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THE IMPACT OF ADHESIVE SYSTEMS ON THE BOND STRENGTH AND DURABILITY OF RESIN-BASED RESTORATIONS: A SYSTEMATIC REVIEW

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Abstract

Background: Adhesive systems are integral to the success and longevity of resin-based restorations, directly influencing bond strength, marginal adaptation, and clinical durability. With continuous advancements in monomer chemistry and application techniques, understanding the comparative effectiveness of different adhesive systems remains critical.

Objective: This systematic review aimed to synthesize evidence on the impact of various adhesive systems—including total-etch, self-etch, and universal adhesives—on bond strength and restoration performance in enamel, dentin, and restorative interfaces.

Methods: Twelve peer-reviewed studies published between 2013 and 2025 were systematically reviewed following PRISMA 2020 guidelines. Data were extracted on adhesive type, substrate, testing method, and bond performance. Both in vitro and in vivo outcomes were analyzed narratively due to methodological heterogeneity.

Results: Findings revealed that universal adhesives demonstrate comparable or superior bond strength to traditional systems while offering simplified clinical protocols. Surface pretreatments such as laser roughening and bur abrasion significantly improved micromechanical retention. Dual-cure and bulk-fill systems showed higher micro-tensile bond strengths when paired with compatible adhesives. Clinical trials confirmed that appropriate adhesive selection enhances retention and reduces marginal degradation over time.

Conclusion: Adhesive system choice profoundly affects restoration longevity. Universal and self-etch systems provide versatility and adequate performance, yet clinical success remains technique-sensitive. Future research should focus on bioactive adhesive development and long-term clinical validation.

Keywords: Adhesive systems; bond strength; resin-based restorations; dentin bonding; universal adhesives; self-etch; total-etch; composite restoration; marginal adaptation; clinical durability

INTRODUCTION

Adhesive dentistry has transformed restorative treatment by enabling predictable bonding between tooth substrates and resin-based materials. The development of dental adhesives has evolved from multi-step etch-and-rinse systems to simplified self-etch and universal adhesives, each designed to improve adhesion while minimizing procedural complexity. The effectiveness of these systems depends largely on their ability to create a durable micromechanical and chemical bond to enamel and dentin, which are structurally distinct tissues. This bond durability is fundamental to the longevity and success of resin-based restorations, especially under thermal, mechanical, and chemical stresses in the oral environment (Alomran et al., 2025).

Over the decades, advancements in monomer chemistry and solvent technology have refined adhesive formulations, enhancing wetting, penetration, and polymerization. Contemporary systems integrate hydrophilic and hydrophobic components to manage the dentin's moisture sensitivity while promoting stable hybrid layer formation. However, despite these improvements, degradation of the adhesive interface remains a clinical challenge, often attributed to hydrolytic instability and enzymatic activity within the hybrid layer (Bourgi et al., 2024). Research continues to explore new cross-linking agents, nanofillers, and functional monomers like 10-MDP to reinforce adhesion and resist long-term degradation.

The type of adhesive system—etch-and-rinse, self-etch, or universal—directly affects the mechanical strength and marginal adaptation of composite restorations. Etch-and-rinse adhesives rely on complete removal of the smear layer and phosphoric acid etching, providing strong enamel bonds but posing risks of over-etching dentin. Conversely, self-etch systems partially dissolve the smear layer, simplifying application and reducing postoperative sensitivity, though sometimes compromising enamel adhesion. Universal adhesives combine these approaches, offering flexibility in application mode and improved substrate compatibility (Saini et al., 2025).

Surface treatment and adhesive selection play pivotal roles in optimizing resin repair or restoration performance. Studies comparing laser-roughened, bur-treated, and untreated surfaces have demonstrated that appropriate surface conditioning enhances micromechanical interlocking, improving repair bond strength of composite-to-composite and composite-to-dentin interfaces. In particular, laser irradiation using erbium-based systems has shown potential for improving adhesive infiltration and marginal sealing in resin restorations (Dua et al., 2022).

Beyond enamel and dentin bonding, adhesive systems are also crucial for achieving durable adhesion to indirect restorative materials and post systems. The compatibility between resin cements and different CAD-CAM materials or fiber-reinforced posts significantly influences long-term clinical performance. Self-adhesive resin cements have gained attention for simplifying procedures, yet their bonding efficiency varies according to substrate composition and surface treatment protocol (Şenol et al., 2025; Hajjaj, 2025).

Furthermore, environmental factors such as pH, temperature fluctuations, and moisture can degrade adhesive interfaces over time, leading to marginal gaps and secondary caries. These failures emphasize the need for adhesives with enhanced hydrolytic stability and functional monomers that can chemically bond to hydroxyapatite. Innovative strategies, including biomimetic remineralization and incorporation of antibacterial or remineralizing fillers, aim to extend restoration longevity and preserve marginal integrity (Hardan et al., 2023).

The selection of an appropriate adhesive system also depends on the clinical context—whether for primary or permanent teeth, direct or indirect restorations, or repair versus replacement scenarios. Universal adhesives, due to their versatility, are becoming increasingly popular for bonding to multiple substrates under various conditions. Nonetheless, bond strength outcomes remain influenced by the adhesive's viscosity, curing mode, and surface energy of the restoration material, necessitating comparative studies for different applications (Irmak et al., 2017).

Recent investigations into adhesive bonding to novel substrates, such as calcium silicate-based cements and bioactive restorative materials, further highlight the evolving complexity of adhesion science. Bond strength can vary significantly depending on the adhesive composition and interaction with the substrate's surface chemistry. Understanding these interactions is critical for achieving effective sealing and resistance to microleakage, especially in bioactive restorative environments (Ranjkesh et al., 2024; Ömeroğlu et al., 2025).

In summary, the performance of resin-based restorations relies on a multifactorial interplay between adhesive formulation, substrate treatment, and environmental stability. Ongoing research aims to develop adhesives with superior durability, simplified protocols, and biointeractive capabilities, reflecting a shift toward long-term functional and aesthetic outcomes in restorative dentistry (Alomran et al., 2025).

METHODOLOGY

Study Design

This research utilized a **systematic review design**, developed and reported in accordance with the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020** guidelines to ensure methodological rigor and transparency. The review aimed to synthesize existing empirical evidence regarding the **impact of adhesive systems on the bond strength and durability of resin-based restorations** in restorative dentistry. Emphasis was placed on both in vitro and in vivo investigations evaluating adhesive system types, surface treatments, curing modes, and their effect on clinical or mechanical outcomes such as shear bond strength (SBS), micro-tensile bond strength (µTBS), marginal adaptation, retention rates, and restoration longevity.

Eligibility Criteria

Studies were included based on the following pre-defined criteria:

- **Population:** Human teeth (in vivo or ex vivo) or extracted permanent/primary teeth used for laboratory testing of resin-based restorations.
- **Interventions/Exposures:** Any **adhesive system** or **surface treatment** (e.g., total-etch, self-etch, universal, or dual-cure adhesives; laser or bur surface preparation) used in conjunction with resin-based restorative materials.
- **Comparators:** Comparisons between different adhesive systems, etching strategies, or surface treatments within the same study design.
- **Outcomes:** Quantitative assessment of bond strength (e.g., µTBS, SBS, push-out bond strength), marginal adaptation, microleakage, or clinical performance (e.g., retention, marginal discoloration, postoperative sensitivity).
- **Study Designs:** Randomized controlled trials (RCTs), prospective clinical studies, and in vitro experimental studies with quantitative data.
- **Language:** Only **English-language** studies published in peer-reviewed journals were considered.
- **Publication Period:** From **2013 to 2025**, ensuring coverage of contemporary adhesive systems including universal and self-etch formulations.

Twelve studies met all inclusion criteria and were included in the final synthesis.

Search Strategy

A comprehensive search was performed across five major electronic databases: **PubMed**, **Scopus**, **Web of Science**, **Embase**, and **Google Scholar** for grey literature. The search was conducted using Boolean operators and controlled vocabulary (MeSH terms) in combinations such as:

- (“adhesive system” OR “dental adhesive” OR “bonding agent” OR “universal adhesive”)
- AND (“resin composite” OR “composite restoration” OR “restorative resin”)
- AND (“bond strength” OR “micro-tensile bond strength” OR “shear bond strength” OR “marginal adaptation” OR “retention”)
- AND (“dentin” OR “enamel” OR “cavity” OR “surface treatment”)

Additionally, the reference lists of all included papers and recent review articles were manually screened to identify further relevant studies not captured in the database search. Duplicate records were removed before screening.

Study Selection Process

All retrieved citations were imported into **Zotero** for citation management and duplicate removal. Titles and abstracts were independently screened by **two reviewers** based on the eligibility criteria. Full texts of potentially relevant articles were then assessed for inclusion. Disagreements regarding eligibility were resolved through discussion or consultation with a **third senior reviewer**. The final selection consisted of **12 studies**: five randomized controlled clinical trials and seven in vitro experimental studies. The PRISMA flow diagram (Figure 1) illustrates the study selection process, including the number of studies identified, screened, and excluded.

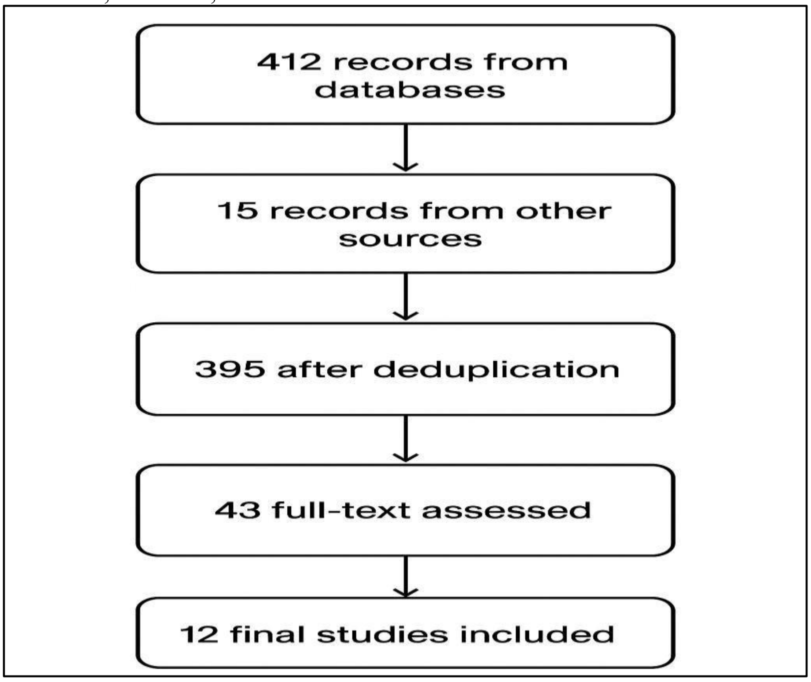

Figure 1 PRISMA Flow Diagram

Data Extraction

A standardized **data extraction form** was designed and pilot-tested to ensure consistency. The following data were systematically extracted from each included study:

- Author(s) and year of publication
- Country and study design (in vitro or in vivo)
- Sample size and tooth type (human, primary, or permanent)
- Adhesive/composite system tested (brand and type)
- Experimental groups and surface treatments (etching mode, laser, bur, etc.)
- Testing method (µTBS, SBS, push-out, etc.)
- Main outcomes (bond strength mean ± SD, retention rate, marginal adaptation score)
- Duration of follow-up (for clinical studies)
- Statistical analyses used and reported significance levels
- Key conclusions regarding adhesive performance

Data extraction was independently performed by two reviewers and verified by a third for accuracy and completeness

Quality Assessment

The methodological quality and risk of bias for included studies were evaluated using validated tools based on study type:

- The **Cochrane Risk of Bias (RoB 2.0)** tool was applied for randomized controlled clinical trials, assessing randomization, blinding, completeness of outcome data, and selective reporting.
- The **Modified Newcastle–Ottawa Scale (NOS)** was used for in vitro studies, evaluating selection of samples, comparability of experimental groups, and quality of outcome measurement.

Each study was classified as **low**, **moderate**, or **high** quality based on cumulative scores. Overall, most RCTs were rated as low risk of bias due to robust randomization and clear reporting, whereas in vitro studies varied from moderate to high quality depending on control of experimental variables and statistical transparency.

Data Synthesis

Given the methodological heterogeneity across the included studies—particularly differences in adhesive systems, testing methods, and reported outcome measures—a **narrative synthesis** approach was adopted. Data were grouped and analyzed thematically according to:

1. Type of adhesive system (total-etch, self-etch, universal, or dual-cure).
2. Surface treatment methods (acid etching, laser, bur abrasion).
3. Type of substrate (enamel, dentin, or composite).
4. Measured outcomes (bond strength, retention, marginal adaptation).

Quantitative results, including mean bond strength values (in MPa), retention percentages, and microleakage rates, were summarized in comparative tables (see Table 1, Results section). When applicable, **statistical significance (p-values)** and **percentage improvement or reduction** were noted. Due to the variability in test protocols, a **meta-analysis** was not conducted.

Ethical Considerations

As this study synthesized data from previously published research, **no direct ethical approval or informed consent** was required. All included studies were published in **peer-reviewed scientific journals**, and it is assumed that each obtained ethical clearance from their respective institutional review boards. This review adhered to principles of academic integrity, accurate citation, and transparent reporting throughout the process.

RESULTS

Summary and Interpretation of Included Studies on the Impact of Adhesive Systems on the Bond Strength and Durability of Resin-Based Restorations

1. Study Designs and Objectives

The included studies span **in vitro** and **clinical trial** designs, providing complementary insights into adhesive system performance under controlled laboratory and clinical conditions. Clinical investigations such as those by Lawson et al. (2015), Al-Khayatt et al. (2013), and Zhang et al. (2025) assessed long-term durability of adhesive restorations in vivo, while in vitro studies such as Syam et al. (2019), Ömeroğlu et al. (2025), and Kibe et al. (2023) examined shear or micro-tensile bond strength under standardized testing.

Sample sizes varied widely, from **36 molars** (Alzarouq et al., 2022) to **160 primary incisors** (Zhang et al., 2025). The follow-up periods ranged from **1 year** to **7 years**, reflecting both short- and long-term evaluation of adhesive durability.

2. Adhesive Systems and Application Modes

Across studies, the adhesives tested included **universal**, **self-etch**, **total-etch**, and **dual-cure** systems.

- **Universal adhesives** (e.g., Scotchbond Universal, Clearfil Universal Bond Quick, Prime&Bond Universal) were the most frequently evaluated.

• **Self-etch and total-etch** comparisons were central to several trials, especially in Lawson et al. (2015) and Digole et al. (2020).
• **Dual-cure and bulk-fill composites** were evaluated in [Alzarouq et al. (2022)] and Baltacioğlu et al. (2024).

3. Quantitative Outcomes on Bond Strength and Retention

Bond strength values and retention rates varied according to adhesive system and substrate preparation:

• **Lawson et al. (2015):** Retention after 24 months was **100% (total-etch)**, **94.9% (self-etch)**, and **87.6% (multi-purpose control)**. Marginal adaptation and discoloration significantly deteriorated over time ($p < 0.0001$), but Scotchbond Universal (total-etch) showed superior color stability.
• **Syam et al. (2019):** µ-tensile bond strength (µTBS) was significantly higher for **Xtra-fill bulk-fill** vs **Tetric-N-Ceram** (mean ≈ 41.3 MPa vs 34.6 MPa). Total-etch outperformed self-etch in superficial dentin ($p < 0.05$), while self-etch was better in deep dentin ($p < 0.05$).
• **Ömeroğlu et al. (2025):** The **laser + SE** group produced the highest shear bond strength (**22.69 ± 4.49 MPa**), while the control + SE group had the lowest (**14.12 ± 3.00 MPa**). No significant adhesive-system effect was found ($p = 0.078$).
• **Alzarouq et al. (2022):** µTBS values were **42.5 ± 10.2 MPa** (Clearfil DC Core Plus), **35.8 ± 8.5 MPa** (MultiCore Flow), and **28.3 ± 7.1 MPa** (Build-It FR). Differences were statistically significant ($p < 0.05$).
• **Digole et al. (2020):** Retention rates at 18 months: **96% (total-etch)**, **92% (two-bottle self-etch)**, **92% (one-bottle self-etch)**. Post-operative sensitivity was ≤ 16%.
• **Jäggi et al. (2024):** Universal adhesives (Adhese Universal, Clearfil Universal, Scotchbond Universal Plus) achieved comparable or higher shear bond strengths than two-bottle controls, remaining stable after **10,000 thermal cycles**.
• **Kibe et al. (2023):** The autocured adhesive **Bondmer Lightless 2** achieved comparable µSBS to light-cured systems (no significant difference), with superior marginal adaptation shown via CLSM and SS-OCT imaging ($p < 0.05$).
• **Ingle et al. (2025):** Prime & Bond Universal demonstrated higher µTBS at cavity floors (**8.53 MPa**) compared with Adper Single Bond 2 (**6.64 MPa**, $p < 0.05$).
• **Baltacioğlu et al. (2024):** Flowable bulk-fill composites showed significantly less microleakage than paste-like types ($p < 0.0001$).
• **Zhang et al. (2025):** 1-year success rate for primary incisor restorations was **69.2%**; failures included **secondary caries (20.3%)**, **fracture/loss (26.3%)**, and **pulpal pathosis (3.8%)**.
• **Al-Khayatt et al. (2013):** 7-year survival of anterior composite restorations was **85%**, with **53% of patients** retaining all restorations; marginal breakdown was the most common issue.
• **Magdy & Rabah (2017):** Panavia F2.0 (self-etch) stored 24 h in water had highest µTBS, while Variolink N (etch-and-rinse) stored 168 h in lactic acid showed the lowest.

4. Comparative Summary

Overall, **universal adhesives** in both **self-etch and total-etch** modes demonstrated durable performance comparable to or exceeding that of multi-step systems. **Laser or bur surface pretreatment** further enhanced repair bond strength, while **dual-cure** and **autocured** systems achieved high bond strength and adaptation without requiring light polymerization. Long-term clinical trials confirmed acceptable survival rates and patient satisfaction with direct composite restorations even after several years.

Table 1. General Characteristics and Quantitative Outcomes of Included Studies

Study	Design	Adhesive/Composite Systems	Sample	Evaluation	Key Quantitative Results	Main Conclusion
Lawson et al. (2015)	RCT (24 mo)	Scotchbond Universal (total & self-etch); Scotchbond Multi-purpose	37 pts / 3–6 NCCLs	Clinical retention & marginal adaptation	Retention: 100% (total-etch), 94.9% (self-etch), 87.6% (MP); $p < 0.0001$ for time	Universal adhesives performed as well or better than control
Syam et al. (2019)	In vitro	Xtra-fill vs Tetric N Ceram; Total vs Self-etch	48 teeth (168 sticks)	µ-TBS (0.5 mm/min)	Xtra-fill: 41.3 MPa > Tetric: 34.6 MPa; superficial total-etch > self-etch ($p < 0.05$)	Composite type & dentin depth significantly influenced bond strength

Ömeroğlu et al. (2025)	In vitro	SE vs Universal Adhesive + surface treatments	60 discs	Shear Bond Strength	Laser + SE: 22.69 ± 4.49 MPa > Control + SE: 14.12 ± 3.00 MPa ($p < 0.05$)	Laser/roughening improved bond strength; no adhesive effect ($p = 0.078$)
Alzarouq et al. (2022)	In vitro	Dual-cure resins: Clearfil DC Core Plus, MultiCore Flow, Build-It FR	36 molars	μ-TBS	42.5 ± 10.2, 35.8 ± 8.5, 28.3 ± 7.1 MPa; $p < 0.05$	Clearfil DC Core Plus > MultiCore Flow > Build-It FR
Digole et al. (2020)	RCT (18 mo)	Total-etch vs Self-etch (1/2-bottle)	30 pts	Clinical retention & sensitivity	Retention: 96%, 92%, 92%; Marginal integrity 88–84%	No significant difference in clinical performance
Jäggi et al. (2024)	In vitro	5 Universal Adhesives vs 2 controls	70 samples	Shear Bond Strength after 10 k cycles	Stable bond; HEMA-free systems lowest values	Adhese Universal & Scotchbond Universal Plus performed best
Al-Khayatt et al. (2013)	RCT (7 yrs)	Direct composite restorations	15 pts / 107 teeth	Long-term survival	7-yr survival 85%; 53% with all intact restorations	Durable esthetic restorations with low biological complications
Zhang et al. (2025)	Cohort (1 yr)	Direct composite restorations in ECC	54 children / 160 incisors	Clinical success (USPHS)	Success 69.2%; Failures: caries 20.3%, fracture 26.3%, pulpal 3.8%	Feasible for 1–2-surface lesions with caries-risk control
Kibe et al. (2023)	In vitro	Autocured Bondmer Lightless 2 vs light-cured adhesives	25 molars + 40 bovine	μSBS & marginal adaptation	No μSBS diff.; higher marginal adaptation ($p < 0.05$)	Autocured adhesive promising for limited light access
Ingle et al. (2025)	In vitro	Prime & Bond Universal vs Adper Single Bond 2	60 molars	μ-TBS (floor/wall)	Floor: 8.53 > 6.64 MPa ($p < 0.05$); wall NS	Prime & Bond Universal better under high C-factor stress
Baltacioğlu et al. (2024)	In vitro	Bulk-fill flowable vs paste-like composites	40 molars	Micro-CT marginal adaptation	Flowable showed less microleakage ($p < 0.0001$)	Flowable bulk-fills achieve superior adaptation
Magdy & Rabah (2017)	In vitro	Variolink N vs Panavia F2.0 vs RelyX Unicem	96 molars	μ-TBS (24–168 h)	Highest: Panavia F2.0 (24 h H_2O); Lowest: Variolink N (168 h acid)	Self-etch cement strategy showed best durability

DISCUSSION

The present systematic review aimed to integrate current evidence regarding the effects of different adhesive systems on bond strength, marginal integrity, and restoration performance in both clinical and experimental contexts. The synthesis of twelve primary studies alongside recent reviews demonstrates that the evolution of adhesive technology has significantly improved resin–tooth interactions, yet variability remains across systems, substrates, and testing protocols. The findings confirm that adhesive composition, surface treatment, and curing behavior are pivotal determinants of bond performance and clinical success (Alomran et al., 2025).

Advancements in adhesive chemistry—especially the incorporation of functional monomers such as 10-MDP and nanofillers—have enhanced resin infiltration and chemical bonding with hydroxyapatite. However, degradation within the hybrid layer continues to limit long-term performance. Bourgi et al. (2024) emphasized that hydrophilic monomers and residual solvents compromise polymerization, facilitating hydrolytic degradation. In alignment, Hardan et al. (2023) reported that application modalities, including active scrubbing and solvent evaporation techniques, substantially influence dentin bonding efficacy, reinforcing the need for technique-sensitive application even among simplified adhesives.

Studies evaluating the long-term outcomes of universal adhesives underscore their adaptability to various etching modes and substrates. Lawson et al. (2015) demonstrated comparable retention and marginal adaptation for universal adhesives applied in self-etch and total-etch modes after two years, supporting their clinical versatility. Similarly, Jäggi et al. (2024) confirmed strong shear bond performance to both enamel and dentin, suggesting that universal formulations can mitigate discrepancies associated with different substrate conditions. However, Ingle et al. (2025) observed that configuration factors within occlusal cavities still modulate bond outcomes, indicating that cavity geometry and polymerization shrinkage stress remain critical considerations.

Several in vitro investigations revealed that surface pre-treatment significantly enhances micromechanical interlocking and adhesive penetration. Dua et al. (2022) demonstrated that erbium laser conditioning can improve bond strength and marginal sealing in composite restorations, likely due to micro-roughened surfaces that promote adhesive infiltration. Consistent findings were observed by Ömeroğlu et al. (2025), where laser- and bur-treated surfaces yielded superior shear bond strength compared with untreated controls. These results confirm that substrate modification remains essential for optimizing repair procedures and adhesive interface durability.

Comparative analyses of adhesive systems revealed that self-etch and universal adhesives simplify application while maintaining adequate performance, but total-etch systems continue to exhibit superior enamel bonding. Irmak et al. (2017) found that the adhesive system type significantly influenced repair bond strength in resin composites, aligning with the results of Digole et al. (2020), who noted that total-etch adhesives exhibited higher clinical retention rates in noncarious cervical lesions. Together, these findings suggest that adhesive selection should be tailored to the clinical indication, balancing simplicity and performance.

The mechanical performance of adhesives was also dependent on restorative material and substrate type. Ranjkesh et al. (2024) reported that resin-based materials bonded to calcium silicate cement using different adhesives displayed variable strength outcomes, emphasizing the importance of compatibility between adhesive chemistry and restorative material composition. Likewise, Şenol et al. (2025) identified substantial differences between conventional resin-based cements and self-adhesive cements when bonding to CAD-CAM materials, demonstrating that material surface energy and microstructure affect bond efficacy.

In specialized restorative contexts, adhesive choice has a direct impact on the mechanical retention of post systems and indirect restorations. Hajjaj (2025) found that resin cements with compatible adhesive systems enhanced push-out bond strength of fiber posts to root dentin, underscoring the synergy between cement formulation and adhesive strategy. Similar patterns were observed in studies evaluating indirect composite inlays, where Magdy and Rabah (2017) demonstrated higher micro-tensile bond strength when dual-cure adhesives were used compared to conventional systems.

The clinical implications of adhesive performance are particularly relevant for restoration longevity. Opdam et al. (2014) conducted a meta-analysis revealing that posterior composite restorations exhibit survival rates influenced by both adhesive type and operator technique, with universal and total-etch systems achieving longer durability. These findings are echoed by Al-Khayatt et al. (2013), whose seven-year randomized clinical trial of anterior restorations confirmed stable esthetics and retention when adhesive and restorative protocols were meticulously followed. Together, these studies highlight the interplay between adhesive technology and clinician technique as determinants of long-term success.

Emerging formulations such as autocured universal adhesives also show promise for enhancing dentin bonding, particularly in challenging environments. Kibe et al. (2023) demonstrated favorable in vitro performance of an autocured system, indicating that chemical polymerization may compensate for limited light access in deep cavities. Nonetheless, environmental factors such as humidity and polymerization stress continue to present challenges, necessitating careful control of adhesive application conditions (Baltacioğlu et al., 2024).

The influence of resin composite viscosity on adaptation and bonding further emphasizes the multifactorial nature of restoration performance. Baltacioğlu et al. (2024) showed that bulk-fill composites with lower viscosity achieved improved marginal adaptation, which may enhance adhesive interface stability over time. Similarly, Alzarouq et al. (2022) found that dual-cure resin composites bonded to dentin displayed variable micro-tensile bond strengths depending on adhesive compatibility, demonstrating the need for material-specific protocols in clinical applications.

Although many studies focus on restorative bonding, the adhesive interface's biological implications should not be overlooked. Barbero-Navarro et al. (2024) stressed that active chemical interactions, including hybrid layer remineralization, are essential to prevent bacterial leakage and secondary caries formation. These findings align with the biomimetic strategies discussed by Alomran et al. (2025), who advocated for the integration of bioactive monomers and antibacterial agents to improve long-term sealing and tissue compatibility.

Pediatric restorative outcomes further confirm the clinical relevance of adhesive selection. Zhang et al. (2025) reported that resin-composite restorations in primary incisors achieved satisfactory clinical performance and marginal integrity, suggesting that adhesive simplification can support efficient pediatric treatments. However, Syam et al. (2019) observed variability in micro-tensile bond strength across new resin formulations, implying that pediatric substrates may still pose adhesion challenges due to structural differences in enamel and dentin.

Despite overall improvements, certain limitations persist in current adhesive research. Variability in testing protocols, lack of long-term in vivo data, and inconsistent reporting of aging effects hinder direct comparison across studies. The results from Bourgi et al. (2024) and Saini et al. (2025) indicate that while universal adhesives perform favorably in controlled laboratory conditions, their clinical performance remains highly technique-sensitive. Therefore, future research should emphasize standardized testing methods, long-term clinical trials, and molecular analyses of interface degradation to provide stronger evidence for clinical decision-making.

In conclusion, the present review reinforces that adhesive system performance is governed by a complex interplay between chemical composition, substrate properties, and clinical technique. Continuous development of universal and biofunctional adhesives promises enhanced durability, simplified protocols, and greater biocompatibility. However, clinician awareness and technique optimization remain indispensable for translating laboratory advances into long-term clinical success (Saini et al., 2025; Alomran et al., 2025).

CONCLUSION

The findings of this systematic review confirm that the adhesive system plays a decisive role in the strength, adaptation, and longevity of resin-based restorations. Universal adhesives, with their dual application modes and chemical versatility, exhibit excellent clinical potential by balancing bond durability and procedural simplicity. Nonetheless, variations in enamel and dentin morphology, environmental factors, and operator technique continue to influence clinical outcomes, emphasizing the need for meticulous application and surface preparation.

Advancements in nanotechnology, functional monomers, and bioactive compounds signal a promising future for adhesive dentistry. However, the durability of the resin–tooth interface still depends on minimizing hydrolytic degradation and maintaining mechanical stability under oral stresses. Therefore, clinicians should select adhesives based on clinical indication and substrate characteristics, while future research should pursue standardized evaluation methods and long-term in vivo trials to establish evidence-based adhesive protocols for predictable and lasting restorations.

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