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Impact of ethanol-assisted and non ethanol-assisted mixing methods on the mechanical properties of impregnated polymethylmethacrylate with MgO and Ag nanoparticles

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This study aims to elucidate the effect of non ethanol-assisted and ethanol-assisted mixing methods and adding MgO-and Ag-nanoparticles (NPs) into PMMA on flexural strength, impact strength, microhardness (HV) and compressive strength. NPs (1%, 3% and 5% concentrations) were mixed with poly (methyl methacrylate) (PMMA) powder by either using ethanol as a solvent (ethanol-assisted) or without ethanol (non ethanol-assisted). A total of 91 specimens were examined. One- and Two-way ANOVA tests were used to find the effect of mixing methods and concentration of NPs on mechanical properties of PMMA. The results showed an increase of flexural strength for all NPs concentrations (except 1% MgO-NPs) and HV (5% both NPs) in ethanol-assisted groups compared to non ethanol-assisted group ($p < 0.05$). Furthermore, the combined effects of NPs and mixing methods revealed statistically significant increases in flexural strength and HV in ethanol-assisted group (except in 1% and 3% MgO-NPs) compared to the control group. Meanwhile, no statistically significant differences were detected in impact strength and compressive strength between ethanol-assisted and non ethanol-assisted groups ($p > 0.05$). The combined effects of NPs and mixing methods presented a statistically significant increase only in compressive strength of 5% of both NPs in ethanol-assisted group in comparison to the control group. Ethanol-assisted mixing of MgO-NPs and Ag-NPs with PMMA showed an increase in the mechanical properties of flexural strength, HV and compressive strength compared to non ethanol-assisted, whereas no improvement in the impact strength property of PMMA was detected. Furthermore, synergetic effects of adding NPs and mixing methods were identified.

KEYWORDS

PMMA, MgO, Ag, nanoparticles, ethanol mixing, mechanical properties, anova

1 Introduction

Poly (methyl methacrylate) (PMMA) resin is the material of choice in dentistry to make removable partial and full dentures as well as orthodontic appliances (Alqutaibi et al., 2023). The reasons for selecting PMMA resin are mainly related to its unique combination properties, such as ease to handle in the laboratory, lightweight nature, cost-effectiveness, durability, pleasing aesthetic appearance and colour match, repairability and biocompatibility (Zafar, 2020). However, there are concerns regarding the mechanical properties of PMMA resin, for example, due to the inadequacy of its mechanical properties, such as flexural strength, impact strength, microhardness (HV) and compressive strength, the PMMA resin is highly susceptible to fracture during use (Gad et al., 2017).

It has been reported that augmenting PMMA resin by incorporating nanoparticle (NP) fillers can improve the resin's mechanical properties (Apimanchindakul et al., 2022). NPs possess a considerably greater surface area-to-volume ratio compared to larger particles, resulting in more robust interactions with the polymer matrix consequently improving in the mechanical properties of the PMMA resin (Abdulrazzaq Naji et al., 2018). NPs provide extra connective bonding to link polymer chains together, forming an interconnected structure within the PMMA resin. These extra links within the PMMA resin improve the transmission of loads and promote a more even distribution of stresses across the PMMA resin, thereby resulting in better strength and rigidity in the formed PMMA-NP nanocomposite (Naznin et al., 2021).

NPs exhibit energetic instability due to elevated surface energy and the aggregation of these NPs causes a decrease in surface energy through an increase in particle size. Employing chemical surface treatment on metal oxide NPs proves to be an effective and crucial method for minimizing surface energy and preventing NP aggregation such as Silane compounds, serving as bifunctional modifiers, possess the ability to establish a stable bond between organic and inorganic materials (Ahangaran and Navarchian, 2020).

Many studies reported that the incorporation of MgO-NPs and Ag-NPs enhances the mechanical properties of PMMA resin. A notable enhancement in flexural strength was observed at a lower MgO-NPs concentration (1.25%). However, with higher concentrations (2.5% and 5%) of MgO-NPs, there was a marked decrease in the flexural strength (Altaee and Al-Ali, 2022). Furthermore, 2% and 4% MgO-NPs content in PMMA had favorable effects on the surface hardness. However, any further increase in MgO-NPs concentration negatively affect on surface hardness (Abdulsattar, 2023). Adding Ag-NPs at 0.2%–2% into PMMA resulted in a significant increase in compressive strength (Ghaffari et al., 2014) while 0.8% and 1.6% Ag-NPs in PMMA nanocomposite revealed decreased flexural strength, but decreasing concentration to 0.3% had no effect on flexural strength (Köroğlu et al., 2016).

It is important to acknowledge that the mechanical properties of the PMMA-NPs nanocomposite can be influenced by various factors associated with NPs, such as size, shape, dimensions, bonding, and their distribution within the PMMA resin matrix (Gad et al., 2019).

The effect of introducing Ag-NPs into PMMA resin on flexural strength has been shown to vary depending on the concentration and size of the NPs. It was reported that a lower concentration of Ag-NPs of larger size is associated with higher flexural strength (Oyar et al., 2018). Furthermore, the use of an ultrasonic device to ensure uniform mixing and prevent aggregation of NPs increased flexural strength when MgO-NP was incorporated with PMMA resin (Altaee and Al-Ali, 2022).

On the other hand, the effects of adding NPs into PMMA on impact strength, HV and compressive strength have been shown to vary according to the shape, size and concentration of the NPs (Salman et al., 2017; Alhotan et al., 2021; Earar et al., 2021; Azmy et al., 2022; Barbur et al., 2023; Nabhan et al., 2023).

It is worth noting that the impact of using different methods for mixing NPs into PMMA resin on the latter's mechanical properties has yet to be examined. Ag-NPs and MgO-NPs are the NPs most commonly used to improve the resin's mechanical properties, using various concentrations and shapes (Bacali et al., 2019; Sadeq et al., 2023; Aldabbagh et al., 2021; Hilal et al., 2019).

The dispersion of NPs within PMMA resin has been shown to be affected by mixing methods (Sui et al., 2022). Even the dispersion of NPs within the PMMA enhances the desired material properties and performance (Sodagar et al., 2012). Our previous study showed that ethanol-assisted mixing of NPs within PMMA resin is associated with better dispersion and homogeneity in PMMA-NP nanocomposite (Arf et al., 2023). Then, based on this observation, the current study aimed to elucidate the effect on the flexural strength, impact strength, HV and compressive strength of using non ethanol-assisted and ethanol-assisted mixing methods and adding MgO-NPs and Ag-NPs into PMMA.

2 Material and methods

2.1 Material

The clear orthocryl (self-curable acrylate) PMMA (powder: Poly (methyl methacrylate), REF 160-300-00 and liquid: Methylmethacrylate, REF 161-150-00) was used in this study (DENTAURUM). Furthermore, Ag-NPs (20nm, Spherical, 99.99%, metal basis CAS No.:7440-22-4, Hongwu International Group Ltd- China), MgO-NPs (MgO, 99.9%, 10–30nm, SkySpring Nanomaterials, Inc), absolute ethanol (CAS-No: 64-17-5, Sigmaaldrich, Darmstadt-Germany) and separating medium (Cold mould seal) REF 14002, Jammu-India was used.

2.2 Methods

2.2.1 Study groups

Different weights of MgO-NPs and Ag-NPs were incorporated separately into PMMA powder (Table 1) using non ethanol-assisted and ethanol-assisted mixing techniques (Arf et al., 2023). The study groups comprised 1%, 3% and 5% of both MgO-NPs and Ag-NPs using non ethanol-assisted and ethanol-assisted mixing methods with PMMA powder as a control (Figure 1).

2.2.2 Mixing NPs with PMMA powder

2.2.2.1 Non ethanol-assisted mixing of NPs with PMMA powder (without ethanol)

The defined amount of NPs was dissolved in 10 mL of absolute ethanol using a sensitive balance. Next, the solution was

TABLE 1 Percentages and amounts of PMMA powder, monomer and MgO-NPs and Ag-NPs.

MgO- and Ag-PMMA groups	MgO-NPs and Ag-NPs powder/MMA monomer liquid	PMMA powder/MMA monomer liquid (mL)
Control	Zero	25 g/10
1%	0.353 g/10 mL	24.647 g/10
3%	1.082 g/10 mL	23.918 g/10
5%	1.842 g/10 mL	23.158 g/10

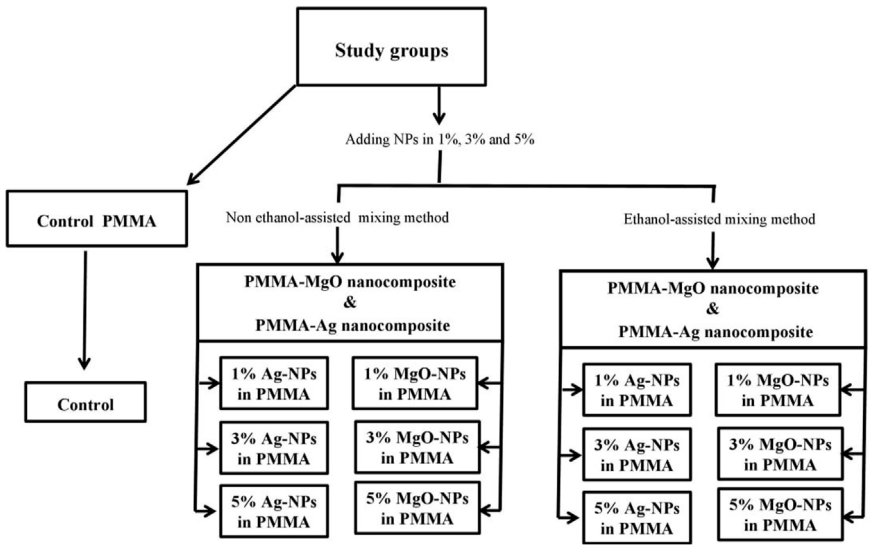

FIGURE 1
Study design and groups.

subjected to sonication (UP100H ultrasonic processor, Hielscher Ultrasound Technology) for 5 min to disperse and break apart any NP aggregates which usually formed during transport and storage (Yeap, 2018; Estrada-Monje et al., 2019). Then, the absolute ethanol was evaporated (Hot dry oven, Memmert GmbH + Co. KG, Schwabach, Germany) at 50°C for 48 h. The remaining NPs were further processed by grinding with a mortar and pestle until they formed a fine powder. This powder was then blended with PMMA powder and stirred (Hot plate magnetic stirrer, BIBBY, Stone, United Kingdom) for 30 min at 400 rpm to achieve homogeneity (Gad et al., 2021).

2.2.2.2 Ethanol-assisted mixing of NP with PMMA powder (with ethanol)

Following the sonication of the NPs in ethanol (as described in the above section), they were combined with the PMMA powder, creating a thick solution. Next, evaporation of ethanol was performed using magnetic stirring at 400 rpm for 2 h at 50°C. The resulting mixture was then manually ground using a mortar and pestle. To ensure complete ethanol evaporation, the PMMA-NP powder was placed in an oven at 50°C for 4 h (Boulerba and Zoukel, 2021).

2.2.3 Preparation of samples

The samples were constructed for each study group using a stainless steel mould (prepared by Hongniu fiber laser cutting machine, Jinan, China). The mould was painted with a cold mould seal separating medium and then sandwiched between two glass pads (Sun et al., 2021). PMMA powder and monomer (2.5:1 ratio) were mixed according to the manufacturer's instruction. The samples were subsequently placed in a polyclave containing water and kept under pressure of 2.2 bar at 50°C for 25 min. Following removal from the mould, the specimens were polished (using 150-, 300-, and 600- grit sandpapers) and stored in distilled water at 37°C for 48 h.

2.2.4 Mechanical tests

The following flowchart describes the mechanical assessment of PMMA-MgO and PMMA-Ag nanocomposite (Figure 2).

2.2.4.1 Flexural strength

A total of 91 (7 samples per group) bar-shaped specimens (65 mm × 10 mm × 3 mm) were fabricated per group using a stainless steel mould: non ethanol assisted (1%, 3%, 5%), ethanol assisted (1%, 3%, 5%) and control. The flexural strength of the

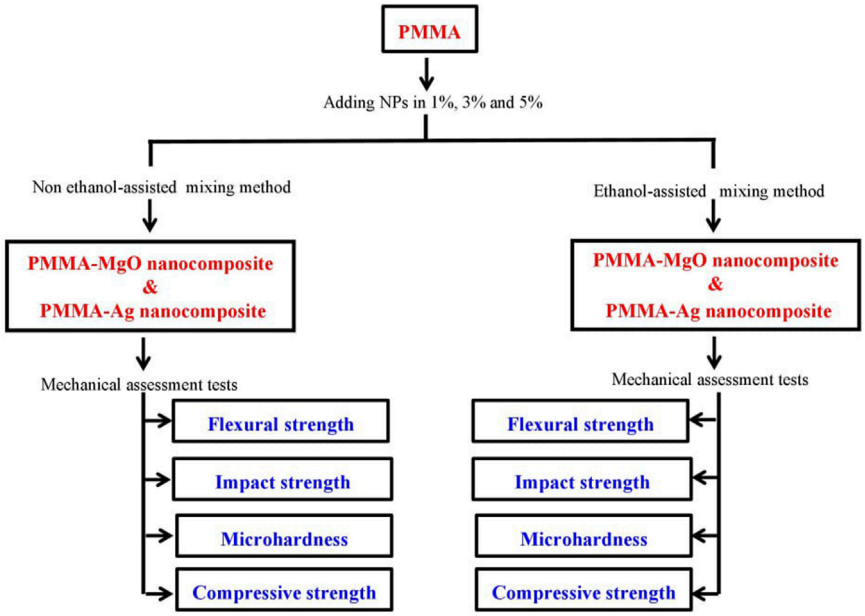

FIGURE 2
PMMA-MgO and PMMA-Ag nanocomposite mechanical assessment flowchart.

specimens was determined according to ISO 20795-1 (Shahabi et al., 2021) using a universal testing machine (AI 3000, GOTECH) at a crosshead speed of 5 mm/min and a span length of 50 mm. The force leading to the specimen fracture was recorded and the flexural strength was calculated using the following formula:

$$\sigma_f = 3Fl/2wh^2$$

Where σ_f is the flexural strength, F is the load at fracture, l is the distance between the supporting points, w is the specimen width and h is the specimen height (Abdelraouf, Bayoumi and Hamdy, 2022).

2.2.4.2 Impact strength

A total of 91 (7 samples per group) bar-shaped specimens (80 mm × 10 mm × 4 mm) were fabricated per group using a stainless steel mould: non ethanol-assisted (1%, 3%, 5%), ethanol-assisted (1%, 3%, 5%) and control. The samples were notched in the middle to a depth of 2.0 ± 0.2 mm with a notch angle of 45° facing opposite to the pendulum of the Charpy impact tester (Zidan, 2020) (XJJD-50 Series).

The machine testing pendulum in the form of a heavy metal disc fell and struck the specimen in the middle of the un-notch side, while the notched side of the sample was facing opposite to the pendulum. Here, the pendulum was set at a weight of 5 N to fall with a velocity of 5.5 mm/s and the energy absorbed by the impact test sample and the resulting fracture were recorded in Joules.

The Charpy impact strength of notched specimens was calculated in KJ/m^2 using the following formula:

$$CVN = (E/b.d) \times 10^3$$

Where E is the energy absorbed to break the specimen, b is the width of the specimen in mm, and d is the thickness of the specimens in mm (Wally, AL-Khafagy and Al-Musawi, 2014).

2.2.4.3 Microhardness

A total of 91 specimens (7 samples per group) were tested for HV. The specimens were highly polished using 150, 300-, 600- and 1,200 grit sandpapers. HV measurements were then carried out, using the Vickers hardness tester (T-TEST, Golden Time Technology). Three indentations were made on each sample and the mean value was recorded as the Vickers hardness (Al-Dwairi et al., 2023).

2.2.4.4 Compressive strength

A total of 91 (7 samples per group) cylindrical specimens (6 mm height and 4 mm diameter) were fabricated according to the ASTM D695-02a (ISO 604) standard, using a stainless steel mould: non ethanol-assisted (1%, 3%, 5%), ethanol-assisted (1%, 3%, 5%) and control. The samples were subjected to a compressive strength test in a universal testing machine (AI 3000, GOTECH) at a crosshead speed of 5 mm/min (Shahabi et al., 2021).

The compressive strength was calculated using the following equation:

$$\sigma c = P/\pi r^2$$

Where P is the compressive load and r is the radius of the specimen.

2.3 Statistical analysis

The Shapiro-Wilk test was used to check the normality of the data. One-way ANOVA was used to find the effects of different types of NP, different concentrations and mixing methods on impact strength and HV, while Kruskal–Wallis was used for flexural strength and compressive strength. Furthermore, statistical analysis was performed using SPSS statistical software (SPSS, Chicago, Il, USA, V.25) and the level of significance was set at $p \leq 0.05$.

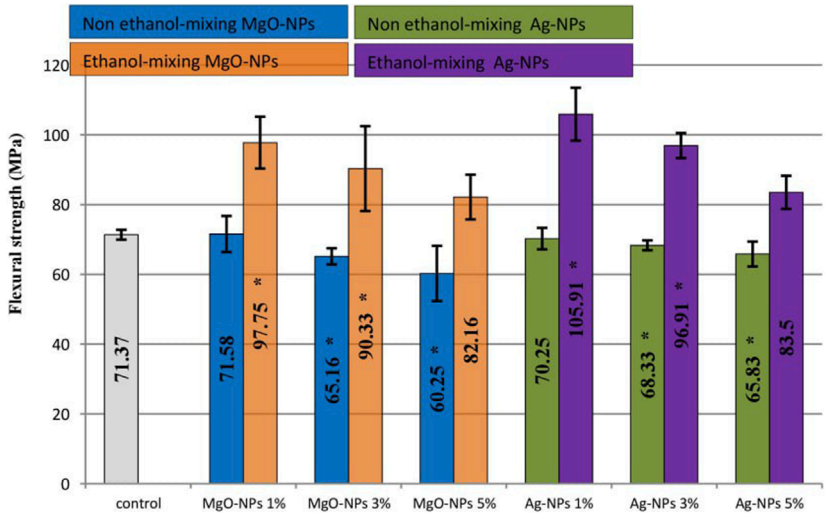

FIGURE 3
Comparison of flexural strength between control and all tested groups (* : Statistically significant).

3 Results

3.1 Flexural strength test

Comparisons between the control and all test groups (both non ethanol-assisted and ethanol-assisted mixing) with median and interquartile range (IQR) for the flexural strength test are presented in Figure 3. It is apparent that the flexural strength of all ethanol-assisted groups was higher than for non ethanol-assisted groups for corresponding NPs and concentrations. Comparison of all non ethanol-assisted and ethanol-assisted tested groups with the control group revealed flexural strength of non ethanol-assisted of both MgO-NPs (3% and 5%) and Ag-NPs (3% and 5%) groups had decreased significantly, with p values = 0.044, 0.000, 0.040 and 0.0001, respectively. Whereas, flexural strength of ethanol-assisted groups of both MgO-NPs (1% and 3%) and Ag-NPs (1% and 3%) had increased significantly, with p-value = 0.0001, 0.007, 0.0001 and 0.01, respectively.

Furthermore, no statistical difference in the flexural strength was observed between Ag-NPs and MgO-NPs when using the same concentration and mixing method. When non ethanol-assisted groups were compared against ethanol-assisted groups at the same NPs and concentration, there were significant differences between all non ethanol-assisted and ethanol-assisted groups except MgO-NPs 1%, for the same NPs and concentration (Table 2).

3.2 Impact strength test

The mean and SD for the impact strength test for all test groups (both non ethanol-assisted and ethanol-assisted with control) and comparisons between all tested groups and control group are shown in Figure 4. While increases in impact strength were observed for all ethanol-assisted and non ethanol-assisted groups compared to the control group, no statistically significant differences were detected.

Moreover, when comparing the impact strength between tested groups of different NPs using the same concentration and mixing method, and different mixing methods using the same NPs and concentration, no statistically significant differences were identified (Table 3).

3.3 Microhardness test

In the HV test, the mean and SD for the control and all test groups (both non ethanol-assisted and ethanol-assisted) were compared (Figure 5). The HV of all ethanol-assisted groups was higher than for non ethanol-assisted groups except for the 1% MgO-NPs group, for the same NPs and concentration. In addition, a comparison of the HV between the control group and non ethanol-assisted and ethanol-assisted groups showed statistically significant increases of HV for ethanol-assisted 5% MgO-NPs and all ethanol-assisted Ag-NPs concentrations (1%, 3% and 5%), with p-value = 0.0001, 0.028, 0.035 and 0.001, respectively. However, no statistically significant differences were found for non ethanol-assisted groups.

Additionally, comparing different NP groups, using the same concentration and mixing method, non ethanol-assisted 3% Ag-NPs, ethanol-assisted 1% and 3% Ag-NPs groups had statistically significantly higher HV compared to their corresponding MgO groups at the same concentrations. Moreover, a comparison between tested groups using different mixing methods and the same NPs and concentrations showed statistically significant differences in 5% MgO-NPs and 5% Ag-NPs, with p-value = 0.0001 and 0.007, respectively (Table 4).

3.4 Compressive strength test

Comparisons for the compressive strength test between the control and all tested groups (both non ethanol-assisted and

TABLE 2 Comparison of flexural strength between tested groups with different NPs using same mixing method and concentration. And for different mixing methods using the same NPs and concentration.

MgO groups (%)	Ag groups (%)	*p*-value *	Non ethanol-assisted groups (%)	Ethanol-assisted groups (%)	*p*-value *
Non ethanol-assisted MgO-NPs 1	Non ethanol-assisted Ag-NPs 1	1.000	MgO-NPs 1	MgO-NPs 1	0.078
Non ethanol-assisted MgO-NPs 3	Non ethanol-assisted Ag-NPs 3		MgO-NPs 3	MgO-NPs 3	0.003
Non ethanol-assisted MgO-NPs 5	Non ethanol-assisted Ag-NPs 5		MgO-NPs 5	MgO-NPs 5	0.003
Ethanol-assisted MgO-NPs 1	Ethanol-assisted Ag-NPs 1		Ag-NPs 1	Ag-NPs 1	0.005
Ethanol-assisted MgO-NPs 3	Ethanol-assisted Ag-NPs 3		Ag-NPs 3	Ag-NPs 3	0.008
Ethanol-assisted MgO-NPs 5	Ethanol-assisted Ag -NPs 5		Ag-NPs 5	Ag-NPs 5	0.006

*: Kruskal–Wallis test.

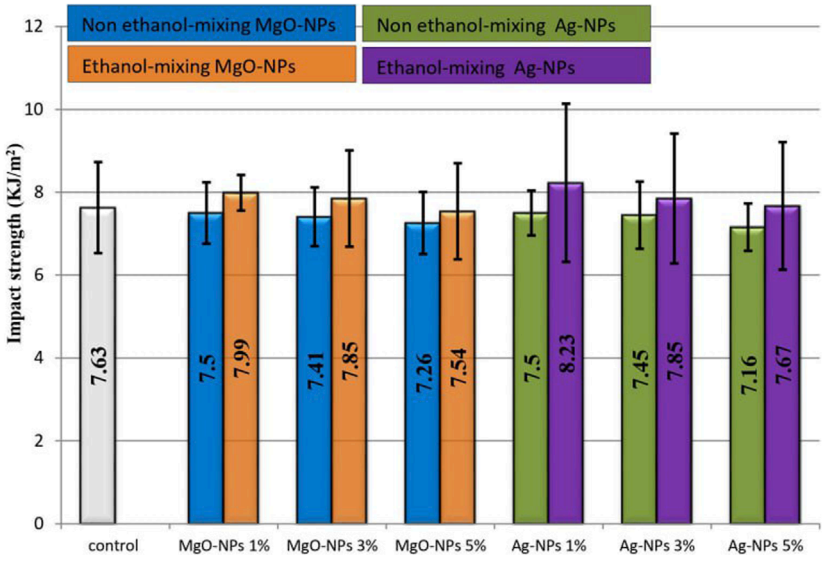

FIGURE 4
Comparison of impact strength between control and all tested groups.

ethanol-assisted) in terms of the median and IQR are presented in Figure 6. The compressive strength was higher in all ethanol-assisted groups than non ethanol-assisted groups for corresponding NPs and concentration, with statistically significant increases in the compressive strength of ethanol-assisted 3% MgO-NPs and 3% Ag-NPs, with *p*-value = 0.006 and 0.0001, respectively.

Furthermore, no statistically significant differences in compressive strength were observed between tested groups with different NPs when using the same concentration and mixing method. Similarly, no statistically significant differences were found between tested groups using different mixing methods and the same NPs and concentration (Table 5).

TABLE 3 Comparison of impact strength between tested groups with different NPs using the same mixing method and concentration. And for different mixing methods using the same NPs and concentration.

MgO groups (%)	Ag groups (%)	*p*-value *	Non ethanol-assisted groups (%)	Ethanol-assisted groups (%)	*p*-value *
Non ethanol-assisted MgO-NPs 1	Non ethanol-assisted Ag-NPs 1	1.000	MgO-NPs 1	MgO-NPs 1	0.948
Non ethanol-assisted MgO-NPs 3	Non ethanol-assisted Ag-NPs 3		MgO-NPs 3	MgO-NPs 3	0.967
Non ethanol-assisted MgO-NPs 5	Non ethanol-assisted Ag-NPs 5		MgO-NPs 5	MgO-NPs 5	0.997
Ethanol-assisted MgO-NPs 1	Ethanol-assisted Ag-NPs 1		Ag-NPs 1	Ag-NPs 1	0.927
Ethanol-assisted MgO-NPs 3	Ethanol-assisted Ag-NPs 3		Ag-NPs 3	Ag-NPs 3	0.997
Ethanol-assisted MgO-NPs 5	Ethanol-assisted Ag -NPs 5		Ag-NPs 5	Ag-NPs 5	0.988

*: One way ANOVA.

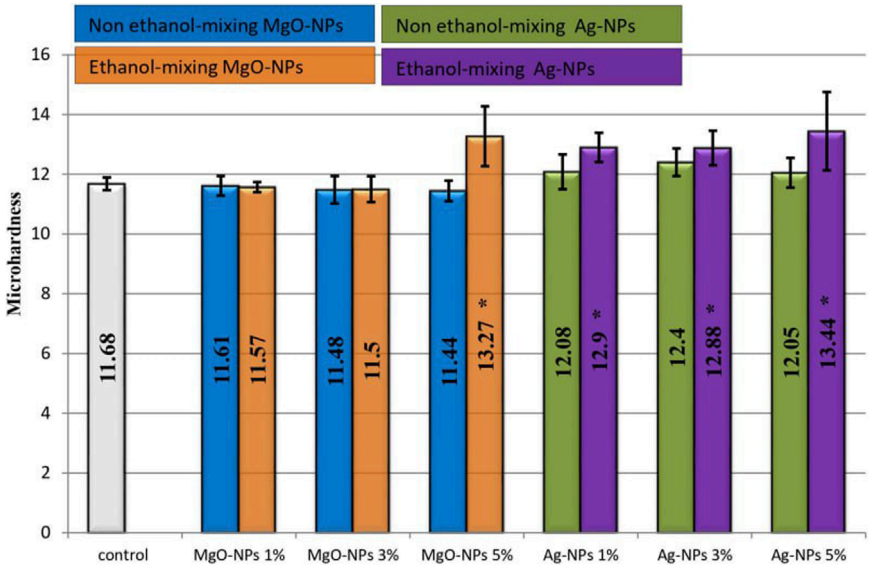

FIGURE 5
Comparison of HV between control and all tested groups (* : Statistically significant).

4 Discussion

PMMA is a polymer resin commonly used in dentistry and has shown inadequate mechanical properties in terms of flexural strength (Mansour et al., 2013), impact strength (Arıkan et al., 2010), HV (Nandal et al., 2013) and compressive strength (Hamad, 2019). Therefore, NPs have been added to address these drawbacks (Ghaffari et al., 2014; Gad et al., 2019; Ali Sabri et al., 2021; Abdulsattar, 2023). The rationale behind the current study was based on the premise that the method used to mix NPs with PMMA can affect the mechanical properties of the produced nanocomposite material by achieving a uniform and homogeneous dispersion of NPs within the PMMA matrix (Alsayed and Aqeel Ashraf, 2021). Moreover, the agglomerated NPs within PMMA have been reported to act as stress concentration points and weaken the mechanical properties of PMMA (Zidan et al., 2019).

Ethanol-assisted mixing of NPs with PMMA resulted in a better dispersion and homogeneity of NPs within PMMA (Arf et al., 2023). To the best of our knowledge, no study has examined the effect of ethanol-assisted mixing of MgO-NPs and Ag-NPs with PMMA on the mechanical properties of PMMA. Thus, the current study aimed to evaluate the impact of ethanol-assisted and non ethanol-assisted

TABLE 4 Comparison of HV between tested groups with different NPs using the same mixing method and concentration and using different mixing methods and the same NPs and concentration.

MgO groups (%)	Ag groups (%)	*p*-value *	Non ethanol-assisted groups (%)	Ethanol-assisted groups (%)	*p*-value *
Non ethanol-assisted MgO-NPs 1	Non ethanol-assisted Ag-NPs 1	0.498	MgO-NPs 1	MgO-NPs 1	1.000
Non ethanol-assisted MgO-NPs 3	Non ethanol-assisted Ag-NPs 3	0.011	MgO-NPs 3	MgO-NPs 3	1.000
Non ethanol-assisted MgO-NPs 5	Non ethanol-assisted Ag-NPs 5	0.199	MgO-NPs 5	MgO-NPs 5	0.0001
Ethanol-assisted MgO-NPs 1	Ethanol-assisted Ag-NPs 1	0.016	Ag-NPs 1	Ag-NPs 1	0.248
Ethanol-assisted MgO-NPs 3	Ethanol-assisted Ag-NPs 3	0.013	Ag-NPs 3	Ag-NPs 3	0.824
Ethanol-assisted MgO-NPs 5	Ethanol-assisted Ag -NPs 5	0.999	Ag-NPs 5	Ag-NPs 5	0.007

*: One way ANOVA.

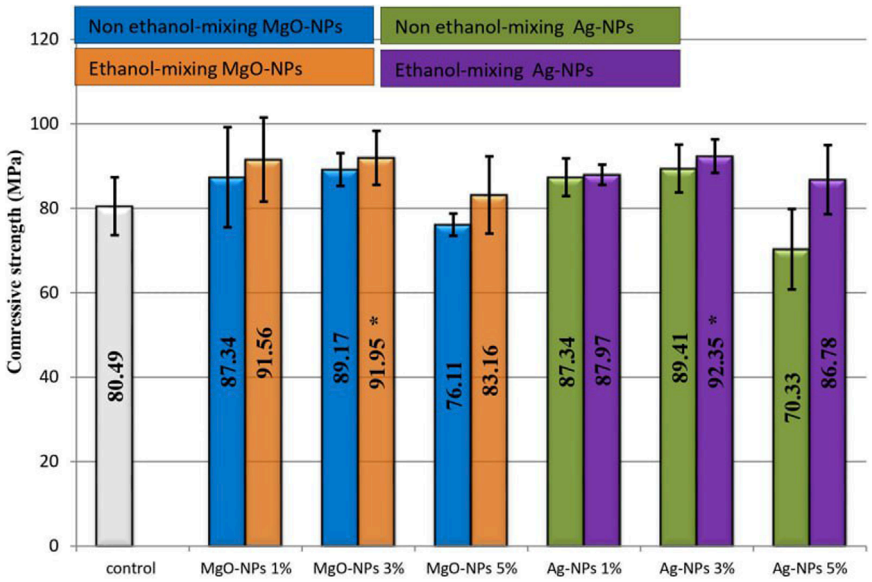

FIGURE 6
Comparison of compressive strength between control and all tested groups (* : Statistically significant).

mixing methods for MgO-NPs and Ag-NPs on the flexural strength, impact strength, HV and compressive strength of PMMA. The results show that in the cases of both tested NPs the ethanol-assisted mixing method improved the mechanical properties of flexural strength, HV and compressive strength at specific concentrations.

Flexural strength is one of the most important properties of PMMA resin; hence, many studies have investigated it (Somani et al., 2019). The present results showed that with ethanol-assisted mixing at 1% and 3%, both MgO-NPs and Ag-NPs significantly increased the flexural strength of PMMA. Additionally, no statistically significant differences were noticed between the examined NPs. Therefore, the increase in flexural strength could be mainly related to the mixing method.

The increase in flexural strength using ethanol-assisted mixing as compared to non ethanol-assisted mixing might be related to the fact that in non ethanol-assisted mixing, the NPs in PMMA resin are not homogeneous and act as impurities in the PMMA matrix, which usually decreases the flexural strength in PMMA resins (Sodagar et al., 2012). Or the NPs might have an adverse effect on the degree of conversion

TABLE 5 Comparison of compressive strength between tested groups using different NPs and the same mixing method and concentration. And using different mixing methods and the same NPs and concentration.

MgO groups (%)	Ag groups (%)	*p*-value *	Non ethanol-assisted groups (%)	Ethanol-assisted groups (%)	*p*-value *
Non ethanol-assisted MgO-NPs 1	Non ethanol-assisted Ag-NPs 1	1.000	MgO-NPs 1	MgO-NPs 1	1.000
Non ethanol-assisted MgO-NPs 3	Non ethanol-assisted Ag-NPs 3		MgO-NPs 3	MgO-NPs 3	1.000
Non ethanol-assisted MgO-NPs 5	Non ethanol-assisted Ag-NPs 5		MgO-NPs 5	MgO-NPs 5	1.000
Ethanol-assisted MgO-NPs 1	Ethanol-assisted Ag-NPs 1		Ag-NPs 1	Ag-NPs 1	1.000
Ethanol-assisted MgO-NPs 3	Ethanol-assisted Ag-NPs 3		Ag-NPs 3	Ag-NPs 3	1.000
Ethanol-assisted MgO-NPs 5	Ethanol-assisted Ag -NPs 5		Ag-NPs 5	Ag-NPs 5	0.628

*: Kruskal–Wallis test.

in polymerisation and lead to an increase in the amount of residual monomer that acts as a plasticiser (Shibata et al., 2007). Furthermore, in non ethanol-assisted mixing, the NPs agglomerate and the agglomerated NPs act as stress concentration centres in the PMMA resin matrix (Andreotti et al., 2014). Overall, these factors might decrease the flexural strength of modified PMMA when using the non ethanol-assisted mixing method. However, the ethanol-assisted mixing method improves in flexural strength due to better dispersion and homogeneity of MgO-NPs and Ag-NPs in the PMMA matrix (Stojanovic et al., 2009).

It is apparent that the concentration of the NPs might jeopardise the flexural strength of PMMA resin and this is in accordance with Ghaffari et al. (2014), who reported a decrease in the flexural strength with increasing concentration of NPs. The current study found the highest flexural strength in the 1% MgO-NPs NP concentration and the lowest flexural strength in the 5% MgO-NPs concentration. In line with our results, other studies have identified an inverse relationship between increased NP concentration and flexural strength (Ihab and Moudhaffar, 2011; Kul et al., 2016; Omer and Ikram, 2019).

Generally, oral appliances made from PMMA might fracture easily when suddenly struck or accidently dropped. Therefore, PMMA resins need sufficient impact strength to increase their durability and longevity. Our results revealed that with both mixing methods, modification of acrylic resin with MgO-NPs and Ag-NPs of up to 5% had no significant negative effects on the impact strength of acrylic resin, with better impact strength observed using the ethanol-assisted mixing method. It is worth mentioning that few studies have evaluated the effect on impact strength of adding NPs into PMMA. The results of these studies are inconsistent, with some studies showing no significant effect, which is in line with the result of this study (Shahabi et al., 2021; Zidan et al., 2019). While other studies showed a decrease (Al-Harbi et al., 2019) and an increase (Ghahremani et al., 2017) of impact strength. These conflicting results can be explained by the variation in the type and concentration of NPs used as well as the mixing methods. For example, adding Ag-NPs into PMMA at 0.8% and 1.6% did not affect impact strength (Köroğlu et al., 2016).

Wear resistance is a material's capacity to endure surface harm or deterioration resulting from friction, abrasion or other mechanical forces over an extended period of time. HV is an important indicator of the wear of dental materials, including PMMA resin, since greater hardness reduces abrasive wear (Zidan et al., 2019). Low surface HV increases surface roughness and dental plaque retention, pigmentation, and compromises the material's longevity and aesthetic appearance (Farina et al., 2012). The results of the current study showed that the addition of MgO-NPs and Ag-NPs using non ethanol-assisted mixing had no statistically significant effect on HV, which is in agreement with the result of another study that used non ethanol-assisted mixing (Abdelraouf et al., 2022). However, using the ethanol-assisted mixing method, significant improvements in HV were detected and this result is commensurate with another study that used ethanol-assisted mixing (Vojdani et al., 2012). This highlights the importance of the mixing method on the HV property of PMMA resin.

It is important to acknowledge that wear resistance is affected by chemical composition and structure of a material and environmental conditions such as temperature, humidity and oxidation. For example, PMMA nanocomposites with 3% TiO2-NPs exhibited the highest resistance to wear and revealed smoother surfaces (Zhang, 2014) and the inclusion of SiO2 and TiO2 fillers enhanced the wear resistance of artificial teeth (Muhammad et al., 2011). In this study, the impact of environmental factors on wear resistance was not examined as it was beyond the scope of the study.

The compressive strength of PMMA resins is vital to ensure the longevity, functionality and safety of dentures for patients. The present study indicated that ethanol-assisted mixing of the tested

NPs (at 3% for both NPs) will improve the compressive strength of PMMA compared to non ethanol-assisted mixing method. Similar to this study, previous studies have also reported an increase in the compressive strength property of PMMA resin and this improvement was probably due to the uniform distribution of metal particles within the PMMA matrix. (Hamedi-Rad et al., 2014; Abdulridha et al., 2022).

The present study has limitations that include solely examining the mechanical properties of PMMA-NPs nanocomposite without examining the chemical and clinical aspects of the PMMA resin. Nevertheless, this is the first study to evaluate the effect of different methods of mixing MgO-NPs and Ag-NPs into PMMA resin on the four main important mechanical properties of PMMA resin; furthermore, to examine the combined effects of NP and mixing methods at the same time.

5 Conclusion

The results of this study indicate that using ethanol-assisted mixing of MgO-NPs and Ag-NPs with PMMA resin increases the mechanical properties of flexural strength, HV and compressive strength compared to non ethanol-assisted, whereas no improvement in the impact strength property of PMMA was detected. Furthermore, the concentration of NPs was also shown to affect the examined mechanical properties. More studies are recommended to test the impact of these mixing methods for these NPs on the chemical and aesthetic properties of PMMA resin.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AA: Data curation, Formal Analysis, Investigation, Methodology, Writing–original draft. FK: Conceptualization, Project administration, Supervision, Visualization, Writing–review and editing. SG: Project administration, Supervision, Visualization, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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