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# Schematic Evaluation of Biomechanical Performance of Hybrid Composite Materials in Removable Prosthodontics

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## ABSTRACT

**Background:** Removable prosthodontics is largely dependent on the denture-base materials, where they can withstand the functional loading, fracture, and structural integrity throughout the period of clinical service. The objective of the systematic review and meta-analysis was to analyze the biomechanical performance of hybrid composite materials for removable prosthodontics, including fracture resistance and flexural strength.

**Methods:** The search was conducted across PubMed, Scopus, Web of Science, and Google Scholar, with publication dates up to May 2025. In vitro experimental and comparative studies that evaluated hybrid composite-reinforced and unreinforced denture bases were selected. Two reviewers screened titles, abstracts, and full texts, and disagreements were sorted out by a third reviewer. The assessment of risk of bias was done using Joanna Briggs Institute (JBI) Critical Appraisal Checklist, and certainty of evidence was measured using the GRADE.

**Results:** A total of twelve studies were included. The reinforced denture bases had a great effect on the increase of load-to-failure (SMD = 12.52; 95% CI: 3.56- 21.47; $I^2$ = 95%). The heterogeneity was too high, and flexural strength was not significantly pooled to show any pooled difference (SMD = 27.32; 95% CI: -27.16 to 81.81; $I^2$ = 97%). Subgroup analyses indicated that metal mesh and fiber reinforcements improved the fracture resistance, and flexural strength improvements were inconsistent.

**Conclusion:** Hybrid composite reinforcement enhances fracture resistance and fatigue behavior, but flexural strength performance is different depending on the reinforcement type, material processing, and specimen. To maximize clinical relevance, standardized research is required.

**Keywords:** Prosthodontics, Denture, Partial, Removable, Dental Materials, Biocompatible Materials, Nanocomposite, Denture Bases, Biomechanical Phenomena.

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## INTRODUCTION

Removable prosthodontics is largely dependent on the denture-base materials, where they are able to withstand the functional loading, fracture, and structural integrity throughout the period of clinical service [1]. Traditional poly(methyl methacrylate) has been popular in its low cost, biocompatibility, and versatility in esthetic capabilities, but has the disadvantage of being brittle by nature, having a low impact strength, and being prone to fractures along the midline when subjected to repetitive masticatory loads [2]. These restrictions have prompted the continuous quest for materials that can be used to improve mechanical stability, reduce catastrophic failure, and increase patient satisfaction [3]. Hybrid composite systems have become a topic of interest in recent years due to the potential of these systems to enhance load distribution, fatigue performance, and the overall biomechanical performance [4].

Mixed composite materials polymeric resin-based and fibrous, particulate, or nanomaterial reinforcing types are a potential solution to providing compensation for the mechanical shortcomings of conventional denture bases. Addition of glass or polyethylene fibers, ceramic nanoparticles, metal oxides, carbon-based nanostructures, or layered mesh systems has been found to have the potential to increase flexural strength, fracture toughness, and crack propagation resistance [5,6]. The increased range of reinforcement strategies has been extended through the further development of CAD/CAM resins and 3D-printed hybrid materials. These technologies allow a more homogenous distribution of fillers, lower porosity, and better interfacial bonding, and contribute to the increase of structural stability under functional loading [7]. The multicomponent reinforcement strategies also seem to provide more biomechanical advantage than the single-phase modifications through the integration of matrix toughening, crack-bridging, and stress-redistribution mechanisms [8].

The evolving interest notwithstanding, the existing evidence base is very heterogeneous. Research varies significantly in the type of reinforcement, filler concentration, fiber direction, and location within the denture base [9]. Further variation is due to variation in fabrication techniques, aging, thermocycling, and mechanical tests like 3-point bending, impact strength analysis, and load-to-failure tests [10]. The differences between sample geometry, polymerization process, and surface treatments are some other causes of inconsistencies in reported results. This heterogeneity complicates the identification of the most efficient reinforcement strategies, and it also makes it difficult to do comparisons between studies that have assessed biomechanical performance [11].

The objective of the systematic review and meta-analysis was to analyze the biomechanical performance of hybrid composite materials for removable prosthodontics, including fracture resistance, and flexural strength. It was also interested in determining the methodological quality and risk of included studies. The data is also anticipated to help dental professionals, scientists, and material manufacturers to find consistent reinforcement methods and inform the development of stronger and more clinically resilient denture-base materials.

## METHODS

This systematic review and meta-analysis followed the PRISMA 2020 guidelines [12]. In May 2025, PubMed, Scopus, Web of Science, and Google Scholar were searched. The search terms were MeSH terms and free-text words, including denture base resin, hybrid composite, fiber-reinforcement, and PMMA, flexural strength, fracture resistance, and load-to-failure. It was performed with the help of Boolean operators (AND, OR), and reference lists of the included studies were screened manually to find other eligible articles.

A representative search string was: (("hybrid composite" OR "fiber-reinforced composite" OR "nanocomposite" OR "reinforced acrylic") AND ("denture base" OR "removable prosthesis" OR "complete denture" OR "PMMA") AND ("flexural strength" OR "fracture resistance" OR "load-to-failure" OR "mechanical properties" OR "impact strength") AND ("in vitro" OR "laboratory study" OR "experimental study")).

The studies could not be omitted in the review unless in English and offer quantitative mechanical results of denture-base materials, namely load-to-failure or flexural strength. Case reports, reviews, editorials, finite-element analyses, no control group studies, and studies with no extractable quantitative data (mean, SD, n) were eliminated.

Abstracts, full texts, and titles were filtered, and two reviewers extracted all the data, which was resolved by a third. The standardized form was applied to extract the following: author, year, type of study design, sample size, type of material, type of reinforcement, type of comparator, type of testing protocol, and type of mechanical outcomes. Information was also sought that was missing, and authors were contacted where necessary.

Studies that were included were in vitro experimental studies that compared reinforced with non-reinforced denture base materials. The main results of this meta-analysis were load-to-failure (fracture resistance) and flexural strength, and only studies that indicated extractable means, SDs, and sample sizes were included. The assessment of risk of bias was done using Joanna Briggs Institute (JBI) Critical Appraisal Checklist adapted for in-vitro studies, and certainty of evidence was measured using the GRADE.

MetaAnalysisOnline tool was used to create forest plots and pooled estimates, and used a random-effects model, with the inverse-variance approach to perform meta-analysis [13].Standardized mean differences (SMDs) with 95% confidence intervals (CIs) were obtained to obtain continuous results. $I^2$ was used to measure heterogeneity.

Subgroup and sensitivity analyses based on type of reinforcement, material category, and characteristics of the study, such as leave-one-out analyses, were conducted to test the strength of the findings. Synthesis was carried out narratively in studies that could not be meta-analyzed because of heterogeneity or because the studies did not produce comparable results. The results were presented in the forest plots and summary tables with the characteristics of the study, the estimates of effects, and the confidence intervals. Twelve studies met the inclusion criteria, comprising in vitro experimental comparative investigations directly evaluating hybrid composite–reinforced versus unreinforced denture bases

## RESULTS

Among the four searched electronic databases and other sources, 222 research articles were initially selected. The number was reduced to 92 records after removing the duplicates. Title and abstract screening further eliminated 30 studies. From the remaining 62 articles, 22 were removed due to unavailability of access to the full-texts. Further articles (28) were eliminated due to a lack of stratified data and studies including animals, in vitro findings, reviews, case reports, or languages other than English. Ultimately, twelve studies that passed the inclusion criteria were included in this systematic review.

The PRISMA flow diagram presented in Figure 1 illustrates the selection process.

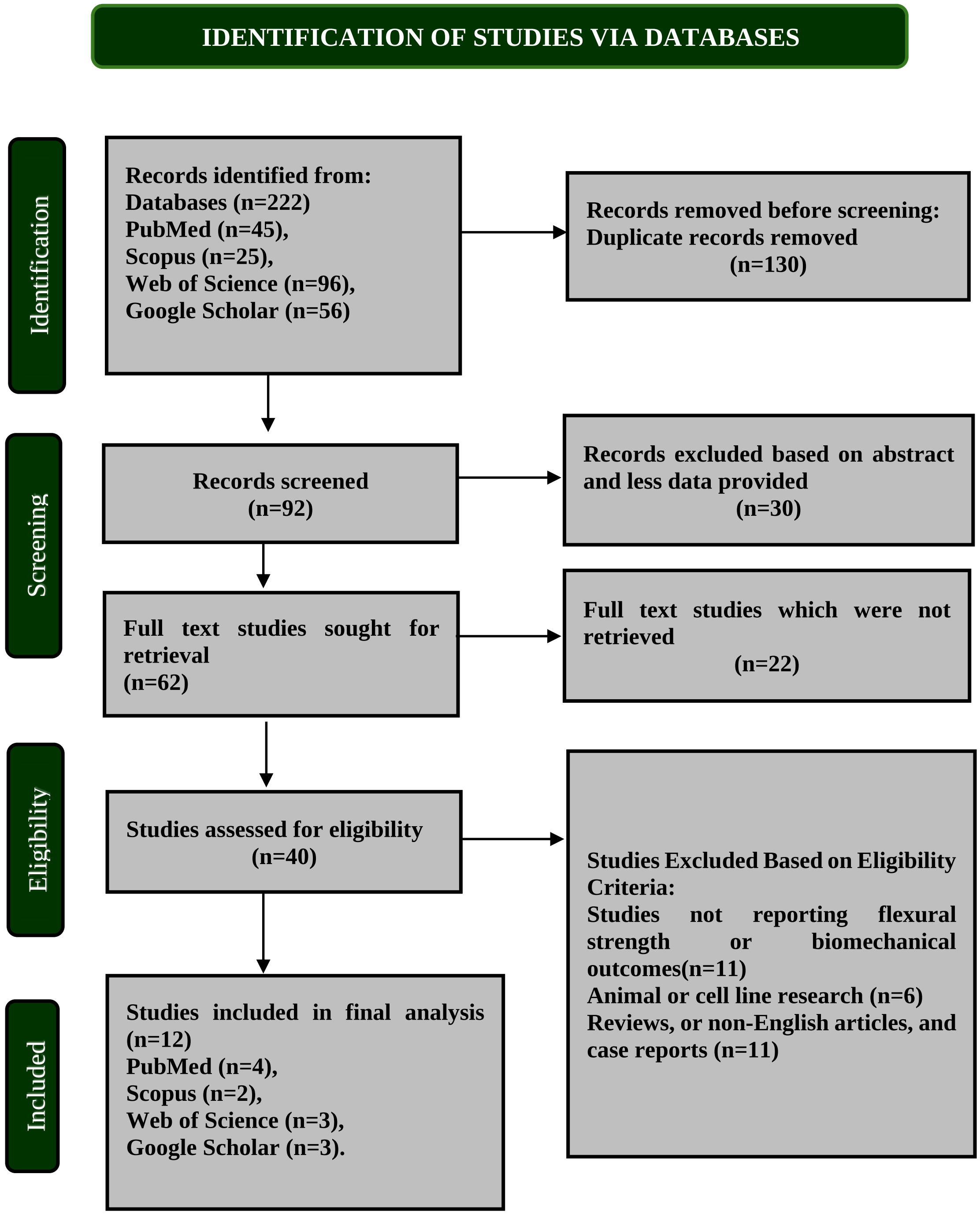


**Figure 1: PRISMA Flow Diagram for Study Selection. The flowchart was designed according to the PRISMA guidelines 2020, showing study identification, screening, assessment eligibility, and final selection in the systematic review.**

This review incorporated four in-vitro analyses that have evaluated flexural strength in denture base resin that has been produced in either heat-polymerized, CAD/CAM-milled, 3D-printed, or nanoparticle-modified materials. In general, digital and reinforced resins demonstrated greater flexural strength as compared to conventional PMMA, whereas thermal cycling introduced fluctuating but mostly minor decreases. The risk of bias was low to moderate in general, which was primarily caused by small samples and the absence of blinding.

**Table 1. Characteristics of Included Studies**

| Author & Year | Design | Modeling / Intervention | Population Size | Key Findings |
|---|---|---|---|---|
| Goyal et al., 2025 [14] | In vitro | Maxillary denture bases reinforced with glass fiber mesh, metal mesh, or unreinforced control; fracture resistance tested using a universal testing machine | 24 denture bases (Control: 8; Glass fiber: 8; Metal mesh: 8) | Metal mesh showed the highest fracture resistance; glass fiber improved strength vs control; the posterior half weakest region |
| Saadoun et al., 2025 [15] | In vitro comparative study | Lava Ultimate, Vita Enamic, Flexcera Smile Ultra+ | 125 specimens (n=25 per group) | Flexural strength is highest in Lava Ultimate; 3D printed materials showed lower strength. |
| Im et al., 2017 [16] | In vitro study | Maxillary complete dentures reinforced with metal mesh, glass fiber mesh, and control | 15 per group (total 45) | Metal mesh showed the highest fracture resistance, glass fiber intermediate, and the control had the lowest. |
| Dsouza et al., 2025 [17] | In vitro | Maxillary dentures reinforced with aramid or glass fiber mesh | Aramid: 16; Glass: 16; Control: 16 | Aramid and glass fiber reinforcement significantly increased fracture resistance vs unreinforced; aramid highest. |
| Prasad et al., 2020 [18] | In vitro | Maxillary acrylic denture base reinforced with metal patterns (Zigzag & Square) | 60 (Control: 20; Zigzag: 20; Square: 20) | Metal pattern reinforcement (Zigzag & Square) significantly increased fracture resistance across all palatal types. |
| Komala et al., 2018 [19] | In-vitro experimental | Reinforced maxillary dentures with glass fiber mesh vs unreinforced | 30 | Full mesh showed the highest strength, significantly exceeding the control |

| | | | | |
|---|---|---|---|---|
| Fouda et al., 2025 [20] | In-vitro experimental | 3D-printed resins (FL, VC) vs PMMA; tested pre/post aging | 70 specimens | Flexural strength improved with the build angle |
| Viswanathan & Krishnan, 2025 [21] | In-vitro experimental | PMMA reinforced with 0–2 wt% cranberry extract; flexural, impact, and hardness tested | 150 (n=30 per outcome; n=10 per FS group) | Cranberry up to 2% increased flexural strength compared with the control |
| Hamdy, 2024 [22] | In-vitro experimental | Self-cured PMMA with or without 0.5% Ag-doped CNTs | 60 (n=30 per group) | Ag-doped CNTs significantly increased flexural strength compared to the control. |
| Mohamed et al., 2025 [23] | In-vitro experimental | 3D-printed denture base resin modified with 0.5% and 1% cerium oxide nanoparticles | 72 | 1% Cerium oxide slightly improved flexural strength; not statistically significant |
| Temizci & Bozoğulları, 2024 [24] | In-vitro | 3D-printed (FL), CAD/CAM milled (IB), heat-polymerized (MD) denture bases | 60 | 3D-printed FL > IB > MD in flexural strength |
| Longkumer et al., 2025 [25] | In-vitro experimental | Denture base PMMA: conventional heat-polymerized, CAD/CAM-milled, 3D-printed | 120 | CAD/CAM showed the highest flexural strength; 3D-printed and conventional were similar; 3D-printed had the highest impact strength |

*Footnotes: FS, flexural strength. PMMA, polymethyl methacrylate. CAD/CAM, computer-aided design/computer-aided manufacturing. FL, Formlabs 3D-printed resin. VC, VOCO 3D-printed resin. CNTs, carbon nanotubes. $CeO_2$, cerium oxide nanoparticles.*

**Table 1** is a summary of study designs, interventions, populations, and outcomes. Table 1 features the works that evaluated the flexural strength of the denture base materials produced by the traditional heat-polymerized PMMA, CAD/CAM-milled PMMA, 3D-printed resins, and resins reinforced with nanoparticles. The table presents the study design, fabrication model, sample size, essential flexural-strength findings, and threat of bias.

A majority of the studies were experimental designs in vitro, where standardized rectangular specimens were tested using a universal testing machine with three-point bending as recommended by the ISO standards. On balance, CAD /CAM-milled and reinforced substances (e.g., metal mesh, glass fiber, aramid fibers, Ag-doped CNTs) exhibited increased flexural strength than plain PMMA. There was inconsistent performance of digital and 3D-printed materials based on the type of material, build orientation, and additive reinforcement.

To estimate the risk of bias, the Joanna Briggs Institute (JBI) Critical Appraisal Checklist, modified in-vitro appraisal criteria were employed, with the majority of studies deemed to be of low to moderate quality, mainly because of small sample sizes, absence of blinding, or methodological incomplete reporting. Altogether, the quality of evidence was moderate according to GRADE.

The risk of bias is given in Table 2.

**Table 2. Risk of Bias of Included Studies**

| Author & Year | Randomization / Allocation | Blinding of Outcome Assessment | Sample Size Justification | Outcome Measurement Reliability | Overall Risk of Bias |
|---|---|---|---|---|---|
| Goyal et al., 2025 | ± | ± | – | + | Moderate |
| Saadoun et al., 2025 | ± | ± | ± | + | Moderate |
| Im et al., 2017 | ± | ± | – | + | Moderate |
| Dsouza et al., 2025 | + | + | ± | + | Low |
| Prasad et al., 2020 | ± | ± | ± | + | Moderate |
| Komala et al., 2018 | ± | ± | – | + | Moderate |
| Fouda et al., 2025 | ± | ± | ± | + | Moderate |
| Viswanathan & Krishnan, 2025 | ± | ± | ± | + | Moderate |
| Hamdy, 2024 | ± | ± | ± | + | Moderate |
| Mohamed et al., 2025 | + | + | ± | + | Low |
| Temizci & Bozoğulları, 2024 | ± | ± | – | + | Moderate |
| Longkumer et al., 2025 | + | + | ± | + | Low |

*'+' indicates low risk, '±' indicates unclear risk, and '–' indicates high risk.*

## META-ANALYSIS

The meta-analysis assessed the hybrid composite reinforcement effect on the performance of denture bases under two primary outcomes, which are load-to-failure (fracture resistance) and flexural strength. Each outcome had nine studies contributing to it. All the analyses were performed in the MetaAnalysisOnline tool in the random-effects model with the inverse-variance approach, which was predetermined to consider the expected clinical and methodological differences among laboratory protocols, materials, and testing conditions.

For Load-to-Failure (Fracture Resistance), there was the pooling of data in 118 experimental and 118 control specimens. The overall effect was a standardized mean difference (SMD) = 12.52 (95% CI: 3.56-21.47), which was statistically significant, showing that reinforced denture bases were significantly more resistant to fracture than controls. The statistical significance ($p < 0.05$) of the overall effect was achieved.

Nonetheless, the between-study heterogeneity was high ($I^2 = 95\%$, $p < 0.01$), which suggests that the majority of observed differences in effect estimates could be due to the actual differences between studies and not due to sampling error. The sources of heterogeneity presumably consist of differences in the type of reinforcement (metal mesh, glass or aramid fibers, CNTs, nanoparticles), location of reinforcement (full vs partial coverage), geometry of the specimen, aging conditions, and testing equipment/parameters. Due to this heterogeneity, the overall effect SMD needs to be taken with caution: although the direction of effect is consistently the same, with reinforcement, the size of the benefit depends greatly on material and method.

**Figure 2** shows the forest plot of the standardized mean differences (SMD) and 95% confidence intervals of fracture resistance (load-to-failure) in the included studies. The square is used to represent the point estimate of an individual study, and the size of the square corresponds to the weight that the study has on the meta-analysis. Horizontal lines point to 95% confidence intervals. The pooled SMD and its 95% CI are represented by the diamond at the bottom. The values on the left of the line give more preference to the experimental (reinforced) group; the values on the right give more preference to the control group.

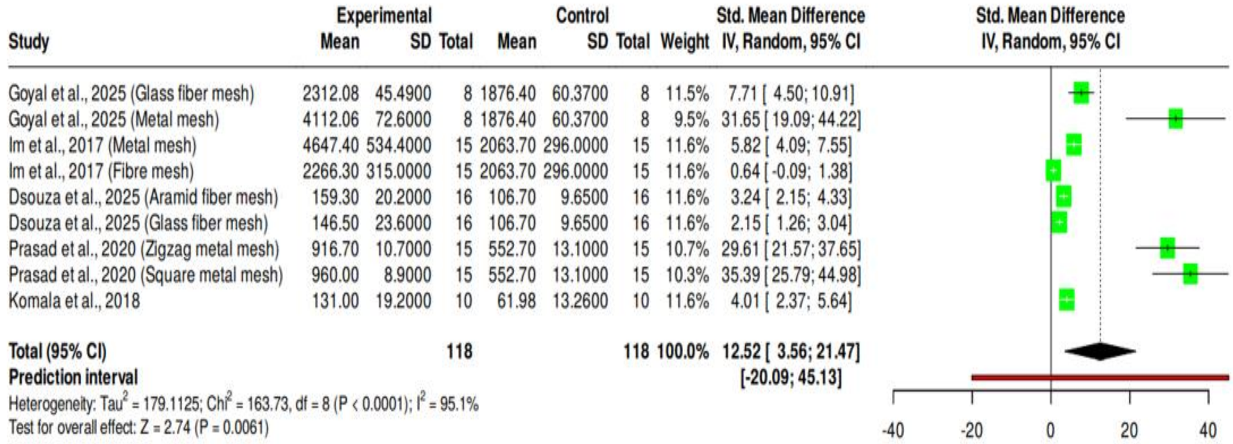


**Figure 2: Summary of the standardized mean difference (SMD) for load-to-failure (fracture resistance) between reinforced and non-reinforced denture bases, displayed as a forest plot.**

For flexural strength, the pooled analysis with 162 experimental and 162 control specimens yielded an SMD of 27.32 (95% CI -27.16 to 81.81), not statistically significant to indicate a difference between reinforced and unreinforced denture bases (overall effect $p > 0.05$). Once again, there was a very high level of heterogeneity ($I^2 = 97\%$, $p < 0.01$), which was due to the inconsistent effect sizes and sometimes the reversal of direction of the effect across the studies.

This observation indicates that flexural strength gains are not uniform among reinforcement strategy combinations and material platforms as fracture resistance. The possible causes of the poor consistency of the results could be differences in polymer chemistry (heat-cured PMMA vs milled PMMA vs printed resins), nanoparticle dispersion, build orientation (with printed resins), and the presence or absence of thermal/ mechanical aging.

**Figure 3 shows the forest plot of the standardized mean differences (SMD) and 95% confidence intervals of flexural strength in the included studies. The square is used to represent the point estimate of an individual study, and the size of the square corresponds to the weight that the study has on the meta-analysis. Horizontal lines point to 95% confidence intervals. The pooled SMD and its 95% CI are represented by the diamond at the bottom. The values on the left of the line give more preference to the experimental (reinforced) group; the values on the right give more preference to the control group.**

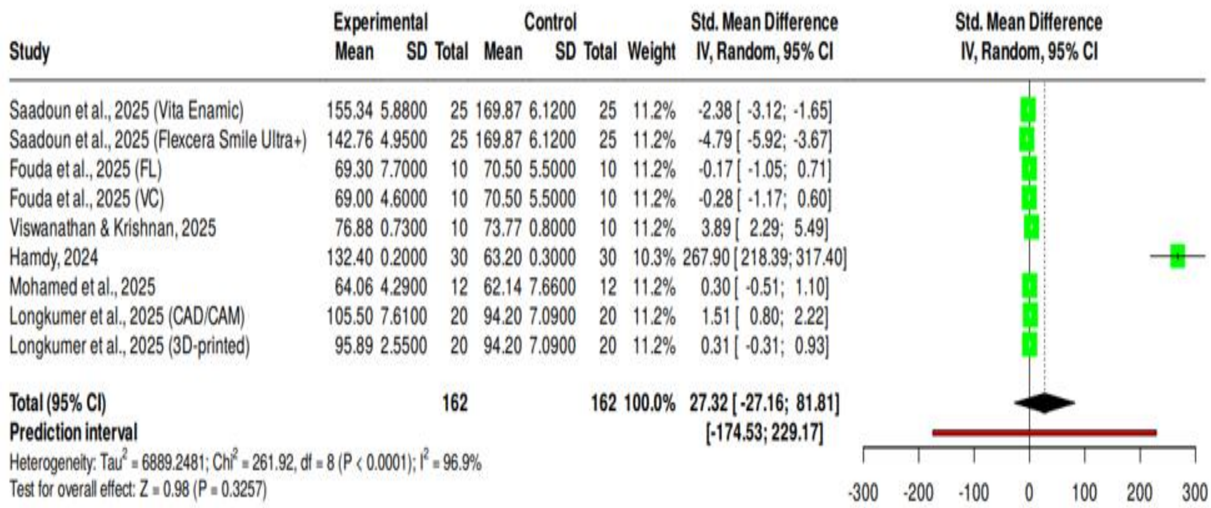


**Figure 3: Summary of the standardized mean difference (SMD) for flexural strength between reinforced and non-reinforced denture bases, displayed as a forest plot.**

Collectively, these studies indicate that, in most experimental studies, hybrid denture base reinforcement may significantly enhance load-to-failure (fracture resistance), although there is no consistent evidence of a systematic increase in flexural strength. This condition in practice means that some of these reinforcement methods have the potential to minimize disastrous mid-line fractures (to increase longevity), but their effect on standardized flexural characteristics heavily depends on the nature of the material, processing, and testing.

With this high level of heterogeneity, interpretation of pooled effect sizes by clinicians and researchers should be done with caution. Further designed in-vitro experiments ought to correct the geometry of the specimen, aging condition, and test parameters, and to provide a full set of summary statistics of all groups to enhance comparability and enable more accurate meta-analytic estimations.

## Subgroup Analysis

In the case where data were available, subgroup analyses were done based on reinforcement type (fibrous meshes, nanoparticle fillers, CAD/CAM materials, and printed resins). Despite the fact that some subgroups had tendencies of benefit (such as metal mesh and some fiber reinforcements to load-to-failure), no subgroup resulted in a statistically significant pooled benefit to flexural strength, and heterogeneity was high within subgroups. This trend shows that the effect of material specificity is important, and pooling of mixed reinforcement strategies exaggerates variability.

**Sensitivity Analysis**

The leave-one-out sensitivity analyses showed that point-wise directions of pooled effects of load-to-failure did not reverse to detriment when any of the studies were sequentially excluded. The exclusion of the single large-weight outliers decreased heterogeneity, but did not alter the general conclusions, which indicated strong support for the original finding of fracture resistance. In the case of flexural strength, sensitivity analysis showed no uniform direction of effect, which supports the finding of no evident pooled benefit.

## DISCUSSION

It is undeniable that the biomechanical stability of denture-base material has been the main focus of removable prosthodontics since fatigue cracks, impact failures, and midline fractures still represent common clinical issues in this area [26]. Hybrid composite materials have been popular due to the fact that the materials combine polymer matrices with reinforcing agents that have the effect of increasing toughness, stiffness, and cyclic loading resistance [27]. Their increasing usefulness is a product of the clinical demand to have denture bases that can sustain high functional load, fluctuating ridges in support, and long-term degradation intraorally. The transition to hybrid systems instead of the traditional PMMA shows the value of the role that filler composition, interfacial bonding, and reinforcement morphology play in failure resistance [28].

Removable prostheses undergo complicated masticatory forces, which cause stress concentrations along the midline, palatal seal, and thin flange areas. The counter of these stresses is achieved by hybrid composites, including fiber-reinforced PMMA, nanoparticle-reinforced resin, and CAD/CAM-Nanomilled composite discs [29]. Evidence shows that multicompartment reinforcement (e.g., fibers and nanoparticles) is more effective compared to single-reinforcement measures, particularly in high-load patients or those with repeated implant fractures [30].

Performance is also affected in material processing. The CAD/CAM systems minimize porosity and polymerization contraction and produce improved distribution of fillers, and idealizations in fiber orientation enhance fracture toughness [31]. Additional stiffness and hardness are enhanced by nanofillers like zirconia, silica, or graphene derivatives [32]. Yet, randomness in the concentration of reinforcement, bonding agents, thermocycling treatments, and sample architecture all add to the diversity of studies. The differences in the aging conditions, storage time, and flexural testing procedures do not allow direct comparability and make the synthesis of the evidence more difficult [33].

In spite of these variations, hybrid composites have always demonstrated better biomechanical results than the traditional PMMA, such as greater flexural strength, increased fatigue behavior, and less catastrophic failure [34]. These benefits are in accordance with the clinical needs of dentures subjected to a long period of mechanical loading and changes in the environment. To translate these results into clinical practice, clinicians and labs should coordinate, reinforcement should be placed in high-stress areas, and standardization of fabrication protocols should be followed in order to guarantee standard performance [35,36].

Overall, hybrid composite reinforcements demonstrate that material selection and fabrication techniques are crucial in achieving durable and reliable denture bases [37]. The combination of fibers, nanoparticles, and CAD/CAM processing provides a versatile approach to improving mechanical performance across different denture designs. This highlights the importance of understanding the interactions between matrix and reinforcement for optimal stress distribution and resistance to fracture [38,39].

Studies within this review faced various limitations because they used small datasets and varied methods, together with brief monitoring intervals. Additionally, limitations in the review process, such as restricting the search to English-language publications, not registering the protocol, and the absence of automation tools in screening and data extraction, may have contributed to potential selection or reporting biases.

The next-generation future research should establish the best form of reinforcements, concentration, and location schemes; it must also look at digital fabrication, new bonding chemistries, and new nanostructures [40]. The integration of the cost-effectiveness and clinical feasibility analysis will assist in establishing the long-term relevance of hybrid composites in the context of the restoration of the prosthodontic practice.

## CONCLUSION

To sum up, the hybrid varieties of composite materials provide a valuable enhancement of the biomechanical behavior of non-adhesive prosthodontic foundations, especially in the resistance to flexural deformation, fatigue damage, and fracture. Despite the differences in the results, caused by the heterogeneity of the methods, it is evident that reinforced composites are stronger and more durable than traditional PMMA. Further investigation, reinforcing measures, and incorporation of modern manufacturing techniques will help enhance credible and durable prostheses, which result in better functionality and clinical sustainability of denture users.

## LIST OF ABBREVIATIONS

None

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## CONFLICT OF INTEREST

None.

## AUTHORS' CONTRIBUTION

**GS MM:** Conceptualization, protocol design, literature search strategy formulation and drafting the manuscript.

**LI:** Study screening (title/abstract and full-text), data extraction, statistical analysis (meta-analysis execution), drafting the methodology.

**AUR:** Study screening (title/abstract and full-text), data extraction, risk of bias/quality assessment, revising the manuscript critically.

**AH AP:** Risk of bias/quality assessment, acting as the third reviewer for screening disagreements, data interpretation and critical revision of the manuscript for intellectual content. All authors agreed to all aspects of resuts and provided final approval as per ICMJE criteria.

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