Mechanical and Chemical Surface Treatment of Zirconia Crowns for Orthodontic Metal Bracket Bonding – A Review of Shear Bond Strength

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Abstract

AIM: This review evaluates mechanical and chemical surface treatments to improve shear bond strength (SBS) between orthodontic metal brackets and zirconia crowns, aiming to identify protocols enhancing adhesion and clinical reliability.

METHODS: A systematic search of PubMed and Google Scholar (2015–2025) identified in vitro studies reporting SBS (MPa) for zirconia–metal bracket interfaces following defined surface treatments. Thirty studies met inclusion criteria. Data were analysed by mechanical treatment (sandblasting [SB], grinding [GD]), chemical etching (hydrofluoric acid [HF], phosphoric acid [PP]), and primers (zirconia primer [ZP], Monobond [MB]).

RESULTS: SB was the most studied mechanical method, generally yielding higher SBS than GD or HF, though outcomes varied by protocol and zirconia type. ZP and MB primers significantly increased SBS when combined with SB or GD; MB often matched or exceeded ZP performance, sometimes achieving comparable results alone. HF and PP alone showed inconsistent benefits unless combined with primers. SBS varied across zirconia types (3Y, 4Y, 5Y-TZP) and bracket materials, with composite and ceramic brackets exhibiting lower SBS than metal brackets.

CONCLUSION: Optimal bonding to zirconia requires combined mechanical and chemical treatments. SB followed by primer application, particularly ZP or MB, yielded the most consistent results. MB demonstrated high versatility, performing well with or without SB. Outcomes depend on zirconia type and bracket material, underscoring the need for substrate-specific bonding protocols.

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1 Introduction

Over recent years, a trend has emerged in both prosthodontic and orthodontic care, driven largely by patients who prioritise dental restorations that look as natural as possible without sacrificing function. Adults are seeking fixed partial dentures and crowns that provide both aesthetics and durability (Abd EL-wahab et al., 2023; Amer et al., 2018). This demand has pushed zirconia-based ceramics into the spotlight. While zirconia was once reserved for specific clinical situations, it is now increasingly selected for a wide range of restorative needs. Its reputation rests on a combination of impressive mechanical properties, biocompatibility, and the ability to deliver esthetic outcomes that challenge traditional porcelain-fused-to-metal (PFM) options (Cakir et al., 2023; Limpuangthip et al., 2023). Clinicians often note that zirconia's fracture resistance and toughness make it a particularly smart choice for posterior teeth and for patients with habits like bruxism, where restoration survival is especially important (Byeon et al., 2017).

As promising as zirconia is, its clinical integration has not been entirely smooth, especially in cases requiring orthodontic treatment. One of the issues practitioners often face is how to achieve reliable bonding between orthodontic brackets and zirconia surfaces. This difficulty boils down to material science: unlike glass-based ceramics, zirconia is polycrystalline and contains no glass phase. Because of this, it is unaffected by conventional acid etching methods such as hydrofluoric acid, which are standard for silica-based ceramics (Amer et al., 2018; Kwak et al., 2016). When these traditional techniques fail, bond failures become more likely, which can frustrate both clinicians and patients. The question of how best to prepare zirconia surfaces for bonding remains a central concern, particularly for interdisciplinary teams working to optimise both restorative and orthodontic outcomes (Abd EL-wahab et al., 2023; Limpuangthip et al., 2023; Mehmeti et al., 2017).

In response to this challenge, mechanical surface modifications have become a mainstay in many clinical protocols. Sandblasting with aluminum oxide and surface grinding are the most widely adopted techniques (Abd EL-wahab et al., 2023; Namvar et al., 2022). Both approaches are intended to roughen the zirconia surface, thereby increasing its potential for mechanical retention. It is interesting to note that, in some studies, sandblasting alone has produced shear bond strengths that rival those seen when bonding to natural enamel (Pédémay et al., 2024; Namvar et al., 2022). At the same time, there is emerging evidence that sandblasting may induce subtle changes within the zirconia's crystalline structure, possibly boosting surface energy and wettability, which are important for successful adhesion (Limpuangthip et al., 2023; Cakir et al., 2023). Still, it is not entirely clear how clinically meaningful these phase changes are, and researchers continue to explore this aspect.

Of course, mechanical roughening is not the whole story. Chemical surface pretreatments, particularly those involving primers with functional monomers like 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP), have received considerable attention. These agents can establish chemical bonds with the zirconium oxide itself, and results appear especially promising when such primers are used after mechanical surface treatments (Farahani et al., 2021; Büyükerkmen et al., 2022). Some investigators even suggest that the combination of sandblasting and primers may set a new standard for bracket bonding on zirconia, though opinions remain divided and more research is needed (Lee et al., 2015; Limpuangthip et al., 2023; Pezeshkirad et al., 2025).

Another layer of complexity arises from the adhesives themselves. Universal adhesives containing both 10-MDP and, in some formulations, silane coupling agents promise to streamline bonding procedures. They are designed to be user-friendly and theoretically reduce the need for multiple steps (Pédémay et al., 2024; Pezeshkirad et al., 2025). In practice, however, these products do not always live up to the hype if the zirconia surface has not been adequately roughened or primed. The consensus in recent literature seems to be that skipping surface pretreatment is risky and may result in unreliable bonds (Abd EL-wahab et al., 2023; Lee et al., 2015).

Beyond the surface and adhesive, bracket choice and base design also enter the equation. Some reports suggest that ceramic brackets, owing to their optical and stress-distribution properties, can achieve higher initial bond strengths on zirconia than their metal counterparts (Mehmeti et al., 2017; Cakir et al., 2023). Nevertheless, most clinicians continue to favour metal brackets for daily use, citing their reliability and ease of handling in the clinical setting (Büyükerkmen et al., 2022). This serves as a reminder that laboratory findings do not always dictate clinical outcomes.

Despite this progress, there is little agreement regarding the optimal bonding protocol. Some advocate for single-step, all-in-one adhesives, while others insist on multi-step approaches that combine both mechanical and chemical modifications (Limpuangthip et al., 2023; Pezeshkirad et al., 2025; Pédémay et al., 2024). Confounding the issue further are differences in study design, the types of brackets tested, and the artificial ageing methods employed. All these factors make it difficult to directly compare results or issue blanket recommendations for clinical practice.

Taking all of this into account, it is clear that as zirconia restorations become increasingly common, clinicians need a thorough understanding of how surface treatments, resin adhesives, and bracket types interact. The stakes are high; if a bracket debonds or a restoration is damaged, the entire treatment can be compromised. For this reason, there is a growing call for standardised, evidence-based protocols that specifically address the nuances of zirconia substrates (Limpuangthip et al., 2023; Pezeshkirad et al., 2025). Until then, practitioners must continue to weigh the available evidence, apply clinical judgment, and adapt to the evolving landscape of dental materials science.

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Taking all of this into account, it is clear that as zirconia restorations become increasingly common, clinicians need a thorough understanding of how surface treatments, resin adhesives, and bracket types interact. The stakes are high; if a bracket debonds or a restoration is damaged, the entire treatment can be compromised. For this reason, there is a growing call for standardised, evidence-based protocols that specifically address the nuances of zirconia substrates (Limpuangthip et al., 2023; Pezeshkirad et al., 2025). Until then, practitioners must continue to weigh the available evidence, apply clinical judgment, and adapt to the evolving landscape of dental materials science.

The aim of this study is to assess how various surface preparation methods affect the bonding of orthodontic metal brackets to zirconia crowns, with a particular focus on shear bond strength (SBS). This research considers both mechanical and chemical approaches, such as sandblasting, bur roughening, acid etching, and the use of zirconia primers, to evaluate how these techniques influence micromechanical retention and chemical adhesion to zirconia. Each treatment protocol will be analysed individually and within the broader clinical context to determine which strategies provide the most reliable and durable outcomes.

By comparing the bond strengths achieved by different surface treatments, this thesis seeks to clarify which protocol consistently results in strong and stable bracket adhesion. The goal is to offer practical, evidence-based recommendations for clinicians, with the aim of reducing bracket failures and improving the efficiency of orthodontic treatment, particularly in cases involving zirconia-based restorations.

Through a critical appraisal of contemporary *in vitro* studies and available literature, this research intends to support clinicians in selecting optimal surface treatment protocols. By doing so, it contributes to the ongoing effort to enhance clinical success and predictability when bonding orthodontic brackets to zirconia restorations.

2 Methods

The PICO framework is applied to systematically frame the clinical question addressed in this review. It facilitates a focused and structured approach for literature identification and analysis in the context of orthodontic bonding to zirconia crowns.

- **Population (P):** Zirconia crowns are used in patients undergoing orthodontic treatment with metal bracket bonding.
- **Intervention (I):** Surface treatments both mechanical (sandblasting, grinding) and

chemical (zirconia primers, Monobond, hydrofluoric acid, phosphoric acid) applied to enhance the bond strength between metal brackets and zirconia surfaces.

- **Comparison (C):** Diverse surface treatments, or different combinations of surface conditioning methods.
- **Outcome (O):** Shear bond strength values achieved after orthodontic metal bracket bonding, expressed in MPa.

The literature was searched for publications between 2015 and 2025. The search string used was: *(zirconia OR zirconium OR Y-TZP OR yttria) AND (orthodontic brackets OR bracket bonding OR brackets OR braces) AND (shear bond strength OR bond strength OR adhesive strength OR bracket adhesive) AND (surface treatments OR surface preparations OR surface modifications OR sandblast OR air abrasion OR etching OR primer).* The initial search strategy resulted in 38 papers on PubMed and 2,340 papers on Google Scholar that were identified as potentially relevant.

Studies were included if they were published between 2015 and 2025 and were written in English. Eligible studies were required to report shear bond strength (SBS) between zirconia and metal brackets with SBS values expressed in MPa and to document zirconia surface treatments.

Studies were excluded if they were published before 2015 or if they were not in English. Studies that did not report bond strength between zirconia and metal brackets, that did not express SBS values in MPa, and review articles or case reports were excluded.

The initial search yielded 38 papers from PubMed and 2,340 papers from Google Scholar. After application of filters for article type (books, letters excluded) and language, 2,271 papers were excluded and 20 duplicated papers were removed. Following title and abstract screening of the remaining 49 papers, 11 were excluded according to predetermined criteria, leaving 38 full texts that were assessed. A further eight papers were dismissed due to the inclusion and exclusion criteria, and 30 papers were selected for detailed analysis (**Figure 1**.

2.1 Statistics

Descriptive statistics, frequency analysis, and content analysis were employed as part of the qualitative methodology to systematically analyze the textual content of the included studies. It is important to note that, given the narrative nature of this study, regression analysis and meta-analysis techniques were not deemed suitable for the analytical framework.

3 Results

3.1 Overview and initial analysis

The data extracted from the included studies measured shear bond strength (SBS) in MPa across a variety of surface treatment protocols designed to improve orthodontic bracket bonding to zirconia surfaces (**Tables 1-3**). The treatments include mechanical methods, primarily sandblasting (SB) and grinding (GD). SB was the predominant mechanical method evaluated, often serving as either a standalone treatment or in combination with chemical

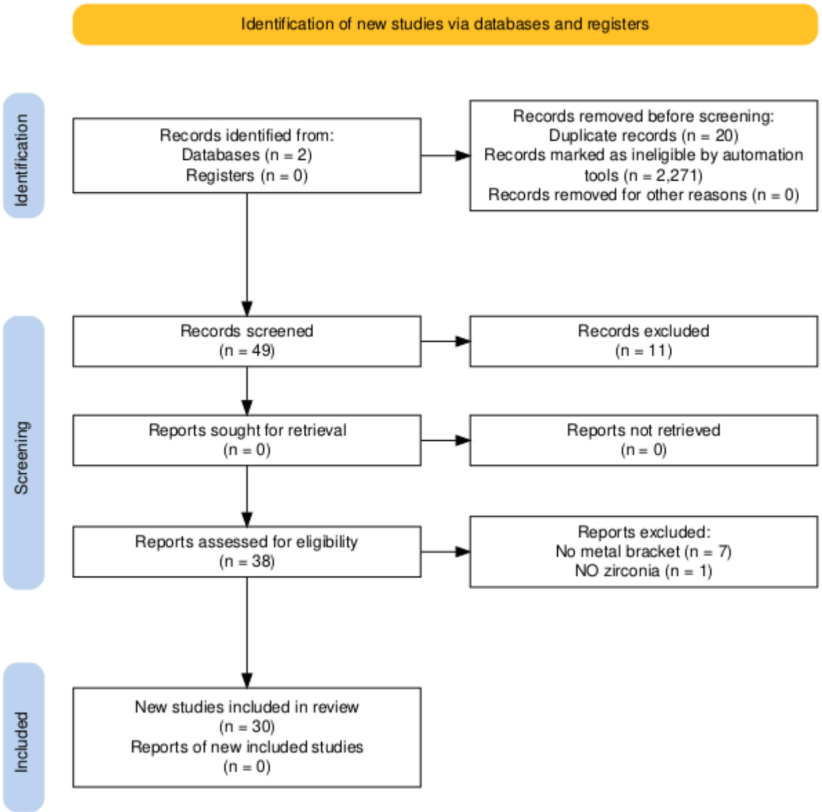

Figure 1. PRISMA flow diagram.

agents (**Table 1**). GD appeared less frequently and generally demonstrated lower bond strength values, particularly when used without adjunctive primers (**Tables 1, 3**).

Chemical etching (hydrofluoric acid, HF; phosphoric acid, PP) was also investigated. HF was more commonly studied and produced variable outcomes depending on the experimental conditions and combination strategies employed. PP was used in fewer studies and generally achieved similar bond strengths to HF under comparable testing conditions (**Table 2**).

Studies additionally assessed the use of primers or bonding agents (zirconia primer, ZP; Monobond, MB; Single Bond Universal, SU; Porcelain Conditioner, PC; Clearfil SE Bond Primer, CF). ZP and MB were the most frequently applied primers, typically tested both independently and alongside mechanical treatments. SU, PC, and CF appeared less often and were typically included in specific protocol comparisons rather than broad surveys (**Table 3**).

The substrates included different types of zirconia (3Y-TZP - a, 4Y-TZP - b, 5Y-TZP - c), representing the diversity of modern zirconia materials. Some studies specified substrate types clearly, while others used unspecified zirconia. Additional comparisons involved composite brackets (e) or ceramic brackets (f). The choice of bracket material and zirconia generation contributed to variation in shear bond strength, reflecting the influence of surface energy, chemical compatibility, and mechanical properties at the adhesive interface (**Tables 1-3**).

Table 1. Mechanical surface treatment of sandblast and grinding.

Author (Year)	Treatment 1	MPa	Treatment 2	MPa	n/group	P-value	Outcome
Lee (2015)	SB+ZP	26.5 ± 2.6	SB	11.6 ± 2.4	10	< 0.01	SB+ZP > SB
Lee (2015)	SB+MB	25.3 ± 1.6	SB	11.6 ± 2.4	10	< 0.01	SB+MB > SB
Yassaei (2015)	SB	7.8 ± 1.0	HF	5.8 ± 0.8	18	< 0.05	SB > HF
Kwak (2016)	SB+ZP	4.6 ± 1.1	GD+ZP	15.5 ± 3.2	10	< 0.05	SB+ZP < GD+ZP
Kwak (2016)	SB+MB	15.8 ± 2.4	SB+ZP	4.6 ± 1.1	10	< 0.05	SB+MB > SB+ZP
Mauwafak (2016)	SB+ZP	6.5 ± 1.4	SB+ZP [d]	4.4 ± 0.7	10	< 0.01	SB+ZP > SB+ZP [d]
Mehmeti (2017)	SB	7.4 ± 3.4	SB [e]	4.7 ± 1.8	10	= 0.04	SB > SB [e]
Kim (2017)	SB+ZP	21.6 ± 3.3	SB+SU	22.9 ± 6.5	10		SB+ZP ≈ SB+SU
Kim (2017)	SB+ZP	21.6 ± 3.3	SB+PC	11.4 ± 5.8	10	< 0.05	SB+ZP > SB+PC
Byeon (2017)	SB	5.0 ± 1.3	SB+ZP	11.9 ± 1.5	10	< 0.05	SB < SB+ZP
Amer (2018)	SB	20.8 ± 4.8	GD	12.3 ± 2.8	10	= 0.001	SB > GD
Mehmeti (2018)	SB	7.6 ± 1.9	Control	4.0 ± 1.3	12	= 0.003	SB > Control
Cetik (2019)	SB	23.3 ± 5.3	SB [e]	20.0 ± 4.1	10	< 0.05	SB > SB [e]
Pouyanfar (2019)	SB	19.3 ± 9.1	PP	9.9 ± 9.3	10		SB ≈ HF
Mokhtarpur (2020)	SB	3.1 ± 0.8	HF	6.2 ± 0.9	18	< 0.001	SB < HF
Farahani (2021)	SB+ZP	14.3 ± 2.6	SB+CF	13.8 ± 2.8	15		SB+ZP ≈ SB+CF
Wiriyaamornchai (2021)	SB	10.4 ± 0.4	GD	10.8 ± 1.0	5		SB ≈ GD
Heidari (2022)	GD+PN	12.8 ± 4.0	GD	2.2 ± 0.9	15	< 0.001	GD+PN > GD
Namvar (2022)	SB	26.2 ± 8.2	Control	11.5 ± 7.0	20	< 0.001	SB > Control
Dönmez (2022)	SB [b]	18.7 ± 2.4	MB [b]	13.3 ± 2.4	11	< 0.001	SB [b] > MB [b]
Dönmez (2022)	SB [c]	19.5 ± 2.6	MB [c]	12.8 ± 2.5	11	< 0.001	SB [c] > MB [c]
Haralur (2023)	SB	5.7 ± 0.3	GD	4.8 ± 0.4	10	< 0.001	SB > GD
Limpuangthip (2023)	SB	2.1 ± 0.3	GD	4.1 ± 0.6	12	< 0.05	GD > SB
Limpuangthip (2023)	SB+ZP	3.9 ± 0.4	GD+ZP	6.9 ± 0.8	12	< 0.05	GD+ZP > SB+ZP
Cakir (2023)	SB	6.5 ± 3.3	GD	6.2 ± 3.1	10		SB ≈ GD
Abd EL-wahab (2023)	SB [a]	14.6 ± 3.7	Control [a]	14.7 ± 3.4	10		SB [a] ≈ Control [a]
Abd EL-wahab (2023)	SB [c]	13.7 ± 6.7	Control [c]	28.8 ± 9.1	10	< 0.001	SB [c] < Control [c]
Abd EL-wahab (2023)	SB [a]	14.6 ± 3.7	HF [a]	11.3 ± 3.8	10		SB [a] ≈ HF [a]
Abd EL-wahab (2023)	SB [c]	13.7 ± 6.7	HF [c]	15.5 ± 5.5	10		SB [c] ≈ HF [c]
Khaled (2024)	SB	4.0 ± 0.1	HF	15.1 ± 0.3	10	< 0.05	SB > HF
Pédemay (2024)	SB+MB	22.8 ± 3.8	MB	19.4 ± 3.0	10		MB ≈ MB+SB
Pédemay (2024)	SB+HF+MB	21.3 ± 2.0	MB+HF	21.5 ± 2.3	10		MB+HF ≈ MB+HF+SB
Pezeshkirad (2025)	SB	7.8 ± 3.3	GD	1.4 ± 0.7	12	< 0.001	SB > GD
Pezeshkirad (2025)	SB+ZP	10.2 ± 4.5	GD+ZP	1.5 ± 1.1	12	< 0.001	SB+ZP > GD+ZP
Almousli (2025)	SB	16.8 ± 3.7	Control	13.3 ± 1.8	10		SB ≈ Control

n/group — Sample per group; SB — Sandblast; GD — Grinding; HF — Hydrofluoric acid etch; PP — Phosphoric acid etch; ZP — Zirconia primer; MB — Monobond; SU — Single Bond Universal; PC — Porcelain Conditioner; CF — Clearfil SE Bond Primer; a — 3Y-TZP; b — 4Y-TZP; c — 5Y-TZP; d — Composite bracket; e — Ceramic bracket; Control — no treatment. SB, GD, HF, PP, ZP, MB, SU, PC and CF result in mean value ± standard deviation in MPa. Indicate the relationship of comparison by > or < for significant difference and ≈ for no significant difference.

3.2 Frequencies and patterns

Most comparisons involve SB either alone or combined with primers, frequently compared against GD or HF treatments. SB was tested in over twenty studies and often appeared in both control and test conditions. For example, Amer et al. (2018) reported that SB produced 20.8 ± 4.8 MPa, significantly higher than GD at 12.3 ± 2.8 MPa. However, Limpuangthip et al. (2023) showed SB at 2.1 ± 0.3 MPa was notably lower than GD at 4.1 ± 0.6 MPa (**Table 1**). SB was also compared with HF in multiple cases. In one study, Khaled et al. (2024) reported HF at 15.1 ± 0.3 MPa exceeded SB at 4.0 ± 0.1 MPa, while Yassaei et al. (2015) reported the opposite pattern, for example with SB at 7.8 ± 1.0 MPa performing better than HF at 5.8 ± 0.8 MPa (**Table 2**).

Table 2. Chemical surface treatment of etching.

Author (Year)	Treatment 1	MPa	Treatment 2	MPa	n/group	P-value	Outcome
Yassaei (2015)	SB	7.8 ± 1.0	HF	5.8 ± 0.8	18	< 0.05	SB > HF
Kwak (2016)	HF+MB	15.2 ± 3.4	MB	14.9 ± 2.8	10		HF+MB ≈ MB
Mehmeti (2019)	HF	11.8 ± 7.3	PP	10.9 ± 5.8	12		HF ≈ PP
Pouyanfar (2019)	PP	9.9 ± 9.3	SB	19.3 ± 9.1	10		SB ≈ HF
Mokhtarpur (2020)	HF	6.2 ± 0.9	SB	3.1 ± 0.8	18	< 0.001	HF > SB
Haralur (2023)	HF	7.0 ± 0.3	MB	8.0 ± 0.5	10	< 0.001	HF < MB
Haralur (2023)	HF	7.0 ± 0.3	SB	5.7 ± 0.3	10	< 0.001	HF > SB
Haralur (2023)	HF	7.0 ± 0.3	GD	4.8 ± 0.4	10	< 0.001	HF > GD
Abd EL-wahab (2023)	HF [a]	11.3 ± 3.8	Control [a]	14.7 ± 3.4	10		HF [a] ≈ Control [a]
Abd EL-wahab (2023)	HF [c]	15.5 ± 5.5	Control [c]	28.8 ± 9.1	10	< 0.001	HF [c] < Control [c]
Abd EL-wahab (2023)	HF [a]	11.3 ± 3.8	SB [a]	14.6 ± 3.7	10		HF [a] ≈ SB [a]
Abd EL-wahab (2023)	HF [c]	15.5 ± 5.5	SB [c]	13.7 ± 6.7	10		HF [c] ≈ SB [c]
Pulido (2023)	HF	2.5 ± 1.0	HF [f]	7.8 ± 4.0	12	< 0.001	HF < HF [f]
Khaled (2024)	HF	15.1 ± 0.3	SB	4.0 ± 0.1	10	< 0.05	HF < SB
Wongrachit (2024)	HF	7.7 ± 2.7	PP	8.4 ± 2.3	14		HF ≈ PP
Pédemay (2024)	HF+MB	21.5 ± 2.3	MB	19.4 ± 3.0	10		MP ≈ HF+MB
Pédemay (2024)	HF+MB+SB	21.3 ± 2.0	HF+MB	21.5 ± 2.3	10		HF+MB+SB ≈ HF+MB

n/group — Sample per group; SB — Sandblast; GD — Grinding; HF — Hydrofluoric acid etch; PP — Phosphoric acid etch; ZP — Zirconia primer; MB — Monobond; SU — Single Bond Universal; PC — Porcelain Conditioner; CF — Clearfil SE Bond Primer; a — 3Y-TZP; b — 4Y-TZP; c — 5Y-TZP; d — Composite bracket; e — Ceramic bracket; Control — no treatment. SB, GD, HF, PP, ZP, MB, SU, PC and CF result in mean value ± standard deviation in MPa. Indicate the relationship of comparison by > or < for significant difference and ≈ for no significant difference.

Several studies compare SB+ZP with SB or GD+ZP, indicating interest in the effect of zirconia primers combined with mechanical treatments. For instance, Lee et al. (2015) showed SB+ZP at 26.5 ± 2.6 MPa significantly outperformed SB at 11.6 ± 2.4 MPa. Kwak et al. (2016) reported GD+ZP reached 15.5 ± 3.2 MPa, while SB+ZP produced only 4.6 ± 1.1 MPa (**Tables 1, 3**). This indicates that combining zirconia primers with different mechanical methods yields varied results.

There are repeated comparisons of SB+MB with SB or ZP, showing MB as a popular primer. For example, Lee et al. (2015) demonstrated SB+MB at 25.3 ± 1.6 MPa versus SB alone at 11.6 ± 2.4 MPa. Kwak et al. (2016) reported MB at 14.9 ± 2.8 MPa was statistically similar to MB+SB at 15.8 ± 2.4 MPa, while also outperforming SB+ZP at 4.6 ± 1.1 MPa (**Table 3**).

Substrates are mostly unspecified zirconia, but some studies specify types a, b and c (3Y, 4Y, 5Y-TZP). Abd EL-wahab et al. (2023) explicitly differentiated SBS for 3Y-TZP (SB a = 14.6 ± 3.7 MPa), 4Y-TZP (SB b = 18.7 ± 2.4 MPa) and 5Y-TZP (SB c = 13.7 ± 6.7 MPa) (**Table 1**). These differences reflect how zirconia type may affect bonding performance.

Some data involve composite brackets (d) or ceramic brackets (e), which generally showed lower bond strengths compared to controls or SB. For instance, Mauwafak et al. (2016) reported that SB+ZP to composite brackets (d) gave 4.4 ± 0.7 MPa, whereas to metal brackets it reached 6.5 ± 1.4 MPa. Similarly, Mehmeti et al. (2017) showed SB (e) with ceramic brackets was 4.7 ± 1.8 MPa, compared to 7.4 ± 3.4 MPa with standard brackets (**Tables 1, 3**).

Table 3. Chemical surface treatment of primers.

Author (Year)	Treatment 1	MPa	Treatment 2	MPa	n/group	P-value	Outcome
Lee (2015)	ZP+SB	26.5 ± 2.6	MB+SB	25.3 ± 1.6	10		ZP ≈ MB
Kwak (2016)	ZP	13.4 ± 2.6	MB	14.9 ± 2.8	10		ZP ≈ MB
Kwak (2016)	ZP+SB	4.6 ± 1.1	MB+SB	15.8 ± 2.4	10	< 0.05	ZP+SB < MB+SB
Kwak (2016)	ZP	13.4 ± 2.6	ZP+SB	4.6 ± 1.1	10	< 0.05	ZP > ZP+SB
Kwak (2016)	MB	14.9 ± 2.8	MB+SB	15.8 ± 2.4	10		MB ≈ MB+SB
Kwak (2016)	MB	14.9 ± 2.8	MB+HF	15.2 ± 3.4	10		MB ≈ MB+HF
Kwak (2016)	ZP+SB	4.6 ± 1.1	ZP+GD	15.5 ± 3.2	10	< 0.05	ZP+SB < ZP+GD
Mauwafak (2016)	SB+ZP	6.5 ± 1.4	SB+ZP [d]	4.4 ± 0.7	10	< 0.01	SB+ZP > SB+ZP [d]
Kim (2017)	SB+ZP	21.6 ± 3.3	SB+SU	22.9 ± 6.5	10		SB+ZP ≈ SB+SU
Kim (2017)	SB+ZP	21.6 ± 3.3	SB+PC	11.4 ± 5.8	10	< 0.05	SB+ZP > SB+PC
Byeon (2017)	ZP+SB	11.9 ± 1.5	SB	5.0 ± 1.3	10	< 0.05	SB+ZP > SB
Franz (2019)	MB	13.7 ± 6.0	MB [g]	14.5 ± 6.2	60		MB ≈ MB [g]
Farahani (2021)	ZP+SB	14.3 ± 2.6	CF+SB	13.8 ± 2.8	15		ZP+SB ≈ CF+SB
Büyükerkmen (2022)	ZP	12.0 ± 5.8	MB	13.4 ± 4.0	13	< 0.05	ZP < MB
Dönmez (2022)	MB [b]	13.3 ± 2.4	SB [b]	18.7 ± 2.4	11	< 0.001	MB [b] < SB [b]
Dönmez (2022)	MB [c]	12.8 ± 2.5	SB [c]	19.5 ± 2.6	11	< 0.001	MB [c] < SB [c]
Haralur (2023)	MB	8.0 ± 0.5	HF	7.0 ± 0.3	10	< 0.001	MB > HF
Haralur (2023)	MB	8.0 ± 0.5	SB	5.7 ± 0.3	10	< 0.001	MB > SB
Haralur (2023)	MB	8.0 ± 0.5	GD	4.8 ± 0.4	10	< 0.001	MB > GD
Limpuangthip (2023)	ZP+SB	3.9 ± 0.4	ZP	3.6 ± 0.4	12		ZP ≈ SB+ZP
Limpuangthip (2023)	ZP+GD	6.9 ± 0.8	ZP	3.6 ± 0.4	12	< 0.05	ZP < GD+ZP
Pédemay (2024)	MB	19.4 ± 3.0	MB+SB	22.8 ± 3.8	10		MB ≈ MB+SB
Pédemay (2024)	MB	19.4 ± 3.0	MB+HF	21.5 ± 2.3	10		MB ≈ MB+HF
Pédemay (2024)	MB+HF+SB	21.3 ± 2.0	MB+HF	21.5 ± 2.3	10		MB+HF+SB ≈ MB+HF
Pezeshkirad (2025)	ZP+SB	10.2 ± 4.5	ZP+GD	1.5 ± 1.1	10		SB+ZP ≈ GD+ZP

n/group — Sample per group; SB — Sandblast; GD — Grinding; HF — Hydrofluoric acid etch; PP — Phosphoric acid etch; ZP — Zirconia primer; MB — Monobond; SU — Single Bond Universal; PC — Porcelain Conditioner; CF — Clearfil SE Bond Primer; a — 3Y-TZP; b — 4Y-TZP; c — 5Y-TZP; d — Composite bracket; e — Ceramic bracket; Control — no treatment. SB, GD, HF, PP, ZP, MB, SU, PC and CF result in mean value ± standard deviation in MPa. Indicate the relationship of comparison by > or < for significant difference and ≈ for no significant difference.

3.3 Heterogeneity

SBS values varied widely across the included studies and exhibited substantial variability. Pezeshkirad et al. (2025) reported the lowest value, 1.4 ± 0.7 MPa for GD, while Abd EL-wahab et al. (2023) reported the highest, 28.8 ± 9.1 MPa for untreated 5Y-TZP Control c (**Table 1**). These values reflect the influence of surface treatment, primer application and zirconia substrate type.

Treatment effect sizes vary substantially depending on substrate and primer combinations. Standard deviations are sometimes large. For instance, Pouyanfar et al. (2019) reported PP at 9.9 ± 9.3 MPa and SB at 19.3 ± 9.1 MPa under the same conditions. HF showed similar variability; Mehmeti et al. (2019) reported HF at 11.8 ± 7.3 MPa (**Table 2**). This suggests inconsistent bonding effectiveness, possibly due to surface condition, etching time or primer compatibility.

Some studies show SB to be superior to GD or HF for SBS, while others report the opposite, suggesting that substrate or procedural differences influence outcomes. Amer et al. (2018) found SB at 20.8 ± 4.8 MPa significantly outperformed GD at 12.3 ± 2.8 MPa, whereas Limpuangthip et al. (2023) showed the reverse, with GD at 4.1 ± 0.6 MPa superior to SB at 2.1 ± 0.3 MPa (**Table 1**). For HF, Yassaei et al. (2015) found SB at 7.8 ± 1.0 MPa stronger than HF at 5.8 ± 0.8 MPa, while Khaled et al. (2024) reported HF at 15.1 ±

0.3 MPa stronger than SB at 4.0 ± 0.1 MPa (**Table 2**). This inconsistency demonstrates how procedural parameters and material properties can reverse treatment outcomes.

Control groups vary widely. In Abd EL-wahab et al. (2023), SB a at 14.6 ± 3.7 MPa and Control a at 14.7 ± 3.4 MPa showed no significant difference, whereas Control c at 28.8 ± 9.1 MPa outperformed SB c at 13.7 ± 6.7 MPa. Almousli (2025) similarly found no statistical difference between SB at 16.8 ± 3.7 MPa and control at 13.3 ± 1.8 MPa (**Table 1**), reinforcing that in some contexts untreated zirconia may bond as well as, or better than, mechanically treated surfaces.

Overall, these findings confirm that SBS values are influenced not only by the presence of mechanical or chemical treatment but also by substrate-specific interactions. The high variability within and across studies highlights the importance of subgroup analysis for accurate interpretation of treatment efficacy.

3.4 Subgroup analysis

3.4.1 Subgroup A: Mechanical treatments alone

The group consists of SB vs GD vs HF vs PP vs Control (no primer, no additional chemical treatment). SB typically resulted in higher SBS compared to GD or HF. For instance, Amer et al. (2018) reported SB at 20.8±4.8 MPa, significantly outperforming GD at 12.3±2.8 MPa (**Table 1**). Similarly, Yassaei et al. (2015) found SB was 7.8 ± 1.0 MPa, superior to HF at 5.8 ± 0.8 MPa (**Table 2**). However, in some studies, such as Mokhtarpur et al. (2020), HF at 6.2 ± 0.9 MPa surpassed SB at 3.1 ± 0.8 MPa, indicating procedural variations or surface sensitivities (**Tables 1, 3**).

PP performed roughly equally to SB in one study but with high variability. In Pouyanfar et al. (2019), PP at 9.9±9.3 MPa showed bond strength comparable to SB at 19.3±9.1 MPa when considering large standard deviations, suggesting variability within groups and possible procedural inconsistencies (**Table 2**). Standard deviation varies widely; reported SBS values for SB ranged from as low as 2.1 ± 0.3 MPa by Limpuangthip et al. (2023) to as high as 26.2 ± 8.2 MPa by Namvar et al. (2022), demonstrating broad heterogeneity within mechanical-only treatments (**Table 1**).

Composite and ceramic bracket groups tend to produce lower bond strength compared to SB, indicating a substrate heterogeneity effect. In Mehmeti et al. (2017), bonding to ceramic brackets with SB achieved 4.7 ± 1.8 MPa, while bonding with metal brackets was 7.4 ± 3.4 MPa (**Table 1**). Cetik et al. (2019) also showed reduced SBS values for ceramic bracket bonding with SB at 20.0 ± 4.1 MPa, while bonding with metal brackets was 23.3 ± 5.3 MPa, reinforcing the effect of substrate variation on bonding outcomes (**Table 1**). Overall, while SB generally improves bond strength relative to GD, HF, and untreated controls, notable exceptions and procedural variations across studies introduce heterogeneity, necessitating careful interpretation.

3.4.2 Subgroup B: Mechanical treatments + ZP

The group consists of SB+ZP vs GD+ZP vs SB vs GD. The application of ZP after SB consistently enhanced SBS compared to SB alone. In Lee et al. (2015), SB+ZP achieved 26.5±2.6 MPa, significantly higher than SB alone at 11.6±2.4 MPa (**Tables 1, 3**). Similarly, Byeon et al. (2017) reported SB+ZP was 11.9 ± 1.5 MPa, outperforming SB alone at 5.0 ± 1.3 MPa. These results suggest that chemical bonding promotion by ZP substantially reinforces the mechanical retention created by SB (**Table 1**).

GD+ZP treatment sometimes produces higher bond strength than SB+ZP. In Kwak et al. (2016), GD+ZP demonstrated superior SBS at 15.5 ± 3.2 MPa compared to SB+ZP at 4.6 ± 1.1 MPa (**Table 3**). Similarly, Limpuangthip et al. (2023) found GD+ZP at 6.9 ± 0.8 MPa significantly outperformed SB+ZP at 3.9 ± 0.4 MPa (**Tables 1, 3**). These outcomes indicate that the underlying mechanical texture created by GD may interact more favourably with zirconia primers in certain conditions, possibly due to different surface roughness or energy profiles.

Variation in substrates and bracket presence affects absolute values. Bracket type influenced performance within ZP treatments. Mauwafak et al. (2016) demonstrated that using composite brackets resulted in lower SBS with SB+ZP. Composite brackets showed 4.4 ± 0.7 MPa compared to conventional metal brackets at 6.5 ± 1.4 MPa (**Table 3**). This highlights the sensitivity of ZP bonding efficacy to bracket material composition.

When comparing SB+ZP to other primers (PC, CF), SB+ZP tends to have superior or equal bond values. Kim et al. (2017) showed SB+ZP at 21.6 ± 3.3 MPa produced significantly better bonding outcomes than SB+PC at 11.4±5.8 MPa. Farahani et al. (2021) observed similar SBS between SB+ZP at 14.3 ± 2.6 MPa and SB+CF at 13.8 ± 2.8 MPa, suggesting that ZP is generally comparable or superior to alternative primers when used after mechanical pretreatment (**Table 3**). Overall, the combination of mechanical treatment with zirconia primer application substantially improves bonding performance compared to mechanical methods alone. However, variations due to mechanical method type (SB vs GD) and bracket material necessitate cautious interpretation when generalising results.

3.4.3 Subgroup C: Mechanical treatments + MB and variants

The group consists of SB+MB vs SB+ZP vs SB vs MB. The application of MB following SB generally resulted in higher SBS compared to SB alone or SB combined with ZP. Lee et al. (2015) reported that SB+MB achieved 25.3 ± 1.6 MPa, significantly higher than SB alone at 11.6 ± 2.4 MPa (**Table 3**). Kwak et al. (2016) further supported these findings, showing SB+MB at 15.8 ± 2.4 MPa outperforming SB+ZP at 4.6 ± 1.1 MPa under identical conditions, suggesting the superior adhesive properties of MB when applied after mechanical treatment (**Table 3**).

When used independently, MB demonstrated bonding performance comparable to MB combined with mechanical surface treatment. Kwak et al. (2016) showed MB alone reached 14.9 ± 2.8 MPa, which was not significantly different from MB+SB at 15.8 ± 2.4 MPa (**Table 3**). Similarly, Pédémay et al. (2024) documented MB at 19.4±3.0 MPa compared to MB+SB at 22.8±3.8 MPa, without significant difference, indicating MB's inherent chemical bonding capability to zirconia (**Table 3**).

Substrate variation played an important role in modifying outcomes. Dönmez et al. (2022) observed that SB-treated zirconia substrates, both 4Y-TZP at 18.7 ± 2.4 MPa and 5Y-TZP at 19.5 ± 2.6 MPa, exhibited higher SBS compared to MB-treated surfaces for 4Y-TZP at 13.3 ± 2.4 MPa and for 5Y-TZP at 12.8 ± 2.5 MPa. These findings suggest that mechanical roughening still contributes beneficially, particularly with the type of zirconia (**Tables 1, 3**).

Combining HF+MB or HF+MB+SB does not show a significant difference, indicating HF addition might negate the influence of SB. Pédémay et al. (2024) reported that MB+HF at 21.5±2.3 MPa and HF+MB+SB at 21.3±2.0 MPa produced statistically equivalent bond strengths. This suggests that the introduction of hydrofluoric acid treatment, when paired with MB, may diminish or override the effects of prior mechanical roughening through SB (**Table 3**). Overall, the use of MB either independently or combined with mechanical treatments provides strong and reliable bond strength outcomes. However, substrate type and the presence of additional chemical treatments, such as HF, can influence the extent of mechanical pre-treatment benefits.

3.4.4 Subgroup D: Other primer or bond systems

The group consists of SB+SU vs SB+PC vs SB+CF vs others. SU and CF show similar bond strengths to ZP protocols. SU and CF demonstrated bonding performance comparable to ZP when used after SB. In Kim et al. (2017), SB+SU achieved 22.9 ± 6.5 MPa, which was statistically similar to SB+ZP at 21.6 ± 3.3 MPa (**Table 3**). Farahani et al. (2021) reported that SB+CF at 13.8 ± 2.8 MPa showed comparable bond strength to SB+ZP at 14.3 ± 2.6 MPa, suggesting that SU and CF can serve as alternative adhesives to traditional ZP systems under specific conditions (**Table 3**).

PC appeared less effective compared to ZP-based treatments. Kim et al. (2017) found that SB+PC at 11.4 ± 5.8 MPa resulted in lower bond strength than SB+ZP at 21.6 ± 3.3 MPa, with statistically significant differences (**Table 3**). This outcome indicates that while PC can enhance bonding relative to no treatment, it does not achieve the same performance level as zirconia-specific primers or universal adhesives.

Although fewer studies evaluated SU, PC, and CF compared to ZP or MB, the available evidence suggests that SU and CF could be considered clinically acceptable alternatives when ZP is unavailable. However, PC consistently demonstrated inferior results, raising questions about its reliability for zirconia bonding applications. In addition, the specific interaction of primer chemistry with different zirconia substrates or bracket types remains an underexplored area, introducing potential variability into these outcomes. Overall, SU and CF offer bond strength comparable to ZP under certain conditions, whereas PC consistently provides lower performance. Further comparative studies are necessary to better delineate their roles relative to ZP and MB.

3.4.5 Subgroup E: Substrate-specific analysis

The group consists of: 3Y-TZP (a), 4Y-TZP (b), 5Y-TZP (c), composite bracket (d), and ceramic bracket (e). Lower bond values were observed for composite and ceramic brackets compared to zirconia. Bond strength outcomes were noticeably influenced by bracket material. In Mauwafak et al. (2016), SB+ZP bonded to composite brackets (d) produced 4.4 ± 0.7 MPa, significantly lower than bonding to conventional metal brackets (**Table 3**). Similarly, Mehmeti et al. (2017) reported SB with ceramic brackets (e) resulted in 4.7 ± 1.8 MPa, compared to metal brackets with SB at 7.4 ± 3.4 MPa (**Table 1**). These results indicate that both composite and ceramic brackets reduce mechanical interlocking or chemical bonding efficiency, thereby diminishing overall adhesion to zirconia.

Zirconia subtypes (3Y-TZP, 4Y-TZP, 5Y-TZP) exhibit variable bonding. Abd EL-Wahab et al. (2023) provided comparative data on all three zirconia types. For 3Y-TZP (a), SBS values between SB (a) at 14.6 ± 3.7 MPa and Control (a) at 14.7 ± 3.4 MPa were statistically similar. However, for 5Y-TZP (c), untreated Control (c) at 28.8 ± 9.1 MPa significantly outperformed SB (c) at 13.7 ± 6.7 MPa, indicating that sandblasting may be ineffective or detrimental on certain high-translucency zirconia materials. Additionally, for

4Y-TZP (b), SB (b) at 18.7 ± 2.4 MPa was superior to MB (b) at 13.3 ± 2.4 MPa, demonstrating that mechanical treatment may still offer benefit depending on the specific zirconia type (**Tables 1, 3**).

This suggests substrate composition critically affects bonding outcomes, necessitating substrate-specific protocols. The variability across zirconia type and bracket materials indicates that bonding success is not only dependent on the surface treatment method but also on inherent material properties. Surface hardness, phase stability, and translucency may all impact the effectiveness of primers and mechanical preparation. Therefore, protocols should be tailored to match the specific combination of zirconia generation and bracket type to optimise clinical outcomes.

3.5 Summary

SB consistently provided higher SBS than GD or HF across most included studies. For instance, Amer et al. (2018) and Yassaei et al. (2015) demonstrated superior bond strengths for SB over GD and HF, respectively. However, some exceptions were observed. Limpuangthip et al. (2023) reported GD achieving higher SBS than SB, and Khaled et al. (2024) found HF outperforming SB in certain cases, highlighting the influence of procedural and substrate factors (**Tables 1, 2**).

The addition of primers notably enhanced bond strength. SB combined with ZP significantly outperformed SB alone in studies such as Lee et al. (2015) and Byeon et al. (2017) (**Tables 1, 3**). Kwak et al. (2016) reported that comparisons between MB and ZP showed no significant difference in some cases, although MB sometimes yielded numerically superior outcomes, affirming its strong chemical adhesion capability (**Table 3**).

GD combined with ZP produced higher bond strength than SB combined with ZP in Kwak et al. (2016) and Limpuangthip et al. (2023), suggesting that not only the presence of a primer but also the mechanical surface characteristics play a critical role in bonding effectiveness (**Tables 1, 3**).

Studies by Abd EL-Wahab et al. (2023) and Mauwafak et al. (2016) revealed that bonding performance varied depending on zirconia type (3Y-TZP, 4Y-TZP, 5Y-TZP) and bracket type (metal, composite, ceramic). Composite and ceramic brackets consistently produced lower SBS, emphasizing the need for substrate-specific bonding strategies (**Tables 1, 3**).

Other primers (SU, CF, PC) produced SBS values comparable to ZP in some studies (Kim et al., 2017; Farahani et al., 2021), whereas PC generally resulted in inferior performance (**Table 3**). Thus, primer selection should consider both material compatibility and clinical handling characteristics. Overall, while mechanical treatment remains fundamental, the combination of surface conditioning and primer selection must be adapted according to substrate type and clinical context to optimise orthodontic bracket bonding to zirconia.

4 Discussion

This review aimed to identify which surface treatments improve shear bond strength (SBS) between orthodontic metal brackets and zirconia crowns. Zirconia's inert surface poses challenges for reliable bonding, necessitating mechanical and chemical conditioning. The review analysed 30 *in vitro* studies comparing mechanical treatments (SB, GD), acid etching (HF, PP), and primers (ZP, MB). The objective was to determine which methods, alone or in combination, produce consistently strong SBS, considering that metal bracket type and zirconia composition influence outcomes relevant to clinical orthodontics.

The results showed notable patterns and variability across different surface treatment strategies. Each subgroup analysis revealed key insights regarding the performance and reliability of mechanical and chemical approaches in enhancing SBS for orthodontic brackets bonded to zirconia crowns.

4.1 Interpretation of subgroup findings

4.1.1 Subgroup A: Mechanical treatments alone

SB generally outperformed other methods. In several studies, SB yielded higher SBS than GD or no treatment. Amer et al. (2018) reported an SBS of 20.8 ± 4.8 MPa for SB, compared to 12.3 ± 2.8 MPa for GD, indicating superior micromechanical retention from SB (**Table 1**). However, results were not universally consistent. Limpuangthip et al. (2023) found GD to outperform SB, with SBS values of 4.1 ± 0.6 MPa and 2.1 ± 0.3 MPa, respectively (**Table 1**). Similarly, while SB generally outperformed HF, Mokhtarpur et al. (2020) reported that HF achieved higher SBS than SB (**Table 1**). These inconsistencies likely reflect variations in surface morphology, zirconia type, or operator technique. Overall, while SB shows promise, mechanical treatment alone appears insufficient for ensuring durable adhesion, highlighting the need for adjunctive chemical conditioning to achieve clinically reliable outcomes.

4.1.2 Subgroup B: Mechanical treatments with ZP

The addition of ZP following mechanical surface treatment consistently improved SBS, affirming the benefit of dual conditioning. Lee et al. (2015) demonstrated that SB+ZP achieved an SBS of 26.5 ± 2.6 MPa, substantially higher than SB alone at 11.6 ± 2.4 MPa (**Table 3**). This increase reflects the synergistic effect of micromechanical interlocking and chemical bonding. However, the effectiveness of ZP appeared to be influenced by the type of mechanical treatment. In Kwak et al. (2016), GD combined with ZP produced an SBS of 15.5 ± 3.2 MPa, which exceeded the value for SB+ZP at 4.6 ± 1.1 MPa (**Table 3**), suggesting that the surface topography created by GD may enhance primer adhesion more effectively than SB under specific conditions. While ZP alone showed moderate results, its use in combination with either SB or GD yielded consistently better outcomes, underscoring the importance of surface preparation in optimising chemical primer performance.

4.1.3 Subgroup C: Mechanical treatments + MB and variants

MB showed high performance, both independently and in conjunction with mechanical surface treatments. In Kwak et al. (2016), MB combined with SB achieved an SBS of 15.8 ± 2.4 MPa, substantially higher than the SB+ZP group at 4.6 ± 1.1 MPa (**Table 3**). Notably, MB alone produced 14.9 ± 2.8 MPa, nearly matching the value obtained with SB, underscoring its intrinsic chemical bonding capability to zirconia. Pédemay et al. (2024) further supported this, reporting SBS values of 19.4 ± 3.0 MPa for MB alone and 22.8 ± 3.8 MPa for MB+SB (**Table 3**), with minimal difference between the two. These results indicate that MB provides strong, reliable adhesion to zirconia surfaces with or without adjunctive mechanical conditioning, suggesting its effectiveness as a standalone primer in clinical scenarios.

4.1.4 Subgroup D: Other primers or bonding systems

This subgroup evaluated the performance of alternative primers and universal adhesives, particularly SU and CF, in comparison to ZP. These agents demonstrated bonding efficacy on par with traditional zirconia primers. Kim et al. (2017) reported an SBS of 22.9±6.5 MPa for SB+SU and 21.6 ± 3.3 MPa for SB+ZP, indicating comparable performance (**Table 3**). Similarly, Farahani et al. (2021) observed equivalent outcomes between SB+ZP and SB+CF combinations (**Table 3**), suggesting CF is suitable for bonding to zirconia when paired with mechanical pre-treatment. In contrast, PC consistently yielded inferior results. In Kim et al. (2017), the SB+PC group achieved only 11.4 ± 5.8 MPa, significantly lower than SB+ZP (**Table 3**). These findings support the efficacy of SU and CF as viable alternatives to ZP, while reaffirming the limited bonding performance of PC in zirconia applications.

4.1.5 Subgroup E: Substrate-specific analysis

This analysis highlights the significant influence of bracket material and zirconia composition on bonding efficacy. Mauwafak et al. (2016) reported that, under identical surface treatment with SB+ZP, composite brackets achieved a lower SBS of 4.4 ± 0.7 MPa compared to metal brackets at 6.5 ± 1.4 MPa, emphasising the superior mechanical retention of metal bases (**Table 3**). Bracket design and base morphology likely contribute to these differences. Regarding zirconia type, Abd EL-wahab et al. (2023) demonstrated that untreated 5Y-TZP yielded an SBS of 28.8±9.1 MPa, notably higher than SB-treated specimens at 13.7±6.7 MPa (**Table 1**). This suggests that certain high-translucency zirconia, particularly 5Y-TZP with increased cubic phase content, may exhibit sufficient surface reactivity or micromechanical interlocking without pre-treatment. These findings underscore that both bracket design and zirconia microstructure can substantially alter adhesive outcomes, and that a uniform bonding protocol may not be universally applicable across material systems.

4.2 Which mechanical methods of SB or GD result in the highest SBS?

Among mechanical surface treatments, SB was the most frequently evaluated method and generally produced higher SBS compared to GD. Amer et al. (2018) reported SBS values of 20.8 ± 4.8 MPa for SB and 12.3 ± 2.8 MPa for GD, indicating SB's capacity to enhance micromechanical retention through surface roughening (**Table 1**). A similar trend was observed by Pezeshkirad et al. (2025), where SB achieved 7.8 ± 3.3 MPa, markedly higher than 1.4 ± 0.7 MPa with GD (**Table 1**). These results support SB's effectiveness in creating a textured surface favourable for adhesive bonding. However, not all studies aligned with this trend. Limpuangthip et al. (2023) found that GD yielded superior results, reporting an SBS of 4.1 ± 0.6 MPa for GD and 2.1 ± 0.3 MPa for SB (**Table 1**). This divergence may stem from variables such as particle size, pressure settings, zirconia composition, or bracket design, which were not consistently standardised. Thus, while SB appears to offer superior performance in most contexts, its success is sensitive to protocol. Optimising these parameters remains essential for maximising bond strength across different clinical scenarios.

4.3 Which etching of HF or PP results in the highest SBS?

HF etching generally produced slightly higher SBS values than PP, although the differences were not statistically significant. In Mehmeti et al. (2019), HF yielded an SBS of 11.8 ±

7.3 MPa, compared to 10.9 ± 5.8 MPa with PP (**Table 2**). Similarly, Wongrachit et al. (2024) reported SBS values of 7.7 ± 2.7 MPa for HF and 8.4 ± 2.3 MPa for PP (**Table 2**), further supporting the marginal and statistically inconclusive differences between the two etchants. However, when HF was used in combination with a primer, enhanced outcomes were observed. Pédemay et al. (2024) found that HF combined with MB produced an SBS of 21.5 ± 2.3 MPa, higher than MB alone at 19.4 ± 3.0 MPa, although the difference did not reach statistical significance (**Table 2**). No similar data were available for PP in combination protocols. While both etching agents perform comparably when used alone, HF appears more effective in multi-step bonding strategies, suggesting its greater clinical utility when combined with chemical primers in enhancing adhesion to zirconia surfaces.

4.4 Which chemical primer systems produce the highest SBS?

Among the chemical primer systems evaluated, MB frequently produced higher or comparable SBS to ZP, often with less reliance on mechanical surface pretreatment. In Kwak et al. (2016), MB alone achieved 14.9 ± 2.8 MPa, outperforming both ZP+SB at 4.6 ± 1.1 MPa and ZP alone at 13.4 ± 2.6 MPa (**Table 3**). Similarly, Büyükerkmen et al. (2022) reported MB at 13.4 ± 4.0 MPa, slightly exceeding ZP at 12.0 ± 5.8 MPa (**Table 3**). While Dönmez et al. (2022) observed higher SBS for ZP+SB at 18.7 ± 2.4 MPa than for MB at 13.3 ± 2.4 MPa on 4Y-TZP zirconia (**Table 3**), such differences were not universal. For example, Kwak et al. (2016) found no statistically significant difference between ZP at 13.4 ± 2.6 MPa and MB at 14.9 ± 2.8 MPa. Lee et al. (2015) further demonstrated that SB+ZP at 26.5 ± 2.6 MPa and SB+MB at 25.3 ± 1.6 MPa yielded nearly equivalent outcomes (**Table 3**). Collectively, these findings suggest that while both ZP and MB are effective, MB offers more consistent performance across varying protocols and zirconia types, indicating greater reliability in clinical applications.

4.5 Substrate factors

Substrate-specific variables, including bracket type and zirconia composition, substantially influenced bonding outcomes. Mauwafak et al. (2016) reported that under SB+ZP treatment, metal brackets achieved a higher SBS of 6.5 ± 1.4 MPa than composite brackets at 4.4 ± 0.7 MPa, with ceramic brackets showing similarly reduced values (**Table 3**). These differences likely stem from base design and material compatibility with resin adhesives. Zirconia type also played a significant role. Abd EL-wahab et al. (2023) observed that untreated 5Y-TZP exhibited an SBS of 28.8 ± 9.1 MPa, considerably surpassing SB-treated 5Y-TZP at 13.7 ± 6.7 MPa (**Table 1**), suggesting certain high-translucency zirconia may offer inherently bondable surfaces. Additionally, Dönmez et al. (2022) found that SB produced higher SBS values than MB for both 4Y-TZP and 5Y-TZP, indicating differential substrate responses to identical surface protocols (**Table 3**). These findings underscore the importance of tailoring bonding strategies to specific material and bracket combinations.

4.6 Consequences of findings

The data synthesized in this review reinforce that neither mechanical nor chemical conditioning alone is sufficient to ensure dependable bracket bonding to zirconia. Consistently, studies that employed a dual-treatment approach—particularly SB followed by primer—reported markedly higher SBS. For instance, Lee et al. (2015) demonstrated that combining

SB with ZP yielded an SBS of 26.5±2.6 MPa (**Table 3**), emphasizing the synergistic effect of micromechanical and chemical adhesion. This supports the clinical use of dual conditioning as a standard for zirconia surface preparation.

MB emerges as a valuable alternative in situations where mechanical pretreatment may be impractical. In Pédemay et al. (2024), MB alone achieved an SBS of 19.4 ± 3.0 MPa without prior SB (**Table 3**), indicating sufficient chemical adhesion for clinical use. Its versatility, particularly on glazed surfaces, broadens its utility in restorative–orthodontic workflows.

Zirconia type is another determinant. Surprisingly, high-translucency 5Y-TZP zirconia demonstrated favourable bonding even in untreated conditions. Abd EL-Wahab et al. (2023) reported SBS values of 28.8 ± 9.1 MPa in the control group (**Table 1**), suggesting that some formulations may inherently facilitate bonding due to surface chemistry or microstructure.

Bracket type also influenced outcomes. Consistently higher SBS values were reported with metal brackets compared to ceramic or composite types. Mauwafak et al. (2016) documented this trend across various primers and treatments (**Table 3**), confirming metal brackets as the more reliable option for zirconia bonding.

In contrast, standalone chemical etching with HF or PP yielded inconsistent and often suboptimal results, failing to meet clinical thresholds. Therefore, relying solely on chemical etchants without primer is not advisable.

4.7 Limitations

Several limitations inherent to the included studies warrant careful consideration. A primary concern is the substantial methodological heterogeneity. Variations in SB parameters—such as particle size, application angle, and air pressure—as well as inconsistencies in etching times, primer formulations, and curing techniques, complicate direct comparison across studies. Although SBS was uniformly reported in MPa, disparities in specimen storage conditions, thermocycling protocols, and testing timelines introduce further variability. These factors reduce the ability to draw definitive conclusions about the relative efficacy of treatment protocols.

Moreover, the studies examined a broad spectrum of zirconia materials and bracket types, which were not always clearly identified or standardized. Given that zirconia formulations differ markedly in terms of yttria content, translucency, and phase distribution, the omission of such details limits the reproducibility and applicability of the results. Similarly, bracket material—whether metal, ceramic, or composite—significantly affects bond behavior. Yet, bracket type was not consistently reported or controlled across studies.

This review also relies exclusively on in vitro data. While such studies offer controlled conditions to isolate treatment effects, they do not simulate the oral environment, where factors such as saliva, occlusal loading, thermal fluctuation, and long-term aging influence adhesion. Consequently, extrapolation to clinical outcomes must be made with caution.

Finally, the potential for publication bias should be acknowledged. Studies with statistically significant or favorable outcomes are more likely to be published, which may skew the perception of treatment efficacy. These limitations highlight the need for standardized testing protocols and longitudinal clinical research to validate laboratory findings in real-world settings.

Conclusions

This review confirms that successful bonding of orthodontic metal brackets to zirconia restorations requires a multifactorial approach. Isolated mechanical or chemical treatments were insufficient to ensure consistently high SBS. In contrast, combined protocols, particularly those employing SB followed by application of a zirconia-compatible primer, produced more reliable outcomes across multiple studies.

Among mechanical strategies, SB remains the most broadly supported, although its efficacy depends heavily on parameters such as particle size, pressure, and zirconia type. GD, less commonly used, demonstrated comparable or superior outcomes in specific studies, reinforcing the importance of technique sensitivity and substrate interaction. Chemical conditioning using HF or PP produced variable results. HF showed isolated efficacy when used with primers but lacked reliability as a primary method.

The most consistent enhancement in bond strength came from primers, especially ZP and MB. When paired with SB, both yielded high SBS values across a range of zirconia surfaces. Notably, MB achieved clinically acceptable SBS without prior mechanical treatment, underscoring its potential in cases where SB is contraindicated or not feasible. This adaptability, combined with its proven performance, positions MB as a versatile agent in clinical orthodontics.

Material-specific variables also influenced results. High-translucency zirconia (5Y-TZP) demonstrated unexpectedly high SBS in some untreated control groups, suggesting that phase composition and microstructure may independently contribute to bond performance. Bracket type was another determinant; metal brackets consistently outperformed ceramic and composite types, supporting their continued clinical preference for bonding to zirconia.

Overall, the evidence supports a dual-treatment protocol, ideally SB combined with ZP or MB. Where mechanical pretreatment is not viable, MB remains a reliable alternative. Future research should focus on standardized testing conditions and explore durability under intraoral aging. For clinical orthodontics involving zirconia restorations, evidence-based selection of surface treatment and bracket material is critical to achieving predictable, long-term success.

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Ethical approval

No ethical approval was required for this study as it did not involve human participants, animal subjects, or sensitive data. This study falls under the category of data collection without participant identification.

Consent for publication

Not applicable.

Authors' contributions

The author(s) declare that all the criteria for authorship designated by the International Committee of Medical Journal Editors have been met. More specifically, these are: (a) Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND (b) Drafting the work or revising it critically for important intellectual content; AND (c) Final approval of the version to be published; AND (d) Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Competing interests

The author(s) declare that there are no competing interests related to this work.

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