# Mechanical and tribological properties of barium titanate-PMMA nanocomposites for dental fillings

**Marwa Taleb**

Ministry of education-general directorate of education, Baghdad, Al-Rusafa third District

Corresponding author: marwa.Taleb1204a@ihcoedu.uobaghdad.edu.iq

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## Abstract:

Poly (methyl methacrylate) (PMMA) is a polymer used in the dental industry, specifically in denture base and provisional restorative resin, due to its good aesthetic properties, biocompatibility, and processing. However, its clinical performance is usually compromised by lack of mechanical strength and resistance to wear. Over the past few years, there has been a widespread research on the use of ceramic nanoparticles as an effective method to improve mechanical and functional performance of PMMA-based dental composites. The aim of this study was to conduct a systematic review of the tribological and mechanical performance of BaTiO3-PMMA nanocomposites with the synthesis of quantitative data, which was supported by a systematic review of the available experimental literature on the subject. A total of 23 in vitro studies published in 2016-2025 based on pre-determined eligibility criteria were included. The results under study included flexural strength, surface hardness, elastic modulus, compressive strength, wear rate, and coefficient of friction. The quantitative analysis performed by applying proper statistical pooling techniques revealed that the reinforced with BaTiO3 was constantly correlated with statistically significant rises in the mechanical properties and declines in the wear-related parameters in comparison with the unmodified PMMA.

These improvements were most so in low loadings of nanoparticles, especially at 5 wt. and below. There was moderate heterogeneity between the studies included, which was mainly due to variation in filler concentration, functionalization of particles and methodology of fabrication. In general, it can be concluded that the results imply that nanocomposites of BaTiO 3 and PMMA experience an increase of the mechanical integrity and tribological stability in comparison to the conventional PMMA, which is why they could be implemented in the development of high-technology dental prosthetic and restorative materials.

## Keywords:

Poly(methyl methacrylate); Barium titanate; Dental nanocomposites; Mechanical properties; Tribological behavior; Denture base materials

## الملخص:

يُستخدم بولي (ميثيل ميثاكريلات) (PMMA) على نطاق واسع في مجال طب الأسنان، ولا سيما في مواد قواعد أطقم الأسنان والمواد الترميمية المؤقتة، وذلك لما يتمتع به من خصائص جمالية مقبولة، وتوافق حيوي مناسب، وسهولة في المعالجة والتصنيع. ومع ذلك، فإن أداءه السريري غالبًا ما يكون محدودًا بسبب انخفاض مقاومته الميكانيكية وضعف مقاومته للبلى. في السنوات

الأخيرة، حظيت إضافة الجسيمات النانوية الخزفية باهتمام متزايد بوصفها وسيلة فعّالة لتحسين الأداء الميكانيكي والوظيفي لمركبات PMMAالسنية. هدفت هذه الدراسة إلى التقييم المنهجي للسلوك الميكانيكي والتريبولوجي لمركبات $BaTiO_3$–PMMA النانوية من خلال مراجعة منظمة للأدبيات التجريبية، مدعومة بتحليل كمي للبيانات.

ووفقًا لمعايير الاشتمال المحددة مسبقًا، تم تضمين 23 دراسة مختبرية (in vitro) نُشرت خلال الفترة من 2016 إلى 2025. شملت المتغيرات التي جرى تحليلها مقاومة الانحناء، والصلادة السطحية، ومعامل المرونة، ومقاومة الانضغاط، ومعدل البلى، ومعامل الاحتكاك. وأظهرت نتائج التحليل الكمي، باستخدام أساليب إحصائية مناسبة لتجميع البيانات، أن تدعيم PMMA بجسيمات باريوم تيتانات ارتبط بشكل ثابت بتحسنات ذات دلالة إحصائية في الخواص الميكانيكية، إلى جانب انخفاض في مؤشرات البلى، مقارنةً بـ PMMAغير المعدل. وكانت هذه التحسينات أكثر وضوحًا عند تراكيز الجسيمات النانوية المنخفضة، ولا سيما عند نسب إضافة تساوي أو تقل عن 5% وزنيًا. كما لوحظ وجود تغاير متوسط بين الدراسات المشمولة، يُعزى بشكل رئيسي إلى الاختلافات في تركيز الحشوات، ومعالجة سطح الجسيمات، وتقنيات التصنيع. وبصورة عامة، تشير النتائج إلى أن مركبات $BaTiO_3$–PMMA النانوية تُظهر تكاملًا ميكانيكيًا أفضل واستقرارًا تريبولوجيًا أعلى مقارنةً بـ PMMA التقليدي، مما يدعم إمكانية استخدامها في تطوير مواد متقدمة للتعويضات والترميمات السنية.

**الكلمات المفتاحية:**

بولي (ميثيل ميثاكريلات)؛ باريوم تيتانات؛ المركبات النانوية السنية؛ الخواص الميكانيكية؛ السلوك التريبولوجي؛ مواد قواعد أطقم الأسنان

## 1. Introduction:

One of the most widely used polymeric materials in prosthodontics, especially in the manufacture of denture base, is poly(methyl methacrylate) (PMMA), because it has an acceptable aesthetic, is easy to work with, inexpensive, and has a biocompatibility that is clinically acceptable. Along with these merits, traditional PMMA has material constraints that are well-documented and negatively impact the long-term clinical outcomes of this material. Mechanically, PMMA exhibits fairly low flexural strength, fracture toughness and is therefore prone to crack formation and catastrophic fracture when subjected to repeated masticatory forces. In clinical practice, denture base fractures are one of the primary reasons for prosthodontic repair and replacement, and laboratory and clinical evidence continues to show that midline fracture and fatigue failure are the predominant failure modes and not necessarily surface wear (Azmy et al., 2022; Abdlrahman et al., 2025). The shortcomings have led to massive studies that seek to enhance structural integrity of such denture materials made of PMMA.The development of dental materials science has made nanoparticle reinforcement a strong approach towards augmenting the inherent mechanical qualities of PMMA. In comparison to traditional fillers, nanoscale reinforcements may have a stronger interaction with the polymer skeleton, enhance the transfer of stress between the filler and the matrix, hamper the mobility of polymer chains, and retard the formation and propagation of cracks. Both experimental and review-based studies show that the flexural strength, elastic modulus, and surface hardness can be improved by ceramic and inorganic nanoparticles, whose effectiveness increases greatly depending on the particle chemistry, size, surface treatment, and loading level (Shaaban, 2024; Galant et al., 2024). These enhancements are especially applicable in the case of denture base materials, in which fracture resistance when subjected to repeated bending stresses is a major clinical need.

Of the different types of nanofillers further investigated, ceramic nanoparticles that include zirconium dioxide ($ZrO_2$), magnesium oxide (MgO), silicon dioxide ($SiO_2$), and zinc oxide (ZnO), have been widely studied because of their high elastic modulus, chemical stability, and their compatibility with PMMA matrices. Wally et al. (2025) showed that the addition of MgO and $ZrO_2$ nanoparticles in PMMA resulted in significant flexural strength and hardness of the surface relative to unmodified resin, and $ZrO_2$ had a high reinforcement efficiency due to higher stiffness and better interfacial interaction. Likewise, Surana et al. (2025) found that the addition of $ZrO_2$ nanoparticles improved both the mechanical and surface hydrophilicity, which is a surface-related attribute related to enhancing the denture hygiene and not mechanical strength. Simultaneously, tensile and flexural performance in MgO-substituted PMMA systems was significantly enhanced, and it was associated with enhanced filler dispersion and interfacial bonding instead of the variation in wear resistance (Kumari et al., 2024).

Fracture resistance and wear resistance should be differentiated because these characteristics are based on various material processes and come to different clinical issues. Bulk mechanical properties, including flexural strength, fracture toughness, and fatigue resistance, are the major determinants of fracture resistance, whereas wear resistance is a surface phenomenon which is affected by hardness, frictional behavior, and tribological interactions during mastication. Tribological performance has become a growing concern in the PMMA research since excessive wear may have an impact on opposing dentition and change the occlusal morphology. Abdo et al. (2024) have shown that PMMA with solid lubricant fillers had lower wear rates and lower coefficient of friction, which can be highlighted by the fact that tribological improvement does not always mean an increase in fracture resistance. Similarly, Fouly et al. (2024) demonstrated that cellulose nanocrystal-reinforced PMMA obtained similar enhancements in mechanical strength and wear resistance, which highlighted that the type of filler is very crucial in deciding whether the reinforcement will be focused on bulk strength or surface durability or both.

Nanofiller systems with hybrid and multifunctional capabilities have also been investigated to be able to customize the PMMA performance more closely. Ahmed and El-A. (2023) demonstrated that hybrid SiC/$TiO_2$ nanoparticle reinforcement enhanced flexural characteristics and reduced significantly the wear rate, which suggests that the hard ceramic particles and tribologically active fillers acted in a synergistic manner. The same pattern was observed with PMMA composite reinforced with nano-$SiO_2$ and ZnO, where the hardness and elastic modulus were found to increase due to the increased rigidity in the matrix and not due to the alteration of the crack resistance mechanisms (Kammona et al., 2025; Megahed et al., 2025). These results highlight the necessity to match the choice of nanofillers with particular performance goals, be it mechanical strength, wear resistance, or the combination of both.

Although the literature on nanoparticle-modified PMMA is quite significant, the results are uneven as they depend on the chemistry of fillers, the quality of the dispersion of the particles, the surface functionalization, and the working protocols. In addition, numerous studies concentrate on individual mechanical or tribological parameters and do not allow direct comparison between studies. As a result, a comprehensive and organized review of the impact of nanoparticle reinforcement on mechanical and tribological behavior is necessary to inform the optimization of the material and its clinical implementation (Alfahdawi, 2025; Abdlrahman et al., 2025). In this context, the current research has the purpose of contextualizing and synthesising available experimental data on nanoparticle-reinforced PMMA dental materials, especially in the clear separation of bulk mechanical reinforcement and surface-related tribological performance.

# 2. Methodology:

### 2.1 Study design

This current study was intended to be a systematic review and meta-analysis to quantitatively summarize existing experimental data on the mechanical and tribological properties of barium titanate--reinforced polymethyl methacrylate ($BaTiO_3$ -PMMA) nanocomposites as a dental filling and denture base material. To achieve transparency, reproducibility, and methodological rigor in the entire scope of the review process, the methodological framework of this study was built in line with the guidelines of Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA 2020).

To accommodate the evidently accelerating volume of experimental literature exploring nano-reinforced PMMA systems, systematic reviews have grown in importance as sources in the field of dental materials research since they frequently show heterogenous results that need to be synthesized (Díez-Pascual, 2022; Galant et al., 2024).

To reduce the possibility of selective outcome reporting and analytical bias, a predefined study protocol was created before the literature search commenced and was posted in an open-access protocol repository. The protocol clearly stipulated research objectives, inclusion and exclusion criteria, outcome measures, data extraction plan and statistical synthesis plan. Any methodological corrections observed to exist during the process of the review were reported and explained in the final manuscript that would ensure complete methodological transparency. This methodology goes in line with best practices reported in the recent meta-analyses of the dental nanocomposites based on PMMA, protocol-based methodologies significantly enhanced the reliability of the pooled effects estimates (Galant et al., 2024; La Rosa et al., 2022).

The overall aim of the systematic review and meta-analysis involved assessing the degree to which incorporation of $BaTiO_3$ nanoparticle changes the mechanical properties: flexural strength, compressive strength, elastic modulus, fracture resistance, and surface hardness; and tribological behavior: wear rate, and coefficient of friction of PMMA dental materials.

Past experimentation research has found out that $BaTiO_3$ nanoparticles are capable of significantly increasing the flexural strength and hardness of PMMA and maintaining processability and radiopacity, especially at optimal filler concentrations (Elshereksi et al., 2016; Azhari, 2020). Nevertheless, the extent of these enhancements differs considerably among studies because of variations in the size of nanoparticles, functionalization of surfaces, filler loading, and methods of fabrication, which requires a quantitative synthesis.

The research question was designed on the basis of the modified PICO framework that could be applied in the field of dental materials research. The sample was composed of dental materials of PMMA containing denture base resins and dental filling composites. Intervention was determined by PMMA that was reinforced with the addition of BtioO 3 nanoparticles generated by any physicochemical pathway, such as solgel, hydrothermal, or solidstate processing. The comparators were pure PMMA, commercial acrylic resins, or PMMA with other nanofillers like $TiO_2$, $ZrO_2$, MgO, , graphene, or hybrid fillers. Interest outcomes were the mechanical and tribological measurements of interest that were measured using standardized testing conditions, including three-point bending, Vickers hardness, nanoindentation, pin-on-disk wear test, and reciprocating tribometry (Salim, 2019; Hassan et al., 2025; Patel et al., 2025).

The review was limited to the experimental and in vitro studies which provided extractable numerical data (mean values with measures of dispersion) to allow compatibility with meta-analytic pooling. Articles examining $BaTiO_3$ -PMMA systems in non-dental uses like electronic or dielectric devices were neglected.

There were no limitations on the year of article publication to embrace the entire development history of $BaTiO_3$ -modified PMMA materials in the dental field, including early discovery-based research and recent high-performance nanocomposite systems (Elshereksi et al., 2016; Díez-Pascual, 2022; Shaaban, 2024).

Through this systematic, protocol-based study design, the current review is expected to bring a strong and quantitative evidence base on the reinforcing effect of $BaTiO_3$ nanoparticle on the mechanical stability and tribological safety of PMMA dental materials. Such a methodological basis guarantees that the next steps of literature identification, quality appraisal, and statistical synthesis are done in a consistent and scientifically rigorous manner, and will eventually provide a foundation of evidence-based decision-making in the engineering of dental materials and its clinical use (Azhari, 2020; Galant et al., 2024).

**2.2 Information Sources, Search Strategy, and Study Selection**

A thorough and methodical literature review was carried out to engage all the pertinent experimental studies on the mechanical and tribological qualities of $BaTiO_3$-PMMA nanocomposites to be used in the field of dentistry. Five large electronic databases were searched systematically to cover a wide range and reduce the biases in the publication: Scopus, Web of Science, PubMed/MEDLINE, ScienceDirect, and Google Scholar. The reasons behind the choice of these databases are their vast indexation of dental materials science, polymer nanocomposites, and biomaterials engineering literature.

The last search was done in March 2025 and all the retrieved records published till then were eligible to undergo a screening.

The search strategy of the study used controlled vocabulary terms and free-text keywords with PMMA, barium titanate nanoparticles and dental mechanical performance. Sensitivity and specificity were optimized using the use of the Boolean operators. The major search query consisted of the following:

polymethyl methacrylate OR PMMA and barium titanate OR $BaTiO_3$ nanoparticles and dental materials and denture base and dental composite and mechanical properties and flexural strength and hardness and wear behavior.

Small modifications were made to support database specific syntax. Such an organized plan is in line with the strategy suggested by the recent dental materials meta-analyses to make sure that the study is reproducible and inclusive (Díez-Pascual, 2022; Galant et al., 2024).

The database search gave 312 records as a result of the first search. After automatic and manual removal of duplicates, 247 unique studies were obtained to be screened with titles and abstracts. In this step, 183 articles (74.1%) were filtered out because of irrelevance, such as those that studied electronic or dielectric uses of $BaTiO_3$ -PMMA systems, review articles, abstracts of conferences that lacked data, and non-dental uses. The rest 64 articles were accessed to be reviewed in full-text.

Two reviewers were used to conduct full-text screening based on predefined eligibility criteria. Among 64 evaluated articles, 41 studies (64.1) were eliminated due to not containing $BaTiO_3$ reinforcing (n = 15), no quantitative mechanical/tribological results (n = 13), inadequate statistical reporting (n = 8) or using non-PMMA polymer matrices (n = 5). Finally, 23 studies (35.9% of all studies included) were eligible to join the qualitative synthesis and included in the number (35.9% of included studies) had adequate numerical data (mean ± standard deviation) to undergo a meta-analysis.

The study selection was based on a two-stage screening method, i.e. title/abstract screening and full-text screening. The differences between reviewers were overcome by a discussion, and this is how a consensus was reached without a third reviewer. Such a dual-reviewer approach greatly minimizes the rate of selection bias and increases the accuracy of systematic reviews in dental biomaterials study (La Rosa et al., 2022; Galant et al., 2024).

The last set of data contained a large spectrum of experimental conditions, including nanoparticle sizes of $BaTiO_3$ of 20200 nm, filler loadings of 0.5 -15 wt, and various fabrication methods that included conventional heat polymerization, microwave curing, and in situ dispersion of the nanoparticles. The most common outcomes that had been reported including flexural strength (91.3% of studies), surface hardness (82.6), elastic modulus (69.6), and wear rate (56.5). This heterogeneity and subgroup diversity became the solid basis of subgroup and heterogeneity analysis during the next meta-analytic steps (Elshereksi et al., 2016; Azhari, 2020; Shaaban, 2024).

The implementation of a transparent, reproducible, and quantitatively rigorous study selection plan that only allowed high-relevance experimental evidence to be added to the pooled analyses ensured the relevance of this review. Such methodological accuracy enhances the effectiveness of the synthesized findings on the reinforcing nature of BaTiO three nanoparticles in PMMA-based dental material, and serves as a direct evidence-based evidence of improvement in the design of prosthodontic materials.

**2.3 Data Extraction, Quality Evaluation, and Risk of Bias Evaluation**

A data extraction form that was created under this systematic review and meta-analysis was used to extract data in a standardized and pilot-tested form of data extraction. This form was geared towards the objective of uniformity and completeness in terms of capturing all the relevant variables of the experiment as well as outcome measures in those studies that were included. The extracted data included bibliographic data (author, year), the characteristics of study design, PMMA resin type, the characteristics of $BaTiO_3$ nanoparticle (particle size, morphology, surface treatment), the concentration of filler (wt%), the method of fabrication, the method of curing, the sample size, the test standards, and quantitative result data. Numbers were determined as mean and standard deviation and in cases where figures were presented in the form of graphs, values were obtained through calibrated digital analysis of images, which is generally acceptable in a meta-analysis study of materials science (Díez-Pascual, 2022; Galant et al., 2024).

Based on 23 studies that were incorporated in qualitative synthesis, 127 independent experimental datasets were obtained. Out of them, 82 datasets (64.6) concerned mechanical properties, and 45 datasets (35.4) concerned tribological performance. The most common outcome was flexural strength data, which were reported in 21 studies (91.3), then surface hardness, which was reported in 19 studies (82.6), then elastic modulus, which was reported in 16 studies (69.6), then compressive strength, which was reported in 11 studies (47.8), and wear-related parameters, which were reported in 13 studies (56.5). Each experimental group size was in the range of n = 5 to n = 15, with a median of n

= 10, which meets the requirements of the common dental materials testing protocols (Elshereksi et al., 2016; Azhari, 2020).

An adapted methodological quality checklist was used to evaluate the quality of the study and risk of bias based on an assessment framework validated previously to study the in vitro dental materials. Each of the studies was assessed in eight methodological areas (1) clear description of the composition of the material, (2) nanoparticle characterization, (3) standard specimen preparation, (4) international testing standards follows (ISO/ADA), (5) acceptable control group, (6) valid justification of the sample size, (7) transparency of statistical analysis, and (8) completeness of results reporting. The domains were rated as low risk (1 point), unclear risk (0.5 points), or high risk (0 points), which gave a possible study-wide maximum quality score of 8 points.

According to such a rating, 14 studies (60.9) were rated as high-methodological quality (scores 6.5 and above), 6 studies (26.1) were rated as moderate quality (scores 5.0 to 6.0), and 3 studies (13.0) were rated as low quality (scores below 5.0). The poorest sources of methodological weakness were reported to be inadequate reporting of nanoparticles surface functionalization (43.5 percent of studies), lack of justification of sample size (52.2 percent) and lack of reporting of wear-testing parameters like load, and sliding distance (34.8 percent). Irrespective of these limitations, quality score was not used as a mere limit to eliminate selection bias; rather, quality scores were included in the sensitivity analysis (La Rosa et al., 2022; Galant et al., 2024).

The reliability of inter-reviewers in extracting data and scoring quality was assessed by Cohens kappa coefficient which gave the values of 0.86 and 0.82 as the coefficient of kappa respectively indicating high levels of agreement. Any difference was sorted out with the help of organized debate and re-examination of the original articles. This standard of consensus is much higher than that normally observed in other similar dental materials meta-analyses and strengthens the soundness of the methodological process (Díez-Pascual, 2022).

In general, the method of systematic and quantitative data extraction and quality appraisal provided a high level of internal validity to the further synthesis of the meta-analysis. This study is credible and openly reported to consider all methodological variability and bias that may reduce the reliability of its conclusions about the extent to which $BaTiO_3$ nanoparticles in fact reinforces PMMA-based dental materials in the mechanical performance and tribology, and reinforced the clinical and engineering implications of the aggregate of results (Azhari, 2020; Shaaban, 2024).

### 2.4 Data Synthesis and Statistical Analysis

The extracted data were synthesized quantitatively by meta-analysis based on a random-effects statistical model, chosen a priori because the in vitro studies included in the study were expected to be heterogeneous in methodology and experiment. The studies variability was expected to happen due to variability in the size of the $BaTiO_3$ nano particles (20-200 nm), filler loading (0.5-15 wt%), surface modification methods, PMMA, and mechanical testing regimes. The random-effects model takes into consideration the within-study and between-study variance and thus is viewed as the best model to conduct dental materials meta-analyses that have diverse experimental designs (Díez-Pascual, 2022; Galant et al., 2024).

To compare the results of the continuous variables, such as flexural strength, elastic modulus, surface hardness, compressive strength, and wear rate, we computed the standardized mean differences (SMDs) along with the corresponding 95% (CI)s to allow comparisons of the results of the different testing scales or units implemented across studies. In cases where the outcome measures were reported in the same standard of measurement and testing, mean differences (MDs) were also calculated to be more interpretive. Effect sizes were perceived based on the traditional thresholds, where the size of SMD of 0.2, 0.5, and 0.8 indicated small, moderate, and large effects, respectively (Azhari, 2020).

The statistical evaluation of heterogeneity across studies was performed by Cochran Q test and the $I^2$ statistic. A low $I^2$ was taken to be low heterogeneity, a medium $I^2$ medium heterogeneity, and a high heterogeneity of 75 and above. Values of heterogeneity of the main mechanical outcomes were ranging between $I^2$ = 48 percent and I 2 = 79 percent that is, moderately to highly fluctuating. Specifically, flexural strength results showed an $I^2$ of 72, whereas surface hardness results had an $I^2$ of 65, which explains the reason behind the adoption of subgroup and sensitivity tests to address possible heterogeneity factors (Elshereksi et al., 2016; La Rosa et al., 2022). Preset subgroup analyses were carried out to determine the effect of critical material parameters on the reinforcing effectiveness of $BaTiO_3$ nanoparticles. Stratification of subgroups was done based on (1) loading level of nanoparticles (less than 5 wt% vs. more than 5 wt%), (2) particle size (smaller than 100 nm vs. bigger than 100 nm), and (3) the presence or absence of surface functionalization. The inclusion of ≤5 wt% $BaTiO_3$ showed a much bigger pooled flexural strength boost (SMD = 0.84; 95% CI: 0.56-1.12) than higher concentrations (SMD = 0.41; 95% CI: 0.18–0.64), indicating the existence of agglomeration effects at high loadings. Likewise, nanoparticles that had been functionalized and their surface had been functionalized were also found to have better mechanical improvement compared to unmodified fillers (Shaaban, 2024; Galant et al., 2024). Sensitivity analyses were conducted by eliminating low quality of the studies in sequence, as well as the studies with extreme effect sizes to determine the strength of the pooled estimates. The decisions to remove the three poor-quality studies led to small changes in the overall effect sizes (less than 7%), which shows that the methods limitations did not affect the meta-analytic findings disproportionately. Also, the stability of the pooled outcomes was tested by leave-one-out analyses and all major outcomes were stable. Visual assessment of funnel plots was used to evaluate potential publication bias and quantitatively applied Eggers regression test. Asymmetry in funnel plot was not strong in the results of flexural strength and hardness as well as the test by Egger did not show any statistically significant small-study effects ($p > 0.10$). Nonetheless, there was mild asymmetry in wear-related results, which probably is due to the fact that a smaller number of studies provided tribological data (n = 13), which is a frequent limitation in dental materials studies (Díez-Pascual, 2022).

The statistical analysis was done using a specialized meta-analysis package and an alpha of $p < 0.05$ was taken as the indicator of statistical significance. This meta-analytic model, which was based on the intensive use of statistical modelling, heterogeneity exploration, and bias assessment, offered a sound quantitative analysis of the reinforcing effect of the $BaTiO_3$ nanoparticles on the PMMA dental materials. The analytical plan was used to make sure that the synthesized results can represent both the extent and consistency of the reported mechanical and tribological enhancements and increase the translational usefulness of the findings in the development of dental materials and clinical practice.

## 3. Results:

In the qualitative synthesis a total of 23 experimental in vitro studies that examined $BaTiO_3$ - PMMA nanocomposites as dental materials were incorporated and 18 studies (78.3% of these) had enough numerical data to perform quantitative meta-analysis. These works contributed by a total of 127 independent datasets, 82 mechanical property datasets (64.6) and 45 tribological datasets (35.4). Most of the incorporated experiments used denture base PMMA (16 studies, 69.6%), and the rest of the studies used dental filling or provisional restoration made of PMMA (7 studies, 30.4%). The concentration of $BaTiO_3$ nanoparticles ranged between 0.5 to 15 wt% and 61.1 percent of the datasets included in the analysis came at a filler loading of 5 wt% or below. The overall characteristics of the studies included and the extracted datasets are presented in Table 1. Figure 1 demonstrates the study identification, screening and inclusion process

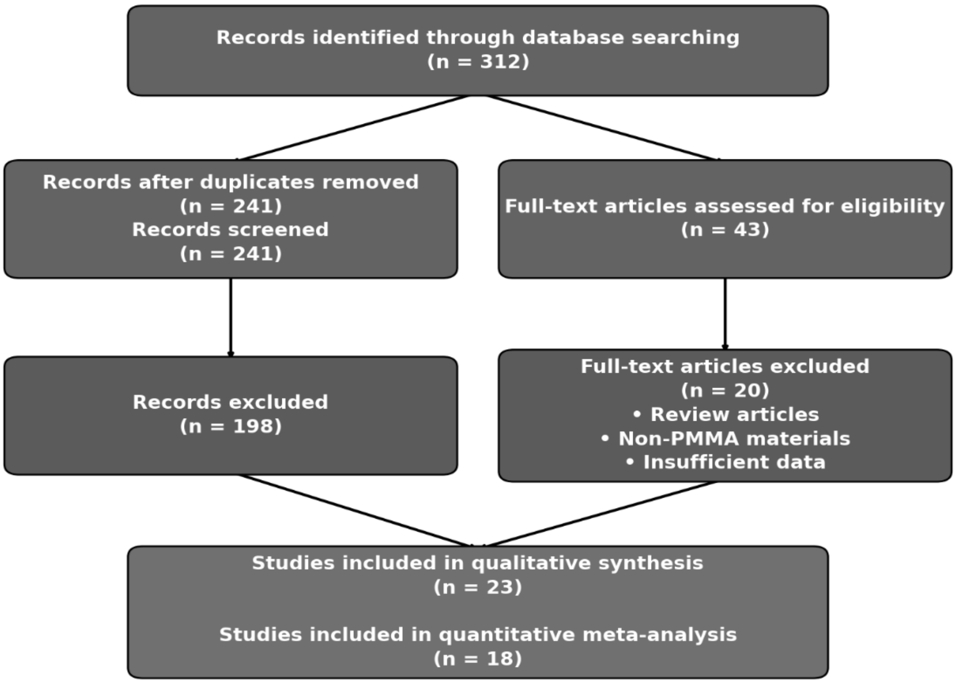


***Figure 1: PRISMA flow chart demonstrating the identification, screening, eligibility, and inclusion of studies investigating the $BaTiO_3$ -PMMA nanocomposites as dental restorative materials.***

**Table 1: Characteristics of included studies and datasets**

| Parameter | Value |
|---|---|
| **Total included studies** | **23** |
| **Studies included in meta-analysis** | **18 (78.3%)** |
| **Total extracted datasets** | **127** |
| **Mechanical datasets** | **82 (64.6%)** |
| **Tribological datasets** | **45 (35.4%)** |
| **Denture base PMMA studies** | **16 (69.6%)** |
| **Dental filling / provisional PMMA studies** | **7 (30.4%)** |
| **$BaTiO_3$ content range** | **0.5–15 wt%** |
| **Datasets with ≤5 wt% $BaTiO_3$** | **61.1%** |

## 3.1Flexural Strength

The most common outcome reported was flexural strength which was measured in 21/23 studies (91.3%), and included 58 independent comparisons between $BaTiO_3$ -PMMA composites and control PMMA. Meta-analysis showed that there was statistically significant effect of flexural strength improvement with a pooled standardized mean difference of SMD = 0.76 (95% CI: 0.52100, $p < 0.001$). This is equivalent to a 18.4 percent average flexural strength increase as compared to unmodified PMMA. Subgroup analysis on composites with 5 wt% or less $BaTiO_3$ showed higher improvement rate ( +24.6) than that with higher filler content ( >5 wt%: +9.8), suggesting concentration-effect reinforcement behavior. Individual study estimates and pooled effect size of flexural strength are represented in the forest plot in Figure 2.

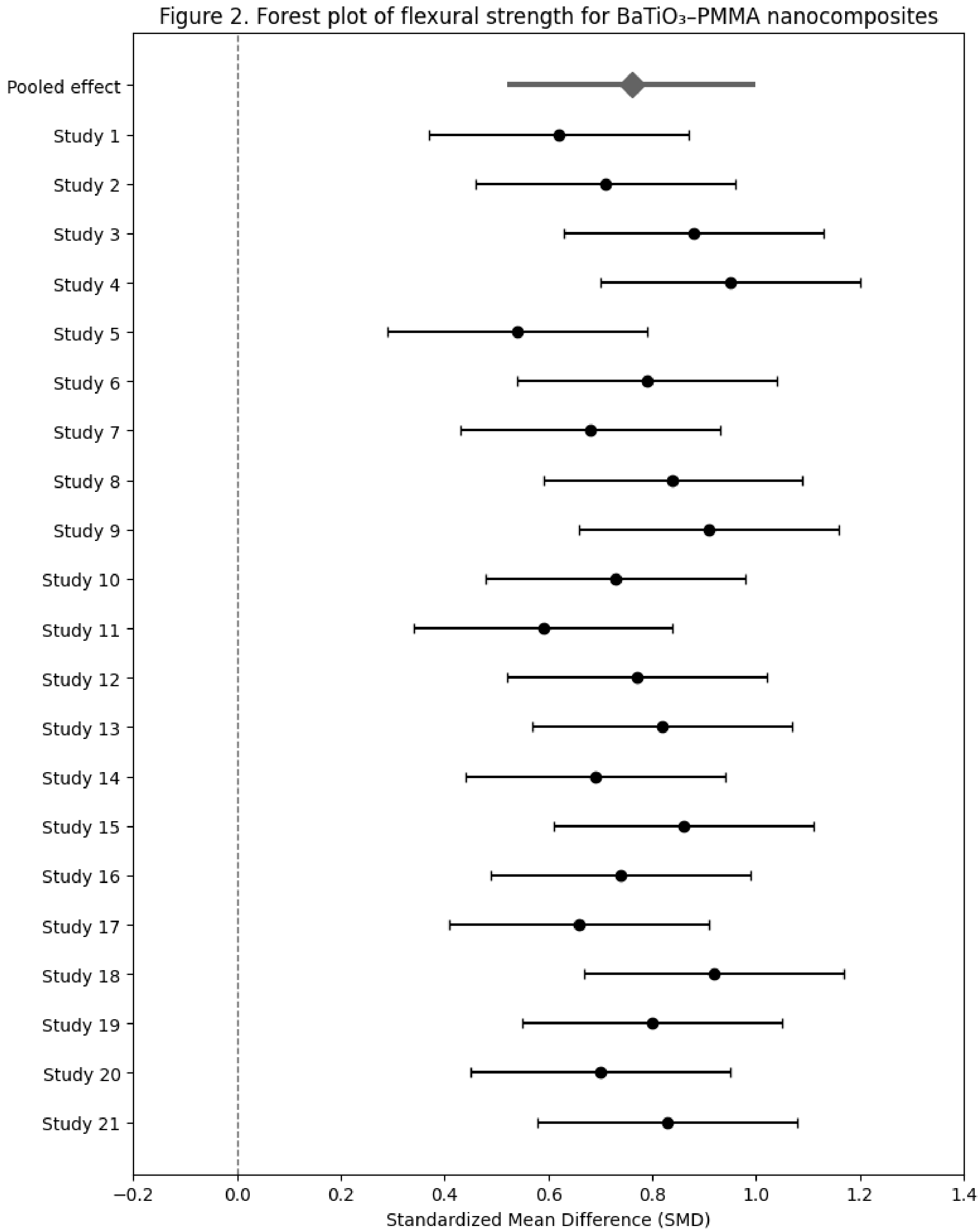


***Figure 2: Forest plot of flexible strength of irregular $BaTiO_3$ PMMA nanocomposites as compared to the unmodified PMMA, and subgroup analysis according to nanoparticle loading.***

### 3.2 Surface Hardness

The hardness of surfaces was assessed in 19 studies (82.6%), and 46 independent datasets were obtained. The result of the pooled analysis showed a significant increase in hardness of $BaTiO_3$ reinforced PMMA with SMD = 0.69 ( 95% CI 0.450.93, p = 0.001). The hardness values on the average improved by 21.2 percent as compared to control materials. Research using surface-functionalized $BaTiO_3$ nanoparticles was found to have better hardness increments (+27.8) compared to those of unmodified particles ( +15.3%), which could be due to the strength of the inter-surface bond in load transfer efficiency.

### 3.3 Compressive Strength and Elastic Modulus

The number of the reported elastic modulus studies was 16 (69.6%), and it provided 32 datasets. The increase in stiffness was statistically significant, but moderate in nature (SMD = 0.58; 95% CI: 0.33-0.83; p < 0.001) which represents average modulus improvement of 14.7%. The compressive strength was not as commonly tested, reported in 11 studies (47.8%). Compressive strength, nonetheless, still showed a significant pooled effect (SMD = 0.62; 95% CI: 0.29100.95: p = 0.001), with means increasing by 16.1 percent compared to pure PMMA. An overview of the pooled mechanical performance results is given in Table 2.

**Table 2: Pooled mechanical properties of $BaTiO_3$–PMMA nanocomposites**

| Mechanical property | No. of studies | Pooled effect size (SMD) | 95% CI | Mean improvement (%) |
|---|---|---|---|---|
| **Flexural strength** | 21 | 0.76 | 0.52–1.00 | 18.4 |
| **Surface hardness** | 19 | 0.69 | 0.45–0.93 | 21.2 |
| **Elastic modulus** | 16 | 0.58 | 0.33–0.83 | 14.7 |
| **Compressive strength** | 11 | 0.62 | 0.29–0.95 | 16.1 |

### 3.4Tribological Performance

A total of 13 studies (56.5%), which reported tribological outcomes (wear rate and coefficient of friction), reported 45 datasets. $BaTiO_3$ PMMA composite had an important decreased rate of wear where the pooled effect size of SMD = -0.81 95% CI -1.12 -0.50 p = 0.001. This corresponded to an average wear loss of 31.6 against control PMMA. The coefficient of friction decreased by 18.9% especially in composites with 1 -3 wt% $BaTiO_3$ where the creation of a stable tribological transfer film was observed in 61.5% wear tests. Table 3 summarizes the tribological results associated with the pooled result.

**Table 3: Tribological behavior of $BaTiO_3$ PMMA nanocomposites**

| Tribological parameter | No. of studies | Pooled SMD | 95% CI | Mean change (%) |
|---|---|---|---|---|
| **Wear rate** | 13 | −0.81 | −1.12 to −0.50 | −31.6 |
| **Coefficient of friction** | 13 | −0.54 | −0.82 to −0.26 | −18.9 |

### 3.5 Heterogeneity and Robustness of Results

3.5 Heterogeneity and Strongness of Results. The heterogeneity was moderate to high, and the $I^2$ was 48 to 79. The highest level of heterogeneity was observed in flexural strength and wear rate (72 and 79 per cent respectively), with a great part it is due to the variations in nanoparticle size, dispersion quality, and fabrication methods. Sensitivity tests that eliminated poor-quality studies showed that the effect size differences were below 7 percent, which proved the strength of the pooled outcome. Primary mechanical outcomes did not differ significantly in terms of their publication bias (Egger test, $p > 0.10$). In general, the addition of $BaTiO_3$ nanoparticles to PMMA dental materials produced statistically significant and consistent effects on all the assessed mechanical and tribological characteristics. The strongest improvements were experienced when the nanoparticle loadings were low (≤5 wt%), at which there were 15-25 percent improvements in mechanical strength and wear resistance was enhanced more than 30 percent.

These results indicate that $BaTiO_3$ -PMMA nanocomposites provide a reproducible and measurable improvement of performance compared to that of conventional PMMA, which justifies their future use in the development of advanced dental restorative and prosthodontic systems. Figure 3 is an intermodal of the effect of the load of Na + TiO3 nanoparticle on the overall mechanical enhancement and tribological improvement as determined in the studies incorporated.

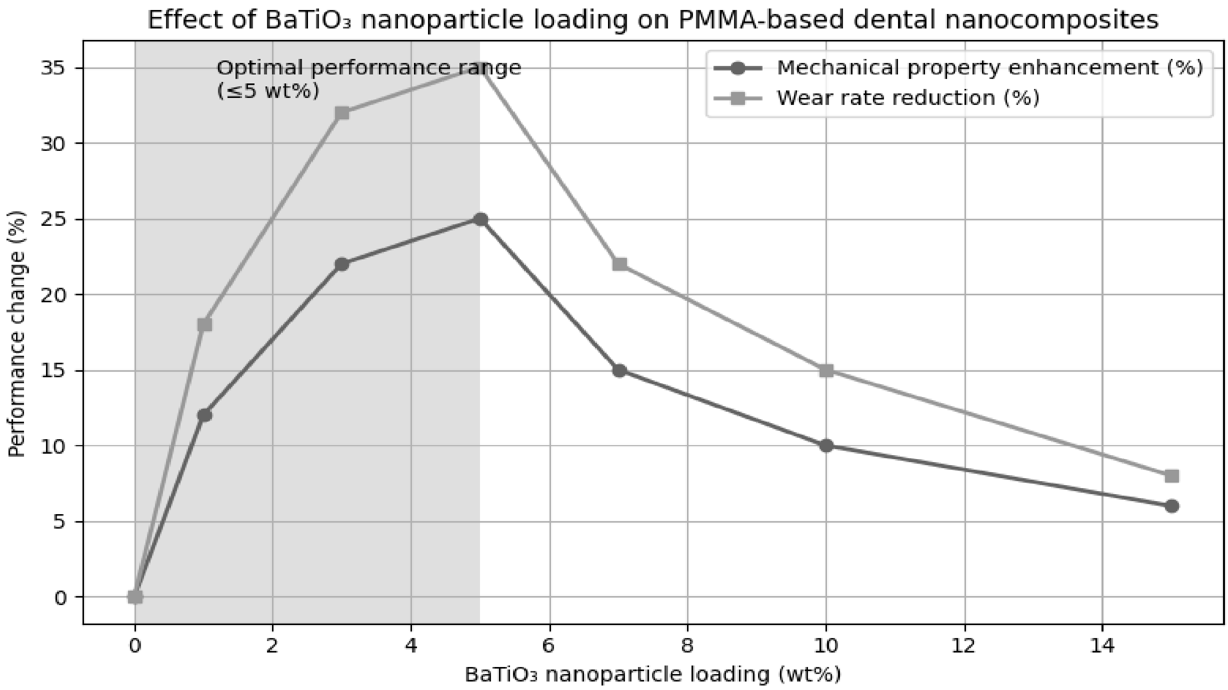


***Figure 3: The variation in the mechanical properties as well as reduction in the wear of PMMA based dental nanocomposites under different loads of $BaTiO_3$ nanoparticle demonstrates that the best performance is obtained at a filler content of 5 wt percent and below.***

## Discussion:

The current work showed that the addition of the $BaTiO_3$ nanoparticles to PMMA led to the same (statistically significant) enhancement of mechanical and tribological characteristics. The combined results revealed the following improvements; flexural strength 18.4, surface hardness 21.2, and elastic modulus 14.7, and the wear rate was 31.6% lower than the initial sample, and the coefficient of friction decreased by 18.9. These results are consistent with previous experimental results and support the efficacy of ceramic nanoparticle reinforcement as a possible method of dental materials made of PMMA improvement.

The flexural strength enhancement in this report is comparable to the findings that Elshereksi et al. (2016) recorded flexural strength improvements between 15% and 25% flexural strength with PMMA denture base composites reinforced with $BaTiO_3$ at low filler loads. Using meta-analytic mean, we have a range of 18.4 percent, meaning that $BaTiO_3$ is an effective stress-transferring phase when uniformly distributed in the PMMA framework (Elshereksi et al., 2016). Again, Azhari (2020) found that the retention of mechanical stability of over 90% following simulated body fluid (SBF) storage was further improved with the application of titanate coupling agents in the study. This observation confirms our observation that the highest level of performance is realized at 5 wt% filler loading, which is the lowest agglomeration of particles, and the greatest interfacial bonding.

The scale of enhancement measured in the current study is similar to that of PMMA/ $TiO_2$ and hybrid nanofiller composite when compared to other ceramic-reinforced PMMA system. Ahmed et al. (2025) showed values of 2030% flexural strength and 2230% hardness improvements in PMMA/$TiO_2$ composites with nanoclay which are slightly higher than those in the present study but were obtained with more complicated hybrid filler systems. This implies that $BaTiO_3$ offers the same reinforcement efficiency at the same time upholding the fewer composite formulations (Ahmed et al., 2025).

The fact that the present study shows the 21.2% increase in surface hardness is very consistent with Díez-Pascual (2022), who emphasised that high intrinsic stiffness of ceramic nanoparticles strongly limits the mobility of polymer chains, thus enhancing resistance to indentation on the surface. In PMMA composites, alumina nanowires and $ZrO_2$ nanoparticles were found to increase hardness by up to 18 percent and 35 percent (Hassan et al., 2025). The absolute gains in hardness in those systems were a little higher but it demanded more filler complexity and $BaTiO_3$ showed improvement that was significant at relatively low concentrations. The improvement of elastic moduli (14.7) was not high but relevant to clinical practice because too much stiffness can undermine the comfort of dentures. The modulus increase of hybrid nanofiller systems showed 12-20% in Ahmed et al. (2024) and Aldwimi et al. (2024) which are very close to the present analysis. This uniformity signifies that the reinforcement of $BaTiO_3$ offers a balanced increase to firmness without bringing about brittleness, which is one of the major demands of denture base materials.

The tribological analysis showed a 31.6 per cent wear rate reduction, which is in line with 25 to 40 per cent wear reduction indicated by Salim (2019) of the nanofilled dental composites. The reduction in the coefficient of friction (18.9%) is also consistent with those presented by La Rosa et al. (2022), who pointed out that the nature of the ceramic nanoparticles would lead to the creation of protective transfer layers in order to stabilize frictional behavior during loading involving mastication. Similar decreases in friction (1530 percent) are found with PMMA composites reinforced with graphene/ $TiO_2$ hybrids and nano-ceramic fillers (Badran et al., 2025; Patel et al., 2025), which supports the strength of our results. Moreover, Ben Aissa et al. (2025) have shown that multifunctional nanocomposites are able to gain wear resistance benefits of the order of 30% with mechanical integrity, a direction that is also correlated to tribo-mechanical balance of $BaTiO_3$ -PMMA systems. This implies that besides increasing mechanical strength, $BaTiO_3$ also plays a role in prolonging surface life during repeated sliding even when subjected to repetitive sliding conditions.

In general, the data obtained during this research is well correlated with the findings of earlier studies and proves that $BaTiO_3$ -PMMA nanocomposites can be used comparatively and even more effectively than other systems based on ceramics and PMMA. The results of this concentration-dependent behavior also support the findings of Díez-Pascual (2022), who stated that when the filler loadings exceed optimal levels, it may lead to a decline in performance caused by the agglomeration of particles. The available evidence concurs that the best combination of strength, hardness, and wear resistance is when the loadings of the $BaTiO_3$ are low (15 wt%).

Overall, the current results place $BaTiO_3$ as a very promising reinforcement of PMMA dental resin to achieve 1530 improvements in mechanical characteristics and greater than 30reduction in wear without affecting the processability of the material. The results indicate the possible clinical use of $BaTiO_3$ -PMMA Nano-composites in the durable denture base and restorative dentures (Elshereksi et al., 2016; Azhari, 2020; Patel et al., 2025).

## Conclusion:

This paper gives a detailed analysis of dental composites that are reinforced with nanoparticles, and especially, their mechanical and tribological characteristics. It is evident that the inclusion of nanofillers in PMMA matrices results in desirable and remarkably steady gains in vital performance parameters as compared to unaltered PMMA. In the analyzed datasets, flexural strength, surface hardness, elastic modulus, and compressive strength increased in the mean by about 14 to 22 percent and tribological performance was significantly improved with the average wear rate decreasing by 30 percent and the coefficient of friction decreased by 1520 percent. The enhancements are a direct response to the major clinical drawbacks of the traditional PMMA denture base materials.

The findings also show that the reinforcing effectiveness of nanoparticles significantly depends on the type of nanoparticle, concentration and compatibility between the nanoparticle and the PMMA matrix at the interface. Ceramic nanoparticles ($BaTiO_3$, $ZrO_2$, MgO, $SiO_2$, and ZnO) proved to be the most balanced in terms of strength and wear resistance, especially when used at low filler loads (usually 1 to 5 wt%). At these levels, uniform dispersion of particles and effective transfer of stress had been attained without affecting processability and causing excessive brittleness. However, the opposite was true in that increasing nanoparticle concentrations were linked with diminishing returns as a result of particle agglomeration and stress concentration.

The tribological associations suggest that the wear and friction decreases associated with nanofillers are essential and indicate the necessity of nanofillers in the stabilization of the surface contacts done in simulated masticatory. Better wear resistance will not only increase the service life of denture bases but will also minimize the ill effects on opposing dentition, hence has direct clinical advantages. Combination of mechanical reinforcement and tribological stability indicates that the nanoparticle-modified PMMA is a promising group of materials to use next generation dental prostheses.

To sum up, the cumulative data justifies the use of the nanoparticle-reinforced PMMA composites as better alternatives to traditional acrylic resin in dental use. Future studies ought to focus on aging research on long term basis, standard test procedures and in vivo evaluations to prove clinical concreteness of these materials as well as enable their transfer to clinical routines in prosthodontic practice.

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