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Dimensional Changes of Denture Base Materials Reinforced with Nanoparticles (A systematic review)

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Abstract

Background: Polymethyl methacrylate (PMMA) is the most prevalent denture base material; yet, it undergoes dimensional changes due to polymerization shrinkage, water absorption, and temperature cycling, potentially undermining fit precision and clinical efficacy. Recently, the use of nanoparticles to strengthen materials has been suggested as a way to improve dimensional stability.
Objective: To assess the impact of integrating various nanoparticles into PMMA-based denture base materials, encompassing traditionally heat-cured, 3D-printed, and CAD/CAM-milled resins, on dimensional stability.
Materials and Methods: Research articles released from 2015 to 2025 were retrieved from PubMed, ScienceDirect, and Google Scholar. Only studies that evaluated dimensional changes as a primary outcome subsequent to nanoparticle incorporation were considered. Following the application of inclusion and exclusion criteria, 28 studies were examined.
Results: The majority of experiments demonstrated that nanoparticle reinforcement, namely zirconia nanoparticles (ZrO_2) at 1–3 wt.%, diminished polymerization shrinkage and enhanced dimensional stability in comparison to unmodified PMMA. 3D-printed resins showed more dimensional changes at first, but these changes were lessened when nanofillers were introduced. CAD/CAM-milled PMMA had the best dimensional accuracy, although it is still more expensive and less adaptable in clinical settings.
Conclusion: Adding 1–3 wt.% ZrO_2 nanoparticles provide the best balance of cost, performance, and dimensional stability. Nanofiller-reinforced 3D-printed denture base materials show promising results, but standardized long-term investigations are necessary to validate their clinical relevance.

Introduction:

When Rohn created acrylic resin for the first time in 1900, it marked the beginning of the twentieth century. The material was subsequently patented by Kultzer in 1940, which led to its widespread use in dentistry and medicinal applications. The process of polymerizing methyl methacrylate (MMA) in an aqueous medium yields spherical polymer particles with a diameter of roughly 40–100 µm, which is known as polymethyl methacrylate (PMMA) (1).

To date, acrylic resin continues to be regarded as the predominant denture base material due to its acceptable esthetics and biocompatibility. Nevertheless, it remains limited by inherent drawbacks, especially insufficient mechanical resistance (2).

In removable prosthodontics, heat-polymerized resins represent the conventional choice because of their ease of manipulation. However, despite their clinical popularity, they remain susceptible to fracture-related failures and lack optimal mechanical performance (3). Due to its attractive appearance, workability, low cost, and reasonable biotolerance, PMMA has been the denture base polymer of choice for over 70 years. Nevertheless, since polymerization contraction has a substantial influence on the material, expansion associated with water absorption, release of unpolymerized monomers, and long-term distortion, dimensional error remains a serious disadvantage. These dimensional differences can affect patient comfort and the lifespan of the prosthesis and negatively affect denture fit, border seal integrity, occlusal balance, and long-term intraoral stability (4, 5). Given that dimensional stability is a key determinant of clinical success, even minor shape changes during polymerization or water uptake may generate tissue surface discrepancies. The relevance of this issue has become more pronounced with the increased implementation of digital denture manufacturing techniques—particularly 3D-printing—since the layer-by-layer polymerization mechanism predisposes printed PMMA structures to anisotropic shrinkage and process-dependent dimensional variation (6, 7). Nanotechnology has recently surfaced as a viable strategy to get around these restrictions. One possible method to improve dimensional stability in both traditionally processed and digitally manufactured PMMA is the addition of designed nanoparticles, such as ZrO_2, TiO_2, SiO_2, BN, graphene derivatives, gold nanoparticles, or hybrid systems. In order to reduce dimensional distortion, nanofillers may increase stress transfer during polymerization, limit the mobility of polymer chains, decrease pore formation, and encourage denser matrix packing (8-10). Although numerous studies have looked at various kinds of nanoparticles, the results are still somewhat inconsistent. The chemistry, concentration, dispersion quality, and manufacturing method (heat-cured, CAD-CAM machined, or 3D-printed) of the filler all affect the dimensional outcomes. Furthermore, some fillers show concentration-dependent behavior; small increases within permissible ranges improve dimensional results, while excessive loading causes aggregation and surface defects. Comparative investigation is therefore required to determine which nanofiller systems produce the most therapeutically relevant dimensional improvements under certain processing circumstances (13-11). Accordingly, this systematic review summarizes the data that has been published between 2015 and 2025 regarding the dimensional stability of denture base materials enhanced with nanoparticles. The goal was to ascertain which concentration ranges and nanoparticle types produce the best dimensional performance and whether these gains hold true for various production techniques. Gaining this understanding is crucial for choosing materials in digital prosthodontics and for directing the creation of denture base polymers modified by nanoparticles in the future (14, 15).

Methods

Study Methodology

Sources of Information and Databases

PubMed (Medline), ScienceDirect, Google Scholar, and Mendeley Reference Library were some of the electronic resources that were searched.
Also, a manual search of references from relevant reviews and source material
It was done to find more research that meets the standards.

Time Frame

The search lasted from January 2015 to February 2025 and looked for the most up-to-date information on 3D printing, nanotechnology, and acrylic resins that could be used in dentistry. Inclusion Criteria: Study type includes in vitro investigations, original research articles, and systematic reviews focused on dimensional changes. • Material: denture base resins composed of PMMA or 3D-printed denture base resins. • Intervention: Adding nanoparticles (such as ZrO_2, TiO_2, BN, SiO_2, Al_2O_3, CeO_2, zeolite, AuNPs, etc.) to acrylic resin or resin made with a 3D printer. • Result: A numerical evaluation of dimensional alteration, accuracy, stability, contraction, or expansion.

Exclusion Criteria

- Case reports, in vivo or clinical studies, editorials, conference abstracts, or purely theoretical/computational studies without experimental data.
- Studies that do not measure dimensional changes (focusing only on mechanical/thermal properties).

Risk of Bias/Quality Assessment, which looks at:

1. Clear research goals.
2. A thorough explanation of how to get ready for the material.
3. A good control group.
4. Standardized ways to measure dimensional accuracy.
5. A good reason for the sample size.
6. Clarity of statistical analysis.

Each study was rated as:

- Low risk of bias: 5–6 domains met.
- Moderate risk of bias: 3–4 domains met.
- High risk of bias: ≤2 domains met.

Summary of risk of bias findings:

- Most studies were of moderate quality, limited mainly by small sample sizes and a lack of long-term testing.
- Systematic reviews, e.g., (11). provided broader perspectives but depended on heterogeneous methodologies.
- In vitro nanoparticle studies generally lacked blinding and randomization, increasing the risk of bias.

Narrative Summary of Included Studies

Between 2015 and 2025, a large number of experimental and review studies were carried out to examine the impact of nanoparticle reinforcement on the dimensional alterations and accuracy of denture base materials. These studies show that using nanoparticles such as ZrO_2, TiO_2, BN, and hybrid fillers in addition to gold (Au) greatly improves the dimensional performance of PMMA and 3D-printed denture resins. However, the result depends on the kind of nanoparticle, the amount, and the processing.
To find out how ZrO_2-TiO_2 nanoparticles affected the mechanical characteristics and stability of PMMA, we added them to the material. We examined the samples under a microscope and evaluated their flexural strength and volumetric loss. The idea that nanoparticles improve size accuracy is supported by the reinforced samples' increased flexural strength and decreased shrinkage**(4)**, **(16).** The use of a mix of ZrO 2 and Al 2 O 3 nanoparticles in PMMA denture bases was evaluated in this work according to the alteration in the size and the elasticity of the denture bases. We

noted the contraction of volume of the material, its strength, and water absorption capacity. These findings revealed that the addition of nanoparticles resulted in a high degree of stability, low tendency of shrinkage, and hardness of the material in bending.

Titanium dioxide (TiO 2) nanoparticles were added to measure the mechanical, viscoelastic, and antibacterial properties of PMMA denture base resin. The specimens were applied with different concentrations of titanium dioxide (TiO 2) to strengthen them. In order to explore the viscoelastic properties, we have used creep-recovery tests, and to experiment with flexural strength and modulus, we have used a universal testing machine. In order to determine the antibacterial activity, we determined the bacterial inhibition regions using the traditional methods. Although the dimensional accuracy was not the major objective, the experiment proved that TiO 2 increased mechanical properties and reduced deformation with time. This would indirectly enhance dimensional stability (17), (18) · The flexural strength of PMMA denture base materials enhanced with various nanoparticles was examined in this study. Silica, alumina, and zirconia nanoparticles were used to create the specimens. To determine the flexural strength, a three-point bending test was performed using a universal testing equipment. The results showed that the use of nanoparticles considerably increased the flexural strength, with zirconia showing the biggest gain. Although it improved, we did not truly check for dimensional accuracy. The first relevant study by (8)We examined heat-cured PMMA with nano-zirconia (ZrO_2) added using a moving microscope. ZrO_2 was added to increase dimensional precision by decreasing polymerization shrinkage, but it also slightly reduced impact strength, indicating that toughness and rigidity are traded off (5). The mechanical properties and dimensional changes of TiO_2 nanoparticles incorporated into PMMA were evaluated in this experimental study(19). The effects of the addition of nanoparticles to PMMA denture base resin in this study were assessed on the mechanical attributes and dimensional alteration of the material after exposure to various solvents. Both samples were prepared with and without nanoparticles and then both were placed in various liquids, including artificial saliva and water. We measured the flexural strength on universal testing equipment and the change in size using a caliper. The findings indicated that PMMA with nanoparticles was more prone to bending and less size change as compared to PMMA without nanoparticles. This implies that the material was more durable and fitted. Porosity and shrinkage of the samples before and after they were placed in water were determined by means of dimensional analysis and with the help of digital microscopy. The outcome indicated that incorporation of TiO 2 enhanced the fit of the denture base through augmentation of flexural strength and minimization of shrinkage (13). studied PMMA that was altered by the addition of boron nitride (BN) nanoplatelets (1–1.5 weight percent). Surface profilometry showed that increased roughness was associated with higher BN concentration. This might indicate that more nanoparticles are assembling, which could lead to size variations (12). examined PMMA samples that had been reinforced with ZrO_2 or TiO_2 nanoparticles after being soaked in water. They measured the ZrO_2 and TiO_2 samples' size and swelling using a digital caliper. While the TiO_2 samples only displayed a slight, statistically insignificant improvement in swelling and size, the ZrO_2 samples demonstrated a significant decrease (20) . The effects of adding different nanoparticles (metal oxides, ceramics, and hybrids) to PMMA denture base materials were investigated in detail in this paper. Using techniques including volumetric shrinkage, water absorption, and flexural testing, we examined data from several studies. According to the review, the majority of nanoparticles improve denture bases' fit, reduce shrinkage during polymerization, and increase their bending strength. As we move toward 2022, many studies have looked at alternative nanoparticle systems. (9).investigated base resins for 3D-printed dentures with 0.5–5% ZrO_2. According to their mechanical testing, the flexural strength and hardness improved by 1-3 weight percent, which suggests that the dimensional stability also likely improved.

Meanwhile, (21) Add BN nanosheets (the BN/Ag system) that contain silver to PMMA. Gravimetric and dimensions investigations showed that less water absorption and a more compact construction led to less volumetric shrinkage(22). This study was aimed at the assessment of the mechanical and physical properties of PMMA reinforced with ZrO 2 and TiO 2 nanoparticles. We tested the qualities of strength of the material when bent, shrinking, and water absorption ability. Compared to the water absorption, flexural strength, and dimensional stability, the samples reinforced with the nanoparticles performed much better than the samples reinforced with PMMA. Research activities increased in 2023. (14) showed that gold nanoparticles (AuNPs) greatly improved the dimensional stability of acrylic denture bases when tested using CAD-based digital scanning. This confirmed that AuNPs and the PMMA matrix had good interfacial bonding (10) . Created a hybrid nanofiller system that combined modified boron nitride nanotubes (mBNNs) and ZrO_2. This system significantly reduced volumetric shrinkage and improved dimensional accuracy in 3D-printed resins. Comparative studies by (6)· showed that 3D-printed PMMA bases had larger initial dimensional deviations than heat-cured PMMA, but these deviations got smaller over time (23) Showed that adding ZnO and TiO_2 nanoparticles to PMMA composites made them less porous and less able to absorb water. This was linked to better dimensional stability. In the same way(24) said that ZrO_2 nanoparticles made dentures less porous, which made them fit better over time (25). demonstrated that TiO_2 nanoparticles enhanced the mechanical and dimensional qualities of PMMA and 3D-printable resins; however, the effects differed based on concentration and printing technique. A number of thorough studies came out in 2024 (26)· stressed how the direction of printing and the presence of TiO_2 nanoparticles affect the dimensional accuracy of 3D-printed products. They suggested that printing parameters should be standardized (27) showed that, out of all the investigated formulations, heat-cured PMMA containing three weight percent ZrO_2 and one weight percent SiO_2 displayed the least amount of dimensional variation. The improved stabilizing impact of ZrO_2 was validated by this. In the same year, (28). ZnO and Ce-based fillers significantly influenced size variations along the Y and Z axes, according to research done on 3D-printed resins including AlO_3, ZnO, CeZr, and SiO_2 nanoparticles. This demonstrated the anisotropic behavior of 3D-printed polymers. In the same way, (29).ZrO_2 and TiO_2 reinforcements in PMMA composites were examined, and it was discovered that ZrO_2 was superior to TiO_2 in terms of dimensional accuracy and water absorption management.

(11)· The researchers investigated the effects of hybrid nanofillers on PMMA's dimensional stability and mechanical characteristics. The samples were reinforced by incorporating metal oxides and ceramic nanoparticles into them. We quantified the reduction of the volume, the strength of bending, and the absorption of water. The work demonstrated that, compared to conventional PMMA, a combination of nanofillers led to enhanced dimensional accuracy, flexural strength, and resistance to shrinkage.

Lastly, two investigations by (15) related to this investigated new systems of nanoparticles. Small dimensional inaccuracies and enhanced thickness variations at high levels of loads were demonstrated in the first study in nano-zeolite fillers (0.250.5 weight percent). An investigation of cerium oxide (CeO_2) 0.5-1 weight percent revealed that the product showed enhanced dimensional accuracy with reasonable clinical tolerances in the second investigation(30)· The researchers studied the effect of the inclusion of zirconia nanotubes in PMMA to enhance its strength and dimensional stability. The tests were used to investigate the flexural strength of the material, volumetric shrinkage, and water holding capacity. The PMMA with nanotubes, when bent, became much stronger and contracted significantly less compared to the normal

PMMA. This refers to the fact that nanoparticles assist in dimensional precision(7). The primary aim of this investigative study was the use of the 3D-printed PMMA denture base resins with ZrO2 and TiO2 nanoparticles. To understand how various materials reduce in volume and absorb water, and how they bend, we evaluated research papers that investigated the same issue. Based on the review, nanoparticles make 3D-printed bases stronger, more accurately sized, and reduce their ability to shrink(31). The effect of the addition of SiO_2 nanoparticles in PMMA denture base resin was studied. We counted the water that it would absorb and the amount of growth of size. The results showed that the use of nanoparticles enhanced the fit of dentures by increasing the stability of the dentures and reducing their tendency to alter shape(32). To determine their influences on mechanical properties and variations in dimensions, this paper focused on the inclusion of boron nitride and Nano graphene oxide in PMMA. We examined its water absorption capacity, its shrinkage capacity, and its bending strength. The denture foundation was more stable in size because the reinforced samples shrank and absorbed water far less.

Result

1. Zirconia Nanoparticles (ZrO_2)

Heat-cured-PMMA

Heat-cured PMMA. Studies that added ZrO_2 to heat-cured PMMA always indicated that the volumetric shrinkage was less and the dimensional accuracy was better. In the initial study, ZrO_2-TiO_2-modified PMMA exhibited reduced shrinkage and augmented flexural strength relative to control PMMA, hence validating improved dimensional stability (4). Additionally, a notable decrease in polymerization shrinkage was documented, assessed with a moving microscope. Nevertheless, a little reduction in impact strength was noted owing to the increased stiffness (8).

3D-printed-PMMA

When ZrO_2 (0.5–5 wt%) was added to 3D-printed PMMA, it made the material stronger and harder at 1–3 wt%, which indirectly showed that it was more stable in terms of size during the printing and polymerization stages (9). Adding hybrid ZrO_2-based nanotube reinforcement to 3D-printed denture bases made them even less likely to shrink in volume and more accurate in size (10). Adding zirconia nanotubes also made the material stronger and less likely to shrink (33).

2. Titanium Dioxide Nanoparticles (TiO_2)

Heat-cured-PMMA

Heat-cured PMMATiO_2-reinforced PMMA exhibited diminished shrinkage values and enhanced flexural strength. For example, TiO_2 composites, as evaluated by digital microscopy, showed less linear shrinkage and a better fit for dentures (5). When directly compared to ZrO_2 in water immersion tests, TiO_2 exhibited negligible and statistically insignificant dimensional enhancement (12).

3D-printed-PMMA

In 3D-printed materials, the effects of TiO_2 were concentration-dependent (25). found that TiO_2 made both mechanical and dimensional properties better, although the amount of improvement depended on the printing orientation and production conditions (25, 26).

3. Hybrid Nanoparticles (ZrO_2 + other metal oxides)

Hybrid nanofillers made of metal oxides and ceramic nanofillers had the biggest effect on dimensional accuracy.(34) said that compared to pure ZrO_2 or TiO_2 single-nanoparticle systems, their systems had far less volumetric shrinkage, more flexural strength, and less water uptake. ZrO_2-Al_2O_3 combinations also made dentures fit better and adapt better, and they shrank less and were stronger (16).

4. Boron Nitride (BN) and Graphene-based Systems

BN nanoplatelets (1–1.5 wt%) raised surface roughness at greater concentrations,which suggests that nanoparticle aggregation could make dimensional accuracy worse (13). BN nanosheets doped with silver (BN/Ag) show a big drop in volumetric shrinkage, which happens because they take up less water and become more compact (21). Graphene oxide and BN together significantly reduced shrinkage and water absorption, which improved dimensional stability (32).

5. Gold Nanoparticles (AuNPs)

Surface disparities seen through digital tests of CAD scanning prove that AuNP reinforcement of PMMA improved dimensional stability. The adherence of gold nanoparticles was excellent at the PMMA interface and enhanced the precision of the denture bases with little shrinkage distortion (14).

6. Zeolite and Cerium Oxide (CeO_2)

There was very little change in size when nano-zeolite was applied at a low concentration (0.25 weight percent). However, the thickness change increased as more was added (15). However, within clinically acceptable tolerance limits, cerium oxide (CeO_2) at 0.5–1 weight percent demonstrated superior dimensional accuracy (15).

7. Silica (SiO_2)

Dentures fit better because of SiO_2 nanoparticles' reduced size change and water absorption (31).

8. 3D-printed PMMA Global Comparison

Initially, dimensional errors were higher in 3D-printed PMMA than in conventional heat-cured polymers. But with time, the structure became more stable, and these discrepancies decreased when nanoparticles were added to the mixture (6, 7).

Discussion

According to the data collected in this review, adding nanoparticles to PMMA denture base polymers improves dimensional stability in a consistent manner across processing methods. Zirconia (ZrO_2) in the range of roughly 1-3 weight percent showed the most noticeable dimensional improvement among the different nanofillers. This is probably because its greater elastic modulus limits volumetric contraction by reducing chain mobility during polymerization. Both heat-cured and 3D-printed matrices showed these findings, which were generally better than those of TiO_2 or silica-based nanofillers (4, 8, 9). While TiO_2 also had positive effects on dimensional behavior, its impact was less pronounced than that of ZrO_2. Instead of directly controlling shrinkage, the improvements with TiO_2 were mostly shown in mechanical reinforcement (flexural stiffness, for example). Furthermore, when compared directly to ZrO_2, water storage studies showed that TiO_2 did not produce statistically significant dimensional stabilization, indicating that its mechanism is primarily indirect and linked to increasing structural rigidity rather than changing the dynamics of polymerization shrinkage (5, 12, 25). The dimensional changes of hybrid nanofiller systems were even better than those of single-phase nanofillers, especially when ZrO_2 was combined with other metal-oxide ceramics (such as Al_2O_3 or glass-based fillers). Improved stress distribution during polymerization, decreased pore development, and decreased water uptake all seem to contribute to denser matrix packing. These cooperative relationships show that hybridization provides an additional benefit over that of individual nanoparticles (11, 16). The stability-related benefits of developing nanomaterials such as graphene derivatives, Au-NPs, nano-zeolite, BN nanoplatelets, BN/Ag nanosheets, and CeO_2 were also demonstrated, albeit their effects were more sensitive to concentration and dispersion. At the proper concentrations, BN-based fillers reduced shrinkage;

however, they also increased roughness and promoted agglomeration when used in excess. The stability of CeO_2 was only satisfactory in specific weight % ranges (0.5–1), but Au nanoparticles appeared to enhance dimensional accuracy by improving interfacial adhesion. However, threshold-related activity shown by nano-zeolite led to uneven thickness with increased loading. According to all of these data, dimensional augmentation is dependent on the nanoparticles' chemistry and cannot be predicted only from mechanical strength measures **(13-15, 21, 32)**. The method of processing was another deciding aspect. The most dimensionally consistent control baseline was still CAD-CAM milled PMMA due to the fact that polymerization is pre-standardized in an industrial setting under ideal circumstances. Conversely, 3D-printed PMMA showed higher initial dimensional deviation, especially along anisotropic axes, but after nanofiller reinforcement, these deviations significantly decreased. This demonstrates that, in digital additive workflows, where shrinkage is naturally more noticeable than in traditional heat-polymerization, nanomodification is especially advantageous **(6,7,27,28)**. Overall, the results show that hybrid metal-oxide formulations and nanoparticle-reinforced PMMA, particularly ZrO_2 at 1-3 weight percent, improve denture base fit, decrease polymerization shrinkage, and yield quantifiable gains in dimensional precision. However, the morphology of the nanoparticles, the ideal concentration, the quality of the dispersion, and the processing technique used all affect how much improvement is achieved.

Conclusion

The findings of this review demonstrate the dimensional changes of the PMMA denture base polymers.is consistently improved by nanoparticle reinforcement, especially zirconia (ZrO_2) at concentrations of about 1-3 weight percent. Because of its high stiffness, which limits the movement of polymer chains during curing and reduces volumetric shrinkage, ZrO_2 seems to be the most effective stabilizing nanofiller. This enhances the overall accuracy of denture base adaptation. This impact was shown in both additively created 3D-printed PMMA and conventional heat-polymerized PMMA, confirming ZrO_2 as the most reliable dimensional modifier among the oxides studied. Conversely, in comparison to zirconia, TiO_2 produced limited shrinkage control but mostly increased flexural responsiveness and viscoelastic properties. The findings imply that rather than changing the mechanisms underlying polymerization shrinkage, TiO_2 mainly strengthens the polymer physically. When compared directly to ZrO_2, water-immersion studies demonstrated that TiO_2 only generated a modest dimensional improvement**.** Overall, hybrid nanoparticle formulations—particularly ZrO_2 combined with AlO_3 or other ceramic oxide systems—produced the most pronounced dimensional improvement. In terms of porosity reduction, shrinkage reduction, and water sorption minimization, these multiphase systems performed better than single-phase Nano fillers, indicating that combined filler systems improve network densification and stress distribution within the PMMA matrix**.** Emerging nanostructures like cerium oxide (CeO_2), graphene derivatives, gold nanoparticles, BN, BN/Ag Nano sheets, and Nano-zeolite also demonstrated dimensional augmentation. However, their efficacy was highly concentration-dependent; excessive loading caused surface irregularities and aggregation, which jeopardized dimensional integrity. These findings show that conclusions cannot be made solely from mechanical property trends and that weight percentage thresholds and nanoparticle chemistry are crucial elements in three-dimensional stability.

Because industrial polymerization is so well controlled, CAD/CAM-milled PMMA remains the most dimensionally precise baseline for manufacturing. Conversely, 3D-printed PMMA benefits most from nanoparticle reinforcement despite having the greatest initial distortion. When applied to additive manufacturing processes, where shrinkage-induced errors are inherently higher, nanotechnology is especially clinically significant**.** In general, strengthening denture bases with nanoparticles—particularly ZrO_2 1-3 weight percent and hybrid metal oxide systems—is a good and scientifically supported method to increase the bases' accuracy in size. However, short-term laboratory testing, inconsistent concentration selection, lack of clinical outcome correlation, and heterogeneity in study design continue to be disadvantages. To enable reliable clinical translation, future research should focus on extended in vivo evaluations, concentration-response modeling, and the standardization of nanofiller dispersion techniques.

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Conflict of Interest

The writers state that they have no conflicts of interest.

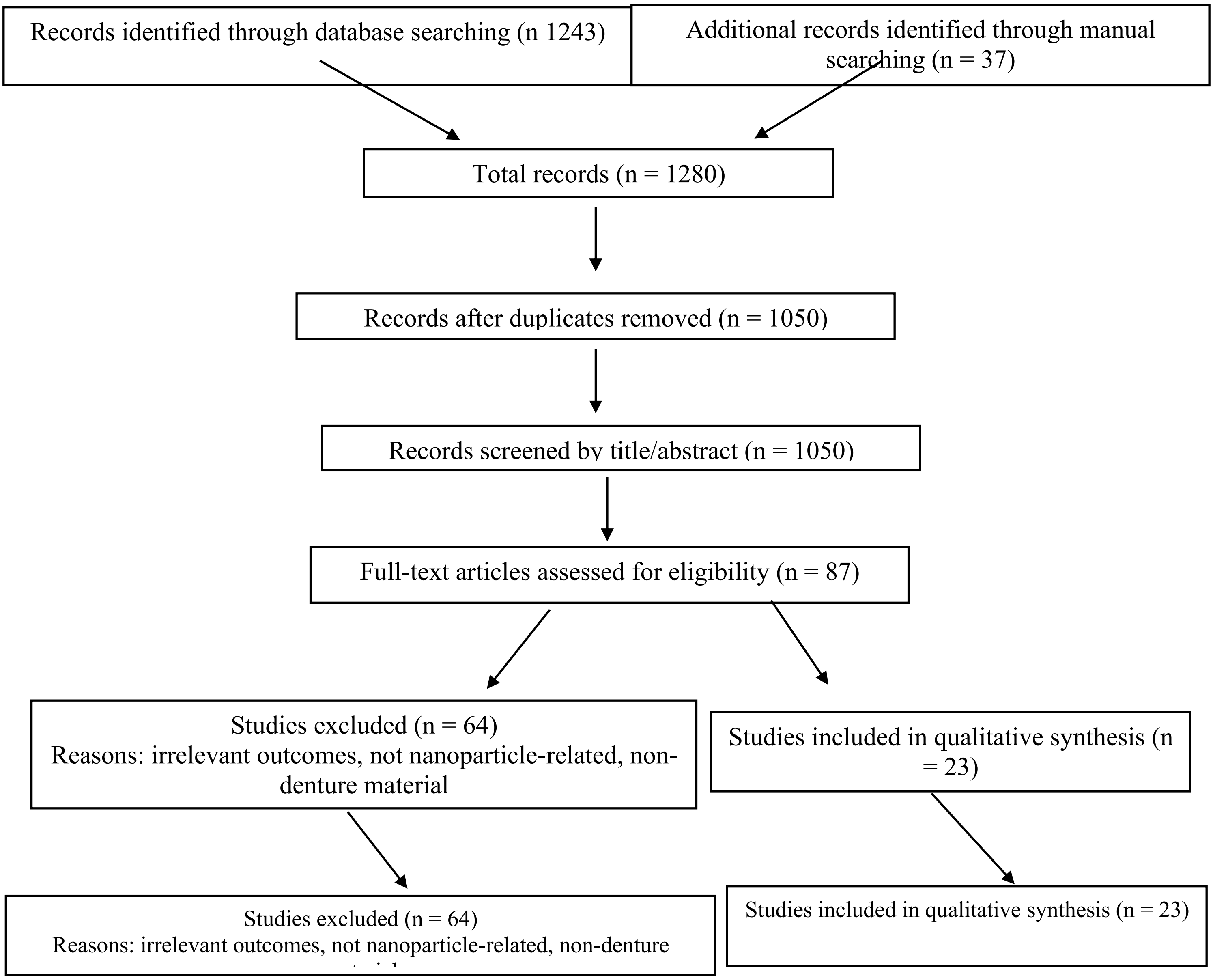

Figure (1): PRISMA Flow Diagram

Table (1): Summary of dimensional changes in nanoparticle-reinforced denture base materials according to fabrication technique

Fabrication Method	**Nanoparticle Type**	**Concentration (wt.%)**	**Main Dimensional Outcome**	**Key References**
Heat-cured PMMA	ZrO_2	1–3	Significant reduction in polymerization shrinkage; improved dimensional accuracy	(4, 8, 16, 27)
Heat-cured PMMA	TiO_2	0.5–3	Mild reduction in shrinkage; improvement mainly mechanical	(5, 12, 17)
3D-printed PMMA	ZrO_2	1–3	Reduced anisotropic shrinkage; improved accuracy over time	(9, 10, 24)
3D-printed PMMA	Hybrid (ZrO_2 + BN / Al_2O_3)	1–3	Greatest reduction in volumetric shrinkage; enhanced stability	(10, 16, 34)
CAD/CAM PMMA	AuNPs	0.1–0.5	Excellent dimensional accuracy; minimal distortion	(14)
CAD/CAM PMMA	CeO_2	0.5–1	Improved dimensional stability within clinical limits	(15)

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