4 presents the FTIR spectra of pure PMMA and nanocomposite specimens (PMMA: 2% WSP) with 2% walnut shell nano-powder reinforcement. FTIR of PMMA symmetric and asymmetric bands attributed to the (C–H) stretching of the methyl group ($CH_3$) in a single structural repeated unit, which is assigned to the peaks at 2975.36 and 2868.08 $cm^{-1}$, respectively. In the FTIR spectrum, the C=O and C-O bands are commonly the most intense, in the regions 1500-2000 $cm^{-1}$ and 1000-1400 $cm^{-1}$, respectively [22]. Therefore, (C–H) symmetric stretching modes are associated with the bands at 1558.94 $cm^{-1}$ and C–C stretching bands are 991.34 and 836.98 $cm^{-1}$ [22], [23].The spectrum of the PMMA: 2% WSP nanocomposite specimens also indicates that its lignocellulosic components, including cellulose, hemicellulose and lignin, display broad peaks at 2800-2900 $cm^{-1}$ for C-H stretching (methyl, methylene and methoxy groups) and around 3300-3400 $cm^{-1}$ for O-H stretching (hydroxyl groups). The intense broad band at 3503.36 $cm^{-1}$ indicates the presence of O-H stretching vibration of hydroxyl groups. The band around 2975.36 $cm^{-1}$ may be assigned to the $sp^3$ C-H stretching bond of alkane [24]. The band at 2358.08 $cm^{-1}$ is ascribed to the (C-C) vibration of the alkyne group. The infrared spectra of the nanocomposite specimens (PMMA: 2% WSP) are shown in Fig. 4, which agrees with the results of [25].

***Tensile Test Result***

As compared to the polymer matrix PMMA (control sample), (Fig. 5, Fig. 6 and Fig. 7) show the result of tensile strength, modulus of elasticity and the percentage of elongation at fracture in (wt%) of both ASP and WSP nano-powder content. These values reached their maximum at a ratio of 2% for composite samples (PMMA: 2% ASP) and (PMMA: 2% WSP), respectively. The increase in tensile strength and elastic modulus is due to the nature of bonding force between the polymer and nanoparticles of both ASP & WSP which is a strong bonding that does not let cracks or any defects formation in a quick manner and in turn, the composite material will have a high tensile strength. Such a behaver may be related to the strong inter atomic bonding, as previously

mentioned by Sadiq et al. [2]. Also, this could be the nature of stiffness between the components of composites materials that means high compatibility between the PMMA and fillers. When using PMMA as a matrix reinforced with 2 wt % WSP, the nanocomposite's tensile strength and elastic modulus increased to 77 MPa and 6.482 GPa, respectively. And for bio composite sample strengthen with (2 wt.%) of ASP equal to (73 MPa and 5.731 GPa), respectively.

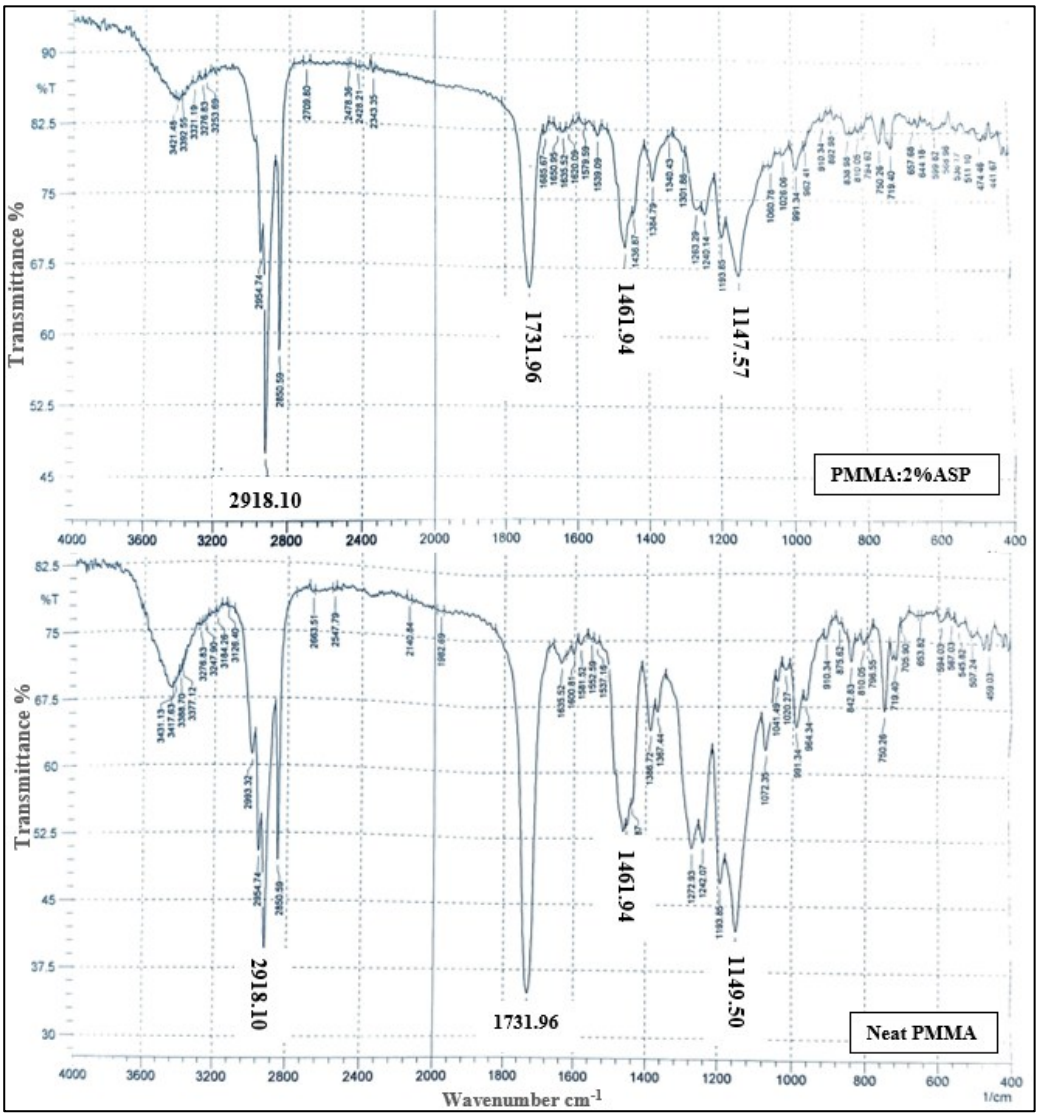


**Fig. 3.** FTIR spectrum of neat PMMA and the nanocomposite specimens (PMMA: 2% ASP) reinforced by 2% almond shell nano powder.

The sample reinforced with 2 wt% WSP showed the highest tensile strength and modules of elasticity, compare to the sample that content on 2 wt% ASP nanoparticles. The superior performance of nanocomposites samples that content on WSP nanoparticles may be linked to its smaller nanoparticle size (78.20 nm vs. 91.93 nm), which lead to higher surface area of WSP nanoparticle through the matrix and that lead to better interfacial bonding. As well as, the finer powders size enables the WSP nanoparticle to best dispersion within the PMMA matrix, resulting

in more effective crack-bridging mechanisms and stress transfer. Moreover, walnut shells WSP possess a relatively higher lignin and silica content, contributing to increased interfacial bonding and stiffness with matrix. These factors collectively increase the tensile response of nanocomposites that reinforced with WSP nanoparticles. Such a behaver may be related to the incorporation of WSP nanoparticles powders into the PMMA matrix will improve the stiffness of the nano composites (PMMA: 2% WSP) by restricting the movement of the matrix carbon chains, based on what was stated in the references [26], [27].

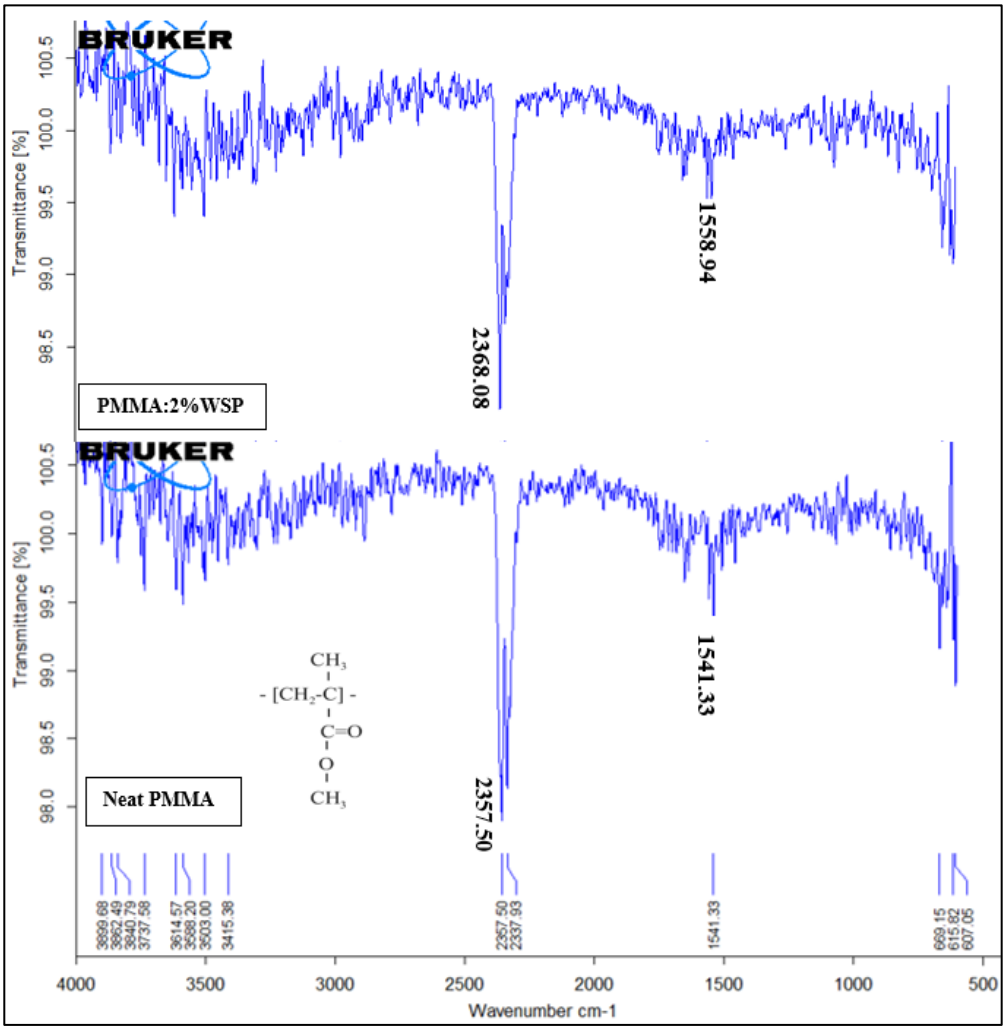


**Fig. 4.** FTIR of pure PMMA and nanocomposite specimen (PMMA: 2% WSP) with the addition of 2% nano-powder of walnut shell

From Fig. 7, the percentage of elongation of samples decreases with increase in weight fraction of ASP & WSP nano powders. When compared to samples with lower ratios of walnut shell powder (WSP), the nanocomposite (PMMA: 2% WSP) showed less elongation and maximum stress at fracture. This nanocomposite could withstand stress (77MPa) with elongation (3.15%) as opposed to the second group nanocomposites samples (PMMA:2% ASP) of nano powder of almond shell reinforced nanocomposite. Conversely, samples with different ratios

exhibit considerable elongation but low stresses. This is because of the size and features of each type of nano-reinforcement particles [26].

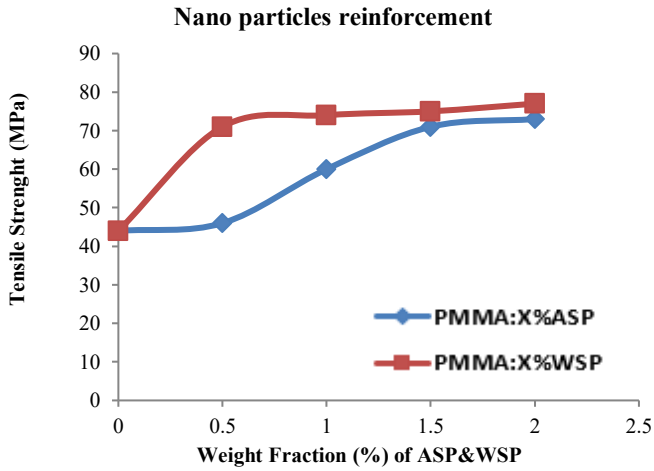


**Fig. 5.** Tensile strength of PMMA bio composite specimens in relation to the weight fraction of (ASP & WSP nano powder) in the composites

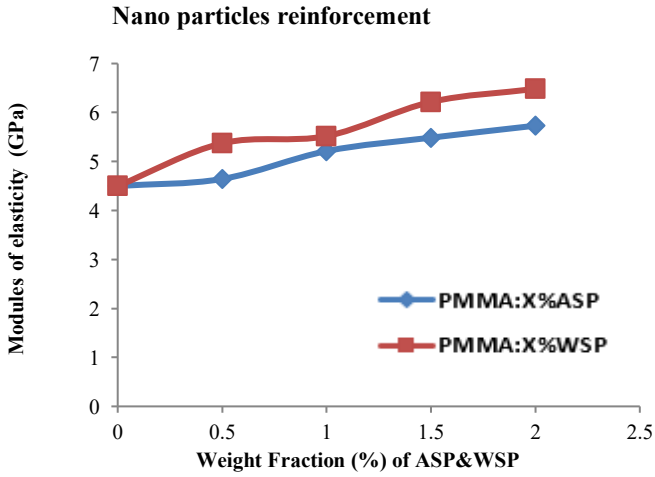


**Fig. 6.** Modules of elasticity of PMMA bio composite specimens in relation to the weight fraction of (ASP & WSP nano powder) in the composites

***Results of The Flexural Test***

The relation between weight percentage of WSP and ASP nanoparticles separately loaded in acrylic resin and flexural strength of samples is shown in Fig. 8. This Figure shows that improve in flexural strength with the increase of the weight fraction of each type of nano-powder (ASP and WSP) content in the produced nanocomposites compared to the PMMA matrix control sample. This improvement is due to the excellent interfacial compatibility between the molecules of the PMMA matrix chains and the naturally occurring nanoscale reinforcing powders (WSP & ASP). [27]. The nanocomposite samples added with walnut shell nanoparticles (WSP) showed better performance in terms of flexural strength than those with almond shell nanoparticles (ASP).

The enhanced flexural performance can be attributed to the strong physical interactions and good interfacial compatibility of the nano-fillers (WSP and ASP) with the PMMA matrix. This compatibility results in a reduction of the free volume in the composite microstructure and, as a consequence, a reduction of the polymer chain mobility. As a result, the total flexural strength of the nanocomposite increases, the plastic deformation decreases, and the stiffness is improved [19]. Moreover, it was observed from the Fig. 8 that flexural strength reaches to maximum value with highest percentage of WSP and ASP increase reached to 92MPa and 93MPa, respectively at 2%wt ratio content in the composite's materials, compare to control sample equal to 78MPa. These results are in good agreement with previous studies. [3], [28].

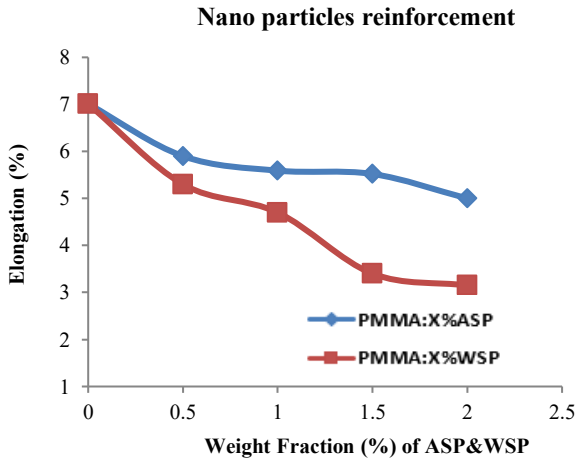


**Fig. 7.** Elongation at break of PMMA bio composite specimens in relation to the weight fraction of (ASP & WSP nano powder) in the composites.

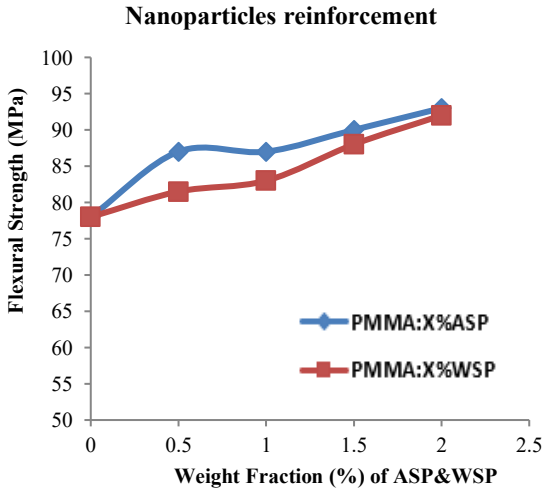


**Fig. 8.** Flexural strength of PMMA bio composite specimens in relation to the weight fraction of (ASP & WSP nano powder) in the composites.

***Results of The Impact Strength and Fracture Toughness***

Figure. 9 and Fig. 10 show the effect of natural nanoparticles derived from powdered almond and walnut shells on the impact strength and fracture toughness of the matrix polymer (PMMA). The impact test is intended to test the behavior of the material under a sudden high-velocity load.

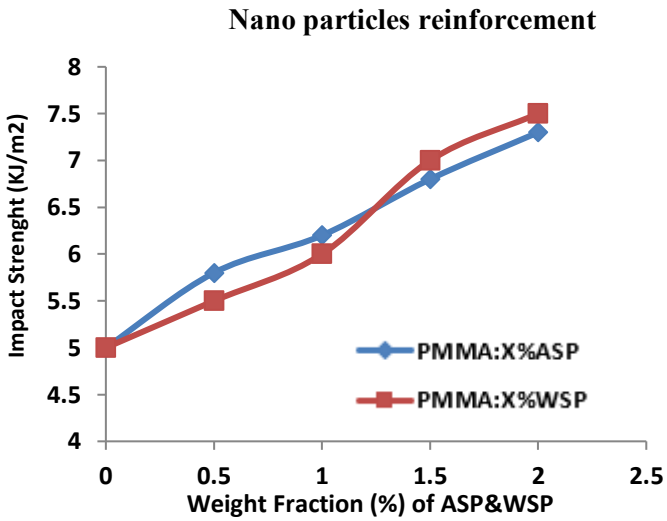


**Fig. 9.** Impact strength of PMMA bio composite specimens in relation to the weight fraction of (ASP & WSP nano powder) in the composites

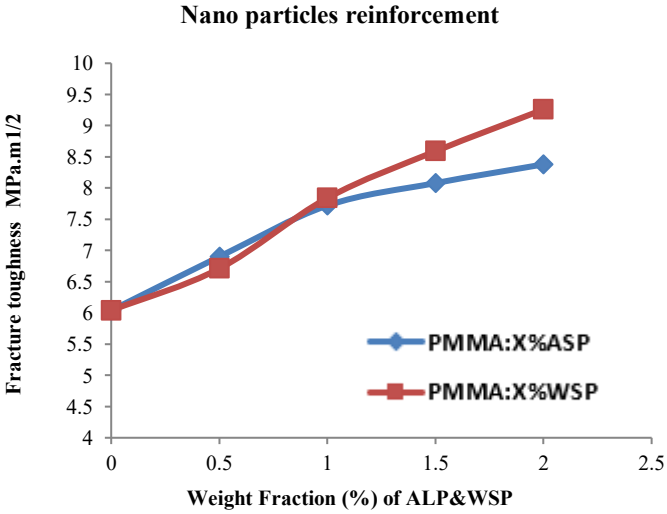


**Fig. 10.** Fracture toughness of PMMA bio composite specimens in relation to the weight fraction of (ASP & WSP nano powder) in the composites

In this test, the device measures the energy absorbed by the specimen at the point of fracture, which is designated as (Uc). Moreover, the flexural modulus ($E_B$), derived from prior flexural tests, is used in conjunction with the absorbed energy (Uc) to calculate both the impact strength (Gc) and fracture toughness (Kc) of bio-composite. A materials toughness was indicatorid by

Impact strength serves, reflecting its ability to resist fracture under sudden mechanical force. In polymer nanocomposites, this resistance is predominantly governed by two main aspects: the ability of the strengthen to dissipate impact energy and obstruct crack development, and the degree of interfacial bonding between the PMMA and powders. low interfacial adhesion can lead to the formation of micro voids, which act as crack initiation points, thereby diminishing the material's performance under impact stresses. [29]. This data also shows that the impact strength and fracture toughness of the produced nanocomposite with the weight fraction content of ASP or WSP nanoparticles are higher than the control polymer (PMMA). This tendency can be related to the fact that the impact test analyses the toughness of a material. The produced nanocomposite specimen of (PMMA:2% WSP) showed maximal impact strength of 7.5 kJ/m² and fracture toughness of 9.26 MPa.m². On the other hand, for the specimen containing 2% almond shell nanoparticles (PMMA: 2% ASP), these values were 7.3 kJ/m² and 8.38 MPa. m², as compare to control sample (PMMA), which was equal to 5 kJ/m² and 6.04 MPa. m², respectively. The enhancement is probably because of the uniform dispersion of natural nanoparticles in the PMMA matrix and the effective interfacial bonding between the filler and the polymer. Therefore, based on previously several studies [30], [31]**.** Such bonding promotes better stress transfer and increases the material's ability to absorb energy during fracture, thereby enhancing the fracture toughness of the resulting bio-nanocomposite.

## Conclusions

From the physical and mechanical properties of the bio-nanocomposite materials developed in the present research, it can be assumed that:

1. AFM analysis confirmed the successful production of WSP and ASP in the nanoscale range, with average particle sizes of (78.20 nm and 91.93 nm), respectively. The small particle size obtained promoted a homogeneous dispersion in the PMMA matrix that played an important role in improving the mechanical properties of the developed denture base nanocomposites.
2. he mechanical properties of cold-cured denture base were significantly improved by addition of Walnut and Almond shells powders in comparison with unreinforced material which proved effectiveness of natural WSP & ASP nanoparticles as reinforcing agents.
3. The optimal mechanical performance of the produced biocomposites was attained at a reinforcement level of 2 wt.% for both WSP and ASP.
4. WSP showed better reinforcement efficiency than ASP especially in tensile strength, impact strength and fracture toughness. This finding suggests that the efficiency of bio-based nanoparticles as reinforcements depends on the properties of particles and the filler-matrix interactions.
5. The results obtained in the research under study are consistent with the results of previous studies, indicating that the addition of natural nano-scale fillers to the PMMA denture base materials could improve their performance. The results presented here also demonstrate that nanoparticles can be used as practical reinforcement materials and at the same time contribute to more environmentally friendly dental composites.
6. Walnut shell nanoparticles exhibited the best overall mechanical performance among the investigated bio-based fillers. This indicates that WSP could be considered as a promising reinforcement candidate for the development of stronger cold-cured PMMA denture base materials.

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