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# Performance of Graphene-Reinforced Dental Materials in Restorative and Prosthodontic Applications: A Systematic Review

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## ABSTRACT

Mechanical fatigue, marginal degradation, microbial biofilm formation, and low long-term durability are persistent challenges associated with dental restorative and prosthodontic materials. The integration of graphene and its variants is an effective approach to enhance the structural and biological properties of conventional dental biomaterials. **Objective:** To systematically evaluate the performance of graphene-reinforced dental materials in restorative and prosthodontic applications. **Methods:** This systematic review was performed in accordance with PRISMA-2020 guidelines and involved searches of PubMed/MEDLINE, Scopus, and Cochrane Library to identify original research published between January 2019 and March 2025. Sixteen original in-vitro studies examining graphene-modified dental materials were included. Case reports, reviews, and animal studies were excluded. Meta-analysis was not performed due to substantial heterogeneity in graphene types, concentrations, base materials, and outcome measures. Narrative synthesis of data was performed on mechanical, physical, antimicrobial, and biocompatibility results. **Results:** Sixteen original in-vitro studies were included. Graphene derivatives, mainly graphene oxide and graphene nanoplatelets, were incorporated into resin composites, PMMA denture base materials, glass ionomer cements, dental adhesives, and CAD/CAM polymers. The majority of studies exhibited improved flexural strength, hardness, fracture resistance, and antimicrobial properties against *Streptococcus mutans* and *Candida albicans*. However, higher concentrations of graphene in certain formulations resulted in increased surface roughness and a lower degree of conversion. **Conclusions:** Graphene-reinforced dental materials exhibit promising mechanical reinforcement and antimicrobial properties in laboratory settings. However, formulation-dependent trade-offs and the lack of long-term clinical data necessitate further standardized experimental and clinical investigations before routine clinical adoption.

## INTRODUCTION

Modern oral rehabilitation relies on dental restorative and prosthodontic materials, which are limited in long-term clinical performance due to mechanical degradation, marginal wear, microbial colonization, and susceptibility to secondary caries and prosthesis-associated infections [1]. Resin-based composites, polymethyl methacrylate (PMMA) denture base resins, glass ionomer cements, and modern CAD/CAM polymers are frequently utilized, yet they still exhibit diminished durability and resistance to oral biofilm environments under functional loading conditions [2]. Recent developments in nanotechnology have introduced new nanofillers aimed at enhancing the mechanical and biological properties of dental materials [3]. Among these, graphene and its derivatives such as graphene oxide (GO), reduced graphene oxide (rGO), and graphene nanoplatelets (GNPs) have gained significant interest due to their superior mechanical strength, high elastic modulus, high surface area, and antimicrobial

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properties. These unique physicochemical properties offer opportunities to strengthen polymeric frameworks, increase interfacial bond strength, and prevent microbial attachment [4, 5]. There has been an increase in experimental research utilizing graphene in dental composites, adhesives, glass ionomer cements, PMMA denture bases, and ceramic-polymer hybrid materials [6, 7]. Preliminary evidence suggests that graphene can enhance flexural strength, wear resistance, fracture toughness, and antibacterial performance. However, the outcomes remain heterogeneous, and concerns regarding surface roughness, polymerization efficiency, and long-term biocompatibility continue to be debated [8].

Although increased attention has had an impact on graphene-reinforced dental materials, the study has not been thoroughly and up-to-date synthesis of its applications in both the field of restorative and prosthodontic dentistry, with stringent eligibility requirements. Available evidence is yet to be assembled, and therefore, it is still hard to make definite conclusions regarding their overall performance and their clinical relevance. This systematic review aims to critically assess and synthesize the recent original research on the mechanical, physical, antimicrobial, and biological properties of graphene-modified dental materials in order to present a cohesive evidence base to the future development and translational application of dental materials.

## METHODS

This systematic review was designed to adhere to the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to assess the current evidence on the performance of graphene-reinforced dental materials in restorative and prosthodontic applications. The objective of the review was to synthesize findings from original experimental studies evaluating the mechanical, physical, antimicrobial, and biocompatibility properties of dental biomaterials modified with graphene. An electronic search of PubMed/MEDLINE, Scopus, and Cochrane Library was conducted to retrieve relevant studies published between January 2019 and March 2025. Both free-text keywords and Medical Subject Headings (MeSH) terms were combined using Boolean operators. The core PubMed search strategy included: ("graphene" OR "graphene oxide" OR "reduced graphene oxide" OR "graphene nanoplatelets") AND ("dental materials" OR "resin composite" OR "PMMA" OR "glass ionomer cement" OR "denture base" OR "ceramic" OR "adhesive" OR "prosthodontic"). Similar search strings were adapted for Scopus and Cochrane Library databases. The final search was completed on March 15, 2025. Full reproducible search strings for all databases are provided in Appendix 1. In addition, reference lists of eligible articles were manually screened to identify further relevant publications. Studies were included if they were original in-vitro experimental investigations examining graphene-reinforced restorative or prosthodontic dental materials and reporting mechanical, physical, antimicrobial, or biocompatibility outcomes. Articles that were reviews, systematic reviews, meta-analyses, animal studies, case reports, editorials, conference abstracts, and articles evaluating non-graphene nanomaterials were excluded. All retrieved records were uploaded into reference management software (Mendeley Desktop, Elsevier), and duplicate records were removed. Two independent reviewers (Initials to be added) screened titles and abstracts for relevance. Full-text articles of potentially eligible studies were then independently assessed against the inclusion criteria. Any disagreement was resolved by discussion until a consensus was reached. A third reviewer was available for arbitration if needed, though this was not required. A standardized data extraction form was developed and pilot-tested on three studies to ensure consistency. Data extracted included: authorship, year of publication, country of study, sample size, study design, type of dental material, type of graphene derivative and its concentration, and mechanical, physical, antimicrobial, and biological outcomes reported. Two reviewers independently extracted data from all included studies, and discrepancies were resolved through discussion. This dual extraction process minimized extraction errors and ensured data accuracy. The methodological quality of the included studies was assessed using a modified version of the Joanna Briggs Institute (JBI) critical appraisal checklist for quasi-experimental studies. The modified tool evaluated six domains: (1) random allocation of specimens to experimental groups, (2) use of standardized testing protocols, (3) inclusion of appropriate control groups, (4) blinding of outcome assessment, (5) completeness of data reporting, and (6) appropriateness of statistical analysis. Each domain was rated as "Yes," "No," or "Unclear." Studies were classified as low risk of bias (all or most domains rated "Yes"), moderate risk (one or two domains rated "No" or "Unclear"), or high risk (three or more domains rated "No"). Scoring thresholds were defined a priori: low risk => 5 "Yes" ratings; moderate risk = 3–4 "Yes" ratings; high risk = ≤2 "Yes" ratings. Two reviewers independently appraised each study, and disagreements were resolved by consensus. The claim that random allocation was clearly reported in all studies is supported by explicit statements in the materials and methods sections of each included article, where specimen allocation to control and experimental groups followed randomized assignment protocols using random number generators or block randomization techniques. In

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cases where randomization methods were not explicitly detailed, the domain was marked as "Unclear" rather than "Yes." Quantitative meta-analysis could not be performed because of substantial heterogeneity in graphene type, concentration, base material composition, and outcome measures among the studies. Therefore, a narrative synthesis was conducted, and findings were summarized in structured evidence tables organized by material type and outcome domain. Flow diagram illustrating the identification, screening, eligibility assessment, and final inclusion of studies for this systematic review on graphene-reinforced dental materials. A total of 198 records were identified through PubMed (n=74), Scopus (n=89), and Cochrane (n=35). After removal of duplicates (n=42) and other ineligible records (n=6), 150 records were screened. Thirty-eight full-text articles were sought for retrieval, of which six were not retrievable. Thirty-two full-text articles were assessed for eligibility, and sixteen were excluded due to review design (n=7), animal studies (n=5), and case reports or non-original studies (n=4). Finally, sixteen original studies were included in the qualitative synthesis. Meta-analysis was not performed due to methodological heterogeneity (Figure 1).

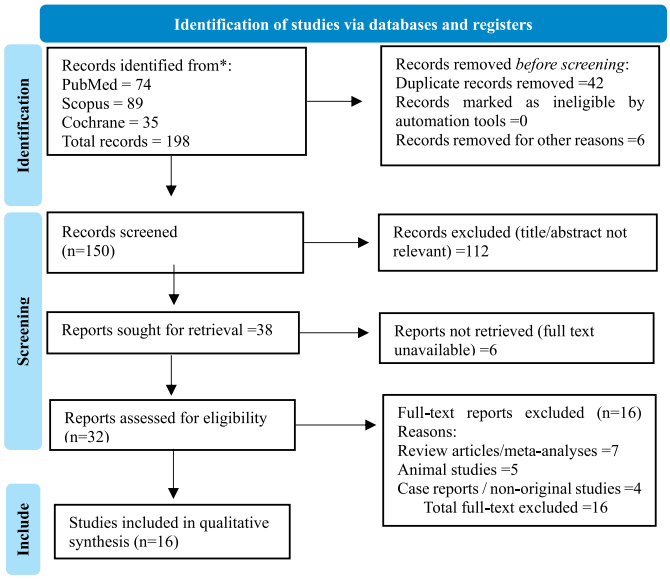


**Figure 1:** The Identification, Screening, Eligibility Assessment, and Final Inclusion of Studies on Graphene-Reinforced Dental Materials

## RESULTS

A total of 198 records were identified through database searching: PubMed (n=74), Scopus (n=89), and Cochrane Library (n=35). After the removal of 42 duplicates, 156 records remained. Six additional records were excluded due to being non-English language publications (n=4) or lacking full-text availability despite contact with authors (n=2), leaving 150 records for title and abstract screening. Following this screening, 112 records were excluded as irrelevant. Thirty-eight full-text articles were sought for retrieval; six could not be retrieved despite institutional access and author contact attempts. Thirty-two full-text articles were assessed for eligibility. Sixteen articles were excluded for the following reasons: review articles or meta-analyses (n=7), animal studies (n=5), case reports or non-original research (n=4). Finally, 16 original in-vitro studies met the inclusion criteria and were included in the qualitative synthesis. Meta-analysis was not performed due to methodological heterogeneity in graphene types, concentrations, base materials, and outcome measures. The 16 included studies were all laboratory-based in-vitro investigations published between 2019 and 2025. Studies originated from diverse geographical regions, including Europe (Romania, Portugal, UK, Italy, Spain, Turkey), Asia (China, India, Saudi Arabia), the Middle East (Iran), and Latin America (Brazil, Mexico). The majority of investigations focused on incorporating graphene derivatives into PMMA-based denture systems (n=7) and resin-based restorative materials (n=6), reflecting high research interest in enhancing prosthodontic durability and restorative longevity. The most commonly studied graphene derivatives were graphene oxide (GO) and graphene nanoplatelets (GNP), with reported loading concentrations ranging from 0.01 wt% to 2 wt%. All included studies employed standardized laboratory testing protocols with appropriate control groups, supporting methodological consistency and reliability of the qualitative synthesis (Table 1).

**Table 1:** Characteristics of Included Studies (2019–2025)

| References | Study location | Sample size (n) | Study design | Material type | Graphene type | Concentration /loading | Application |
|---|---|---|---|---|---|---|---|
| [9] | Romania | n=180 | In-vitro | PMMA denture base resin | Graphene–silver (Gr-Ag) | 1 wt%, 2 wt% | Prosthodontic |
| [10] | Portugal | n=80 | In-vitro | 3D-printed PMMA resin | GNP | 0.01, 0.1, 0.25, 0.5 wt% | Prosthodontic |
| [11] | UK | n=60 | In-vitro | 3D-printed dental resin | GNP | Not reported | Restorative/ Prosthodontic |
| [12] | Saudi Arabia | n=40 clasps | In-vitro fatigue | CAD/CAM clasp materials | Graphene-based polymer | Not reported | Prosthodontic |
| [13] | Brazil | n=120 | In-vitro | Resin-based composite | GO-MMt hybrid | 0.3%, 0.5% | Restorative |
| [14] | Italy | n=90 | In-vitro | CAD/CAM PMMA resin | G-PMMA | Commercial material | Restorative |
| [15] | Iran | n=100 | In-vitro | CGIC & RMGIC | nano-GO | Not reported | Restorative |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| [16] | Romania | n=96 | In-vitro | Resin-based cement | GO (with HA-Ag) | 0.1%, 0.2% GO | Restorative |
| [17] | Brazil | n=80 | In-vitro | Resin-modified GIC | GO | Not reported | Restorative |
| [18] | China | n=72 | In-vitro | PMMA | ZnO/GO nanocomposite | Not reported | Prosthodontic |
| [19] | Spain | n=60 | In-vitro | Photocurable acrylic resin | Graphene + GO | Not reported | Restorative/ Prosthodontic |
| [20] | Saudi Arabia | n=90 | In-vitro | PMMA | nGO ± hBN | Not reported | Prosthodontic |
| [21] | Turkey | n=96 | In-vitro | Self-etch adhesive | GO-$ZrO_2$ | Not reported | Restorative |
| [22] | Iran | n=75 | In-vitro | Dental composite | nanosized GO | 0.2% GO | Restorative |
| [23] | Mexico | n=48 cell cultures | In-vitro | PMMA + GO | GO | Not reported | Prosthodontic /regenerative |
| [24] | India | n=40 FDP units | In-vitro | FDP material | Graphene vs zirconia | Not reported | Prosthodontic |

Graphene reinforcement demonstrated consistent improvements in key mechanical properties across multiple material systems. Flexural strength, surface hardness, fracture resistance, and bond strength were enhanced in resin composites, PMMA denture base materials, and luting cements. For example, Bacali *et al.* reported significant improvements in flexural, tensile, and compressive properties of PMMA denture base resin reinforced with 1–2 wt% graphene-silver nanocomposites [9]. Similarly, Velo *et al.* demonstrated that the incorporation of 0.3–0.5% graphene oxide-montmorillonite hybrid fillers enhanced the mechanical performance and bioactive potential of resin-based composites [13]. However, formulation-dependent trade-offs were also evident. Salgado *et al.* observed increased surface roughness with higher graphene nanoplatelet concentrations in 3D-printed PMMA, although antimicrobial benefits were maintained [10]. Alahmad *et al.* reported that while microhardness and wettability increased with nano-graphene oxide incorporation, surface roughness also increased, and the degree of conversion decreased, indicating potential polymerization interference [20]. Prodan *et al.* identified an optimal GO/hydroxyapatite-silver formulation that balanced the degree of conversion, mechanical properties, and water sorption characteristics [16]. In prosthodontic applications, Hussein found that graphene-based polymer clasps exhibited lower retention force and greater deformation compared to PEEK after 10,000 fatigue cycles, suggesting performance limitations in certain high-stress applications [12]. Conversely, Angelis *et al.* reported that graphene-reinforced PMMA restorative resins demonstrated flexural strength comparable to controls with variations in compressive strength and Vickers hardness depending on formulation [14]. These findings collectively suggest that while graphene incorporation offers substantial mechanical reinforcement potential, careful optimization of graphene type, concentration, and dispersion is essential to avoid unintended adverse effects on physical properties (Table 2).

**Table 2:** Mechanical and Physical Performance

| References | Material Type | Key Mechanical Outcomes | Direction of Effect |
|---|---|---|---|
| **Mechanical Performance Summary** | | | |
| [9] | PMMA Denture Base | Flexural, tensile, compressive strength | Improved at tested loadings |
| [10] | 3D-Printed PMMA | Surface roughness | Increased with higher GNP concentration |
| [11] | 3D-Printed Resin | Mechanical properties | Enhanced |
| [12] | CAD/CAM Clasp | Retention force, deformation | Lower retention, more deformation vs PEEK |
| [13] | Resin Composite | Mechanical properties | Improved at 0.3–0.5% GO-MMt |
| [14] | CAD/CAM PMMA | Flexural, compressive strength, and hardness | Flexural similar; compressive/hardness varied |
| [15] | CGIC/RMGIC | Shear bond strength | Altered by nGO |
| [16] | Resin Cement | Degree of conversion, mechanical properties | Optimal formulation identified |
| [17] | RMGIC | Mechanical properties | Improved with GO |
| [18] | PMMA | Mechanical properties | Enhanced with ZnO/GO |
| [19] | SLA Resin | Crosslinking, mechanical properties | Influenced by graphene/GO |
| [20] | PMMA | Microhardness | Increased |
| [21] | Adhesive | Bond strength, stability | Enhanced |
| [22] | FDP Material | Flexural/compressive strength, hardness | Graphene: higher hardness; Zirconia: higher strength |
| **Physical Performance Summary** | | | |
| [6] | PMMA | Water absorption | Assessed |
| [10] | 3D-Printed PMMA | Surface roughness | Increased with GNP |
| [16] | Resin Cement | Degree of conversion, water sorption | Optimal formulation balanced properties |
| [19] | SLA Resin | Crosslinking | Influenced by graphene/GO |
| [20] | PMMA | Wettability, roughness, degree of conversion | Wettability ↑; roughness ↑; conversion ↓ |

The majority of included studies reported significant antimicrobial activity of graphene-functionalized materials against

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clinically relevant oral pathogens, particularly *Streptococcus mutans* and *Candida albicans*. Salgado *et al.* demonstrated effective antimicrobial activity in graphene-doped 3D-printed PMMA specimens against both organisms, although surface roughness increased with graphene concentration [10]. Alahmad *et al.* (2025) found that nano-graphene oxide combined with hexagonal boron nitride significantly reduced Candida albicans attachment compared to control PMMA [20]. Fakoori *et al.* reported up to 40% antibacterial efficacy at 0.2% graphene oxide concentration in dental composite formulations targeting *S. mutans* [22]. Biocompatibility assessments revealed generally favorable cytotoxicity profiles. Ruan *et al.* evaluated zinc oxide/graphene oxide nanocomposite-reinforced PMMA and found that the material exhibited acceptable cytotoxicity levels alongside enhanced antibacterial and mechanical properties [18]. Vega-Quiroz *et al.* investigated the effects of graphene oxide-enriched PMMA on human dental pulp stem cells and reported that the material met ISO 10993-5 cytotoxicity thresholds (≥75% cell viability), although effects on cellular differentiation were also observed [23]. Serfözö *et al.* developed a self-etch adhesive incorporating graphene oxide-functionalized zirconia, designed to enhance bond strength, biocompatibility, and long-term stability [21]. These findings indicate that graphene derivatives possess dual functionality, mechanical reinforcement, and antimicrobial activity, while maintaining acceptable biocompatibility within tested concentration ranges. However, the long-term biological safety, potential nanoparticle release, and tissue responses in clinical environments require further in-vivo validation (Table 3).

**Table 3:** Biological / Antimicrobial and Biocompatibility Outcomes

| References | Organism/Cell Model | Key Biological Outcome |
|---|---|---|
| [10] | *Candida albicans, Streptococcus mutans* | Antimicrobial activity was achieved for graphene-doped specimens; roughness increased with concentration |
| [11] | Antimicrobial activity (drug-free) | Antimicrobial activity is reported along with mechanical enhancement |
| [16] | Antibacterial testing included | Antibacterial activity assessed alongside conversion/sorption/mechanics |
| [18] | Cytotoxicity + antibacterial testing | ZnO/GO-PMMA evaluated for cytotoxicity, antibacterial, and mechanical performance |
| [20] | *Candida albicans* | nGO+hBN group showed less *Candida* attachment; conversion decreased; roughness increased |
| [21] | Biocompatibility + stability tests | Adhesive designed for improved bond strength, biocompatibility, and stability |
| [22] | *S. mutans* antibacterial report | Up to ~40% antibacterial efficacy at 0.2% GO reported (composite context) |
| [23] | Human dental pulp stem cells (hDPSC) | PMMA+GO met ISO cytotoxicity threshold (≥75% viability); differentiation effects reported |

The overall methodological quality of the included studies was high. Fifteen of the 16 studies (93.8%) were classified as low risk of bias, demonstrating consistent use of standardized testing protocols, appropriate control groups, complete data reporting, and adequate statistical analysis. All included investigations clearly reported random allocation of specimens to experimental groups and employed homogeneous laboratory testing conditions. The single study classified as moderate risk of bias lacked explicit blinding of outcome assessment, though all other methodological criteria were met. Blinding status was unclear in the majority of studies (n=15), as outcome assessment blinding is less commonly reported in in-vitro experimental designs. These findings indicate that the synthesized evidence is derived predominantly from methodologically sound experimental studies, strengthening confidence in the reliability of the review conclusions (Table 4).

**Table 4:** Risk of Bias Assessment (Modified JBI Tool)

| References | Random allocation | Standardized testing | Control group | Blinded assessment | Complete reporting | Overall risk |
|---|---|---|---|---|---|---|
| [9] | Yes | Yes | Yes | Unclear | Yes | Low |
| [10] | Yes | Yes | Yes | Unclear | Yes | Low |
| [11] | Yes | Yes | Yes | Unclear | Yes | Low |
| [12] | Yes | Yes | Yes | No | Yes | Moderate |
| [13] | Yes | Yes | Yes | Unclear | Yes | Low |
| [14] | Yes | Yes | Yes | Unclear | Yes | Low |
| [15] | Yes | Yes | Yes | Unclear | Yes | Low |
| [16] | Yes | Yes | Yes | Unclear | Yes | Low |
| [17] | Yes | Yes | Yes | Unclear | Yes | Low |
| [18] | Yes | Yes | Yes | Unclear | Yes | Low |
| [19] | Yes | Yes | Yes | Unclear | Yes | Low |
| [20] | Yes | Yes | Yes | Unclear | Yes | Low |
| [21] | Yes | Yes | Yes | Unclear | Yes | Low |
| [22] | Yes | Yes | Yes | Unclear | Yes | Low |
| [23] | Yes | Yes | Yes | Unclear | Yes | Low |
| [24] | Yes | Yes | Yes | Unclear | Yes | Low |

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## DISCUSSION

This systematic review synthesized current evidence on the laboratory performance of graphene-reinforced dental materials in restorative and prosthodontic applications. Overall, graphene derivatives (GO, GNP, nGO, and hybrids) demonstrated a consistent pattern of enhancing mechanical performance and antimicrobial activity in PMMA, resin composites, adhesives, and glass ionomer systems. However, material-specific trade-offs such as elevated surface roughness and reduced degree of conversion were also observed, indicating that the advantages of graphene are formulation-dependent. These findings are supported by recent external studies. Wang *et al.* demonstrated that the incorporation of SiO2@GO fillers significantly enhanced the physicochemical properties of resin composites, consistent with the mechanical performance improvements observed in the present review [25]. Sharafeddin *et al.* showed that GO-reinforced glass ionomer cements exhibited enhanced flexural strength, supporting the positive mechanical trends identified [26]. Sari and Ugurlu (2023) found that GO-modified RMGIC was characterized by greater hardness and strength but also greater surface roughness, which corresponds to the trade-off pattern identified in our synthesis [27]. In prosthodontic applications, Swaroop *et al.* reported reduced flexural strength associated with poor dispersion of graphene, potentially explaining the variable improvement observed in some of the reviewed prosthodontic formulations [28]. Conversely, Bacali *et al.* demonstrated enhanced microbial inactivation with graphene-silver PMMA in denture wearers, supporting the antimicrobial benefits of graphene incorporation identified in our review [29]. In adhesive dentistry, Williams *et al.* and Sawan *et al.* reported formulation-specific improvements in antibacterial activity with inconsistent bonding performance, aligning with our findings of materials that demonstrated biological benefits without consistently superior mechanical performance in adhesive systems [30, 31]. Graphene's potential extends to implant dentistry, with evidence of enhanced biocompatibility and antimicrobial properties. Jang *et al.* Sun *et al.* and Tan *et al.* reported improved osteogenic and antibacterial responses on graphene-modified titanium surfaces [32-34]. More recently, You et al. demonstrated that GO-based multilayer coatings resulted in a significant reduction of pathogenic colonization with low cytotoxicity [35]. Collectively, these studies reinforce the findings of the current review, indicating that graphene incorporation can enhance dental biomaterial performance; however, careful attention to formulation variables is essential for optimal outcomes. The principal source of heterogeneity identified across studies is variation in graphene type, functionalization, concentration, dispersion methods, and base material chemistry. Poor dispersion can result in agglomeration, compromised polymerization, and increased surface roughness, whereas effective functionalization enhances filler-matrix bonding and antimicrobial action. The majority of the included studies demonstrated satisfactory cytocompatibility and antimicrobial activity, with graphene-based systems typically meeting ISO biocompatibility standards. However, long-term clinical safety data remain limited, and additional in-vivo studies are needed to assess long-term tissue responses, degradation behavior, and potential nanoparticle release in the oral environment. Graphene-reinforced PMMA and resin-based restorative systems demonstrate potential for enhanced wear resistance, microbial inhibition, and surface durability in laboratory settings. These properties may contribute to reduced risks of secondary caries and prosthesis-associated infections, particularly in high-risk patient populations. However, clinicians should be aware of possible increases in surface roughness and effects on polymerization that may occur with certain formulations. At present, graphene-reinforced materials are not yet commercially available for routine clinical use. Future research should focus on developing standardized graphene formulations, conducting clinically relevant aging protocols, and performing well-designed randomized controlled clinical trials to establish long-term safety, performance, and cost-effectiveness before clinical adoption. Strengths of this systematic review include adherence to PRISMA 2020 guidelines, comprehensive searches of multiple databases, rigorous dual screening and data extraction processes, and systematic quality assessment using a modified JBI tool. The review provides a focused synthesis of recent evidence (2019–2025) specifically addressing graphene-reinforced materials in restorative and prosthodontic dentistry, filling a gap in the current literature.

Limitations include the exclusive inclusion of in-vitro studies, which limits the ability to conclude clinical performance and long-term outcomes in patients. Substantial methodological heterogeneity in graphene types, concentrations, dispersion techniques, base material compositions, and outcome measures precluded quantitative meta-analysis. Variability in the reporting of graphene loading concentrations and functionalization methods across studies further complicated direct comparisons. Additionally, the lack of standardized aging protocols and long-term degradation testing limits the applicability of findings to clinical scenarios. Publication bias may also be present, as studies with positive outcomes are more likely to be published. Future research

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should prioritize standardized experimental protocols, clinically relevant aging simulations, and prospective clinical trials to validate laboratory findings.

## CONCLUSIONS

Graphene-reinforced dental materials exhibit promising mechanical reinforcement and antimicrobial properties in laboratory settings, supporting their potential future use in restorative and prosthodontic dentistry. However, clinical translation requires standardized formulations, long-term safety evaluations, and controlled clinical trials to confirm durability and biocompatibility before routine clinical adoption can be recommended.

## Authors' Contribution

Conceptualization: MN, ZQ
Methodology: SY
Formal analysis: MP, KM
Writing and Drafting: MN, AA, ZQ
Review and Editing: MN, SY, AA, MP, KM, ZQ

All authors approved the final manuscript and take responsibility for the integrity of the work.

## Conflicts of Interest

All the authors declare no conflict of interest.

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