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Advancing Adhesive Strategies for Endodontically Treated Teeth—Part II: Dentin Sealing Before Irrigation Increases Long-Term Microtensile Bond Strength to Coronal Dentin

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ABSTRACT

Objective: To compare the long-term microtensile bond strength (μTBS) to coronal dentin using pre-endodontic dentin sealing (PEDS) and post-endodontic adhesion (PEA) techniques under various endodontic irrigation protocols.

Materials and Methods: Ten study groups ($n = 10$) were established based on the timing of adhesive application (PEDS versus PEA) and irrigation protocol: distilled water (control), 3% sodium hypochlorite (NaOCl), 3% NaOCl followed by 17% ethylenediaminetetraacetic acid (EDTA), 3% NaOCl followed by 17% EDTA and 2% chlorhexidine, and a mixture of 3% NaOCl and 9% etidronic acid (HEDP). Specimens underwent μTBS testing after a six-month microspecimen aging period. Fracture patterns were analyzed, and adhesive interfaces were assessed using scanning electron microscopy (SEM). Statistical analysis employed a mixed linear regression model with a 5% significance level.

Results: PEDS consistently preserved high bond strength across all irrigation protocols (57.4–59.5 MPa), while PEA groups treated with endodontic irrigants resulted in significantly lower values (33.3–40.8 MPa; $p < 0.001$). No significant differences were observed within the PEDS groups ($p > 0.05$). SEM analysis revealed consistent hybrid layers in PEDS and PEA/Control groups, while PEA groups treated with endodontic irrigation solutions showed significant resin–dentin interface variations and interfacial gaps.

Conclusions: The PEDS technique preserved high and consistent μTBS regardless of the irrigation protocol, whereas endodontically irrigated PEA groups exhibited significantly reduced bond strength. PEDS offers a predictable approach to optimizing adhesive performance in endodontic-restorative treatments.

Clinical Significance: Integrating PEDS into routine endodontic-restorative workflow is recommended to enhance long-term bond strength to coronal dentin. The PEDS technique ensures consistent adhesive performance regardless of the endodontic irrigation protocol, enhancing restorative predictability and treatment success while preserving tooth structure.

1 | Introduction

Bacteria and their byproducts have been identified as the primary cause of pulpal and periapical diseases, underscoring the critical importance of stringent infection control during root canal therapy, particularly through irrigation protocols that are vital for achieving successful treatment outcomes [1, 2].

Sodium hypochlorite (NaOCl) remains the most widely used endodontic irrigant during root canal instrumentation, valued for its broad-spectrum antimicrobial activity and capacity to dissolve organic tissue [2–5]. Despite its potent nonspecific oxidizing and proteolytic actions, NaOCl is incapable of completely removing the smear layer as it exerts no effect on inorganic components [2]. Therefore, effective smear layer removal requires a demineralizing agent, such as ethylenediaminetetraacetic acid (EDTA), a strong chelator, or etidronic acid (HEDP), a weak chelator, both of which induce surface decalcification by binding to calcium ions [2]. Traditionally, EDTA is applied after NaOCl, once instrumentation is complete [2]. Conversely, HEDP can be combined with NaOCl in a single mixture for use during mechanical root canal preparation, providing simultaneous antimicrobial, proteolytic, and decalcifying effects [6–8]. Additionally, using chlorhexidine (CHX) after EDTA has been suggested to enhance disinfection. CHX offers broad-spectrum antimicrobial activity, but unlike NaOCl, it lacks the ability to dissolve pulp tissue, making it unsuitable as a primary endodontic irrigant [2, 9]. While the pulp tissue dissolution provided by NaOCl is crucial, it also dissolves both exposed and mineral-shielded dentinal collagen [10]. Given the detrimental effects of NaOCl on dentin collagen, CHX has been proposed as an alternative final irrigant [2, 4, 8, 9].

Coronal seal is a fundamental factor in the long-term success of root-filled teeth [11–15]. The advent of dental adhesion marked an undeniable paradigm shift in restorative dentistry, with the quality of adhesive interfaces playing a pivotal role in the outcome of endodontic-restorative treatments [16–18]. Two primary mechanisms are involved in adhesion to dentin: microretention, provided by the interlocking of adhesive monomers with the demineralized dentin, and chemical bonding, which results from the ionic interaction of the bonding agent's functional monomers with calcium from the hydroxyapatite crystals [16, 19]. Optimizing both mechanisms is paramount to achieving long-term success [19].

During biomechanical preparation, coronal dentin is inevitably exposed to irrigants. While essential to fulfill the goals of root canal treatment, commonly used endodontic irrigation solutions can alter the morphological and chemical properties of dentin (as demonstrated in Part I of this publication series [20]), thereby affecting its interaction with restorative materials [3, 21, 22]. The impact of endodontic irrigants on adhesion to coronal dentin remains a subject of ongoing debate. Despite the conflicting results, most studies demonstrate that NaOCl-treated dentin exhibits impaired adhesion [18, 21–33]. This reduction in bond strength is mainly attributed to NaOCl's oxidative effects, which generate protein-derived radicals that interfere with the polymerization of restorative materials [34, 35]. NaOCl also decomposes into oxygen, which inhibits adhesive polymerization, and damages the collagen matrix essential for microretention, thereby compromising the formation of a consistent hybrid layer [21, 23, 36, 37]. Additionally, residual chemicals can impede adhesive penetration, while the increased surface pH of NaOCl-treated dentin may reduce the effectiveness of self-etching adhesive systems [21, 38, 39]. These mechanisms collectively contribute to the frequently observed bond strength reduction in NaOCl-treated dentin. Despite efforts to identify alternative auxiliary solutions, NaOCl is likely to remain the primary irrigant in endodontics [2]. Furthermore, the use of chelating agents introduces inorganic changes, namely calcium depletion, surface erosion, or even precipitate formation, which may further hinder hybridization [3, 17, 22, 33, 40].

The technique that underlies the modern concept of immediate dentin sealing (IDS) was first introduced by Pashley et al. in 1992 [41]. Within this method, freshly exposed dentin surfaces should be sealed with an adhesive system to ensure optimal bonding [42]. Current evidence encourages the application of the IDS protocol to prevent dentin contamination and reduce hypersensitivity during the provisional phase of indirect restoration workflows [42–44]. Although hypersensitivity is not a concern in endodontically treated teeth, the use of irrigants, temporary materials, intracanal medication and endodontic sealers can adversely impact bonding quality [14, 42, 44–46]. Additionally, the morphologically- and chemically-modified coronal dentin poses a significant challenge and major concern as it becomes an unfavorable substrate for adhesion of the final restoration [3, 17, 18, 22, 24, 25, 28–31, 33, 38, 47–49]. To address these issues, the application of IDS to freshly cut dentin immediately after access cavity completion and before initiating irrigation procedures has been proposed [50]. IDS holds the potential to prevent dentin contamination by endodontic materials and enhance bond strength by facilitating hybridization with freshly cut, uncontaminated dentin while retaining its structural and chemical integrity. The application of IDS in endodontics thus aligns with the medical maxim "primum non nocere"—"first, do no harm." A recent study demonstrated promising results, reporting a significant improvement in immediate resin-dentin bond strength achieved through dentin hybridization prior to limited exposure to endodontic chemical agents [51]. Furthermore, previous research shows significantly better internal adaptation of composite resin restorations and improved fracture resistance when pre-sealing of the access cavity was performed [50, 52]. Presealing the dentin surface has also proven beneficial in reducing tooth discoloration in the context of regenerative endodontic procedures [53].

To the best of our knowledge, no studies have investigated the long-term bond strength to coronal dentin in the context of endodontic irrigation procedures, either with or without the application of IDS. This gap in the literature concerns two distinct restorative sequences:

1. Pre-endodontic dentin sealing (PEDS): a novel restorative approach where coronal dentin sealing is performed prior to irrigation and restoration procedures.
2. Post-endodontic adhesion (PEA): the conventional restorative approach, in which irrigation precedes the coronal adhesive and restorative procedures.

Therefore, this in vitro study aims to compare the microtensile bond strength to coronal dentin of these two restorative strategies—PEDS and PEA—when combined with five different irrigation protocols, following an aging process.

The tested research hypotheses were as follows:

a. PEDS and PEA approaches yield significantly different bond strength values.
b. The irrigation protocols result in significantly different bond strength values.

2 | Materials and Methods

2.1 | Sample Size Calculation

The microtensile bond strength was evaluated across ten (10) experimental groups. The effect size was estimated at 0.42 based on the findings of a pilot study. Sample size calculation was conducted using G*Power 3.1.9.7 software, employing an ANOVA test with a significance level of 0.05 and a statistical power of 80%. Based on these parameters, the estimated sample size was 10 elements per group (Figure 1).

2.2 | Specimen Selection

The study was approved by the Ethics Committee of the Faculty of Medicine of the University of Coimbra (CE-042/2021). One hundred and twenty (120) teeth fulfilling the following criteria were included:

- Intact human third molars;
- Extracted for orthodontic or periodontal reasons;
- Obtained from 16- to 40-year-old individuals.

All tooth surfaces were visually inspected under 16× magnification (M300; Leica Microsystems, Wetzlar, Germany), cleaned using hand periodontal scalers, and polished with pumice and water to remove any adherent organic material or calculus. Subsequently, the teeth were immediately immersed in 1% chloramine-T solution at 4°C for 1 week for disinfection and thereafter stored in distilled water at 4°C, renewed every 2 weeks, for a maximum of 6 months before initiating the experimental procedures (ISO/TS 11405:2015). Figure 2 provides a schematic representation of the experimental procedures employed in this study.

2.3 | Specimen Preparation

The pulp chambers were accessed apically and meticulously cleaned using a spoon excavator and 3% NaOCl. They were then filled with a universal bonding system (Prime&Bond active; Dentsply DeTrey GmbH, Konstanz, Germany) and a flowable composite resin (SDR flow+; Dentsply Sirona, York, Pennsylvania, United States of America). To ensure reproducibility in tooth positioning, the apical root third of each tooth was embedded in autopolymerizing acrylic resin (Laboratorios Schmidt, Madrid, Spain) within a 3D-printed hard PMMA-like resin ring (Dental Pink; HARZ Labs LLC., Moscow, Russia).

The crowns were horizontally sectioned 4 mm below the occlusal surface to expose a flat surface of deep coronal dentin. The sectioning was performed using a low-speed (3000 rpm at 0.050 mm/s) water-cooled diamond saw (Accutom-5; Struers, Ballerup, Denmark). Peripheral enamel was removed using a tapered diamond bur under 16× magnification (M300; Leica Microsystems, Wetzlar, Germany). Dentin surfaces were manually prepared using 600-grit silicon-carbide (SiC) abrasive paper for 30 s in a circular motion under constant irrigation to produce a standardized smear layer [54]. In cases of pulp horn exposure, a purple-shaded flowable composite resin (IPS Empress Direct Color, purple shade; Ivoclar Vivadent

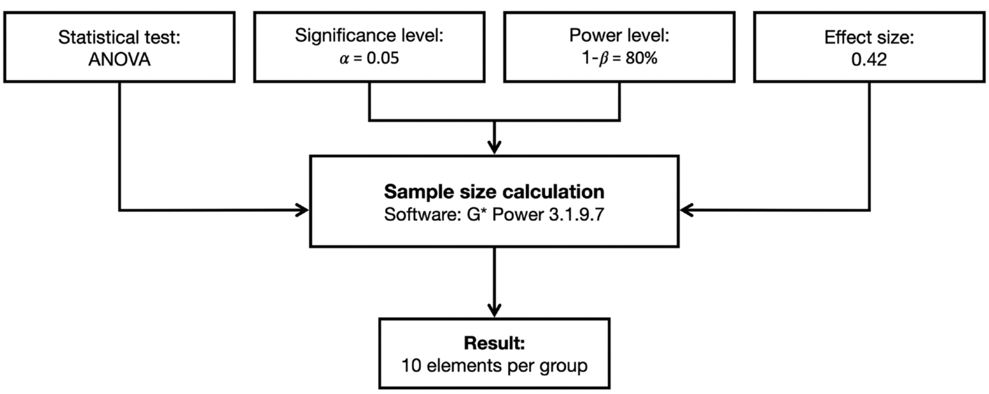

FIGURE 1 | Sample size calculation diagram. Sample size calculation was performed using G*Power 3.1.9.7 software. Input parameters included: ANOVA test, significance level of 0.05, statistical power of 80%, and effect size of 0.42 (estimated from a pilot study). The calculation resulted in a sample size of 10 elements per group, for a total of 10 experimental groups.

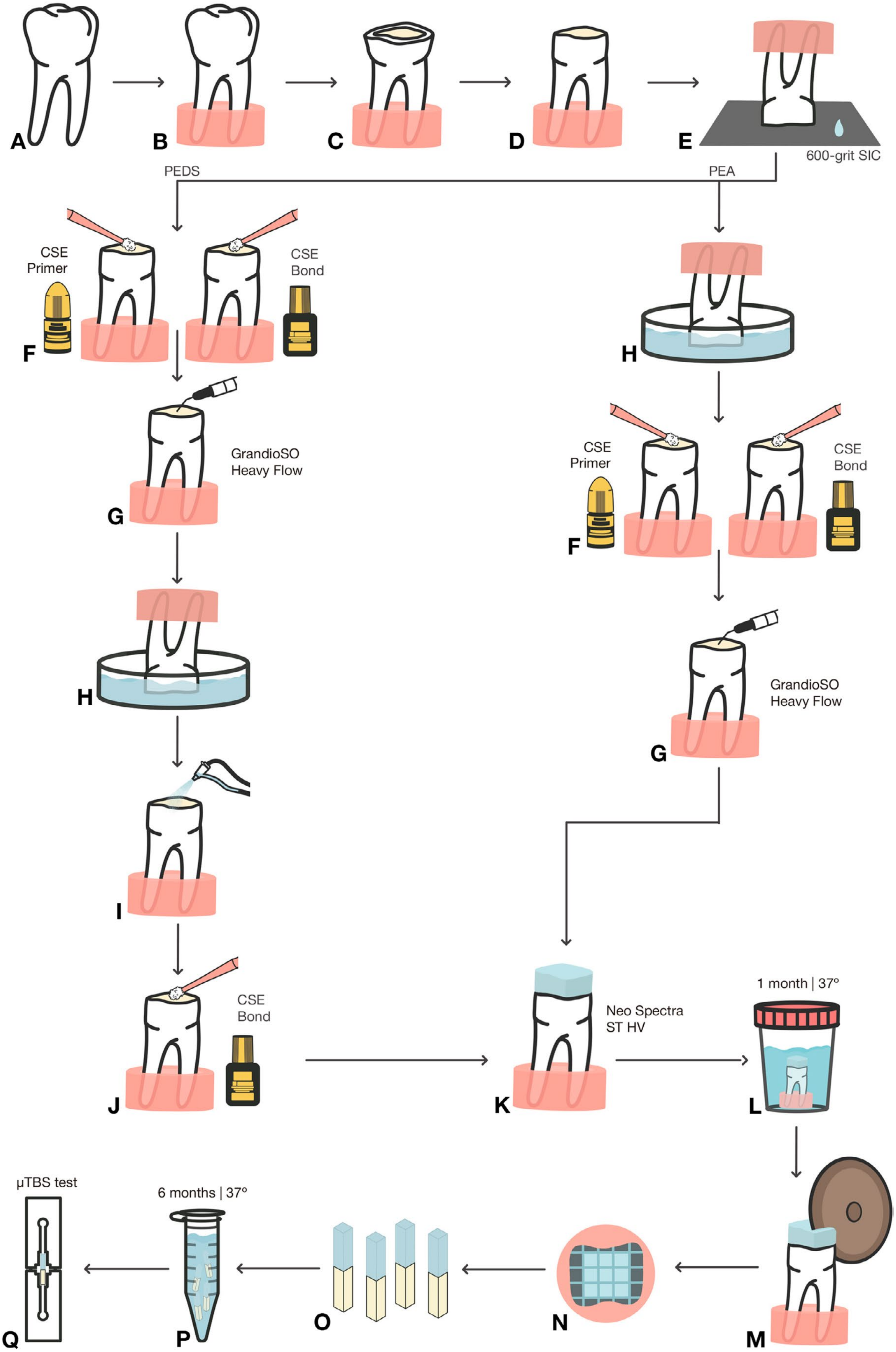

FIGURE 2 | Legend on next page.

FIGURE 2 | Schematic illustration of the experimental procedures: (A) intact human third molar; (B) apical root third embedded in autopolymerizing acrylic resin; (C) horizontal section 4 mm below the occlusal surface; (D) peripheral enamel removed; (E) dentin surface prepared using 600-grit silicon-carbide abrasive paper; (F) two-step self-etch bonding system application; (G) 0.3–0.5-mm thick flowable composite resin layer; (H) irrigation procedures; (I) water–airborne-particle abrasion; (J) hydrophobic bonding resin application; (K) buildup; (L) storage in distilled water at 37°C for 1 month; (M) longitudinal sectioning to produce approximately 1 mm thick serial sections; (N) completed buccal-lingual and mesial-distal sectioning with peripheral sticks identified; (O) individual sticks; (P) microspecimen aging in distilled water at 37°C for 6 months; (Q) microtensile bond strength test. μTBS = microtensile bond strength; CSE Bond = bonding resin of Clearfil SE Bond bonding system; CSE Primer = primer of Clearfil SE Bond bonding system; PEA = post-endodontic adhesion; PEDS, pre-endodontic dentin sealing; SiC, silicon-carbide abrasive paper.

AG, Schaan, Liechtenstein) was applied to the exposure site to allow subsequent identification and ensure the specimen's exclusion from further analysis.

2.4 | Experimental Groups

Ten study groups were established according to the irrigation protocol and the timing of adhesive system application: before irrigation (PEDS) or after irrigation (PEA) (Table 1).

Sample preparation and testing were randomly assigned, alternating between PEDS and PEA groups. All experimental procedures were conducted at a room temperature of 22.8°C ± 0.5°C and 43% ± 1% relative humidity. One experienced operator, blinded to the irrigation protocols, performed all irrigation procedures, receiving the solutions without knowledge of their composition. A second operator, blinded during the bonding step to dentin, performed the adhesive procedure and resin coating without information on whether the samples belonged to the PEDS or PEA group. The same experienced operator carried out all restorative procedures.

TABLE 1 | Experimental groups.

	Abbreviations for the experimental groups	
Irrigation protocol	**Adhesive system application before irrigation**	**Adhesive system application after irrigation**
DW (30 min, renewed every 2 min)	PEDS/Control	PEA/Control
3% NaOCl (37°C, 30 min, renewed every 2 min)	PEDS/NaOCl	PEA/NaOCl
3% NaOCl (37°C, 30 min, renewed every 2 min) 17% EDTA (1 min)	PEDS/NaOCl/EDTA	PEA/NaOCl/EDTA
3% NaOCl (37°C, 30 min, renewed every 2 min) 17% EDTA (1 min) DW (1 min) 2% CHX (2 min)	PEDS/NaOCl/EDTA/CHX	PEA/NaOCl/EDTA/CHX
3% NaOCl/9% HEDP (37°C, 30 min, renewed every 2 min)	PEDS/NaOCl/HEDP	PEA/NaOCl/HEDP

Abbreviations: CHX, chlorhexidine; DW, distilled water; EDTA, ethylenediaminetetraacetic acid; HEDP, etidronic acid; NaOCl, sodium hypochlorite; PEA, post-endodontic adhesion; PEDS, pre-endodontic dentin sealing.

2.5 | Irrigation Protocols

The performed irrigation protocols for each study group were the following:

- *PEDS/Control and PEA/Control*: immersion in 30 mL of distilled water for 30 minutes, renewed every 2 min.
- *PEDS/NaOCl and PEA/NaOCl*: immersion in 30 mL of 3% NaOCl (Coltène/Whaledent AG, Altstätten, Switzerland; lot number 20222220; expiration date 08/2024) at 37°C for 30 min, renewed every 2 min.
- *PEDS/NaOCl/EDTA and PEA/NaOCl/EDTA*: immersion in 30 mL of 3% NaOCl at 37°C for 30 min, renewed every 2 min, followed by a 1 min immersion in 30 mL of 17% EDTA (Coltène/Whaledent AG, Altstätten, Switzerland; lot number 171534; expiration date 01/2024).
- *PEDS/NaOCl/EDTA/CHX and PEA/NaOCl/EDTA/CHX*: immersion in 30 mL of 3% NaOCl at 37°C for 30 min, renewed every 2 min, followed by a 1 min immersion in 30 mL of 17% EDTA. Samples were then copiously rinsed with distilled water for 1 min to completely eliminate the chelating agent and, lastly, immersed in 30 mL of 2% CHX (Coltène/Whaledent AG, Altstätten, Switzerland; lot number 171535; expiration date 01/2024) for 2 min.
- *PEDS/NaOCl/HEDP and PEA/NaOCl/HEDP*: immersion in 30 mL of a combination of 3% NaOCl and 9% HEDP at 37°C for 30 min, renewed every 2 min. The combined NaOCl/HEDP solution was freshly mixed before initiating the irrigation protocol by using a sterile metallic spatula to mix 450 mL of NaOCl with the powder contained in 45 capsules of Dual Rinse HEDP (Medcem GmbH, Weinfelden, Switzerland; lot number DR210419; expiration date 03/2024) for 2 min. The NaOCl/HEDP mixture was refreshed 20 min after its preparation to ensure its therapeutic properties.

Irrigation procedures were performed in a glass container placed in a 37°C water bath (Digital Thermostatic Water Bath;

Nahita, Beriain-Navarra, Spain) to simulate body temperature. Following the completion of the irrigation protocols, the samples were rinsed with distilled water for 1 min and dried using a mild air stream.

2.6 | Restorative Procedures

2.6.1 | Pre-Endodontic Dentin Sealing (PEDS) Groups

Immediate dentin sealing was performed directly following the procedures described in Section 2.3 by applying a self-etch bonding system (Clearfil SE Bond 2; Kuraray Noritake Dental Inc., Okayama, Japan) on the freshly cut coronal dentin surface. The primer was actively applied by scrubbing it onto the dentin for 20 s, with primer renewal performed after 10 s of active application. The surface was dried with a mild air stream for 10 s to promote solvent evaporation. The bonding resin was then also scrubbed onto the surface for 20 s, dried until no movement was observed, and light-cured for 20 s (1.200 mW/cm^2, Bluephase Style 20i; Ivoclar Vivadent AG, Schaan, Liechtenstein). A 0.3 to 0.5-mm thick flowable composite resin (GrandioSO Heavy Flow, A3 shade; VOCO GmbH, Cuxhaven, Germany) layer was subsequently applied and light-cured for 20 s, followed by airblock gel (Liquid Strip; Ivoclar Vivadent AG, Schaan, Liechtenstein) application and an additional 20-s light-curing cycle. Irrigation protocols were then performed as described in Section 2.5. Afterward, the restorative procedures initiated with water–airborne-particle abrasion of the sealed dentin using 29 μm aluminum oxide particles at 4 bar pressure, maintaining a 1 cm tip-to-surface distance and a 45° angle incidence for 5 s in a circular motion (AquaCare Twin; Medivance Instruments Ltd., London, United Kingdom). After rinsing with a distilled water/air stream for 1 min and drying for 30 s, the hydrophobic bonding resin (bond bottle from Clearfil SE Bond 2) was actively scrubbed onto the surface for 20 s, dried until no movement was observed, and light-cured for 20 s. Restoration was performed by applying 1–2 mm increments of a medium-consistency nanohybrid composite resin (Neo Spectra ST HV, A1 shade; Dentsply DeTrey GmbH, Konstanz, Germany), each light-cured for 20 s, until a 5-mm high buildup was achieved. Last, airblock gel was applied and a final 100-s photopolymerization (20 s per quadrant and an additional occlusal cycle of polymerization) was carried out. The restorative materials' specifics are summarized in Table 2.

2.6.2 | Post-Endodontic Adhesion (PEA) Groups

Immediate dentin sealing was not performed. After irrigation procedures (as described in Section 2.5), the restorative procedures were carried out. The bonding system was applied first, followed by the application of flowable composite resin and subsequent restoration. An airblock gel was then applied for the final photopolymerization. The restorative materials, application steps, and technique adhered to the protocol described for the PEDS groups in Section 2.6.1, with the exception that no air abrasion or additional hydrophobic bonding resin was used, as all restorative procedures were performed in a single sequence immediately after irrigation.

2.7 | Microspecimen Long-Term Aging

After irrigation/restorative procedures, samples were immediately stored in distilled water at 37°C (Economy Incubator with fan size 1; Gallenkamp, London, United Kingdom) for 1 month and thereafter longitudinally sectioned (perpendicular to the bonding interface) to produce approximately 1-mm thick serial sections. Sectioning was performed with a low-speed (3000 rpm at 0.05 mm/s) diamond saw under continuous water cooling (Accutom-5; Struers, Ballerup, Denmark). Extra-light silicone (Virtual Extra Light Body Fast Set; Ivoclar Vivadent AG, Schaan, Liechtenstein) was used to stabilize the sections before conducting a second longitudinal section, followed by a final horizontal section, resulting in sticks with approximately 1-mm^2 cross-sectional area. Peripheral sticks were marked with a permanent marker and discarded. The remaining sticks were immediately stored in distilled water and maintained at 37°C (Economy Incubator with fan size 1; Gallenkamp, London, United Kingdom) for 6 months. Storage medium was renewed every 2 weeks.

2.8 | Microtensile Bond Strength Assessment ($n = 10$)

Sticks were initially examined under 40× magnification (M300; Leica Microsystems, Wetzlar, Germany), and those matching the following exclusion criteria were discarded: presence of voids or defects within the adhesive interface and/or restorative material; adhesive interface not perpendicular to the direction of the microtensile bond strength test force vector; pulp horn exposure; or insufficient dentin height to allow stick fixation for testing. Eligible sticks were individually mounted onto a metallic device using black cyanoacrylate adhesive (Permabond 735; Permabond Engineering Adhesives, Winchester, United Kingdom) and subsequently positioned in a universal testing machine (Model AG-I; Shimadzu Corporation, Kyoto, Japan). Microtensile bond strength test was conducted at a crosshead speed of 0.5 mm/min until fracture. Microtensile bond strength (MPa) was calculated by dividing the maximum rupture force in newton (N) by the adhesive interface cross-sectional area (mm^2) of each stick, measured using a digital caliper. Sticks with an adhesive interface area of ≤ 0.8 mm^2 or ≥ 1.2 mm^2, as well as those with microtensile holder glue present on the adhesive interface, were also excluded. On average, 12 ± 3 sticks per tooth were obtained, with a cross-sectional area of 0.95 ± 0.08 mm^2.

2.9 | Fracture Pattern Analysis

Failure mode was assessed by two experienced operators under 40× magnification (M300; Leica Microsystems, Wetzlar, Germany) and categorized as adhesive (at the bonding interface), mixed (involving both the bonding interface and the dentinal substrate or restorative material, with the less prevalent representing at least 10% of the total area), cohesive within composite resin, or cohesive within dentin. In cases of uncertainty, confirmation was performed using a stereomicroscope (Nikon SMZ1500, objective HR Plan Apo 1X WD 54; Nikon Corporation, Tokyo, Japan).

TABLE 2 | Restorative materials' specifics.

Material	Manufacturer (city, country)	Classification	Composition	Lot number and expiration date
Clearfil SE Bond 2	Kuraray Noritake Dental Inc. (Okayama, Japan)	Two-step self-etch adhesive system	Primer: 10-MDP, HEMA, hydrophilic aliphatic dimethacrylate, dl-Camphorquinone, water	Primer 1G0206 04/2026
			Bond: 10-MDP, Bis-GMA, HEMA, hydrophobic aliphatic dimethacrylate, dl-Camphorquinone, initiators, accelerators, silanated colloidal silica	Bond 1C0312 03/2026
GrandioSO Heavy Flow	VOCO GmbH (Cuxhaven, Germany)	Flowable composite resin (83% w/w)	Barium aluminum borosilicate glass, silicon oxide, HEDMA, BisGMA, TEGDMA, BisEMA, fumed silica, initiators, stabilizers, pigments	2218399 08/2024
Neo Spectra ST HV	Dentsply DeTrey GmbH (Konstanz, Germany)	Nanohybrid composite resin (78%–80% w/w)	Barium-aluminum-borosilicateglass, pre-polymerized filler, TEGDMA dimethacrylate multifuncional polymethacrylate, ytterbium fluoride, methacrylate modified polysiloxane (organically modified ceramic), ethyl-4(dimethylamino)benzoate (photoaccelerato), initiator, butylated hydroxy toluene, UV stabilizer, camphorquinone (photoinitiator), titanium dioxide, iron oxide pigments, fluorescent agent	2207000963 07/2025
Aluminum oxide powder	Medivance Instruments Ltd. (London, United Kingdom)	Air abrasion powder	Aluminum oxide (29 μm)	100122
Liquid Strip	Ivoclar Vivadent AG (Schaan, Liechtenstein)	Glycerin gel	Glycerine, water, highly dispersed silicon dioxide and highly dispersed aluminum oxide	Z00HN5 08/2024

Abbreviations: 10-MDP, 10-Methacryloyloxydecyl dihydrogen phosphate; BisEMA, ethoxylated bisphenol A dimethacrylate; Bis-GMA, bisphenol A-diglycidyl methacrylate; HEDMA, hydroxyethyl dimethacrylate; HEMA, 2-hydroxyethyl methacrylate; TEGDMA, triethylene glycol dimethacrylate.

TABLE 3 | Study groups' microtensile bond strength (μTBS) and fracture pattern results. Identical letters within the μTBS column indicate groups with no statistically significant differences ($p > 0.05$).

Study group ($n = 10$)	μTBS (mean ± SD)	Fracture pattern			
		A	CD	CR	M
PEA/Control	56.5 ± 13.9[a]	32 (27.6%)	7 (6.0%)	77 (66.4%)	0 (0.0%)
PEA/NaOCl	40.8 ± 17.8[b]	91 (75.8%)	1 (0.8%)	28 (23.3%)	0 (0.0%)
PEA/NaOCl/EDTA	36.9 ± 13.3[b]	89 (77.4%)	2 (1.7%)	19 (16.5%)	5 (4.3%)
PEA/NaOCl/EDTA/CHX	37.4 ± 14.3[b]	97 (75.8%)	3 (2.3%)	27 (21.1%)	1 (0.8%)
PEA/NaOCl/HEDP	33.3 ± 14.6[b]	87 (82.1%)	0 (0.0%)	16 (15.1%)	3 (2.8%)
PEDS/Control	57.4 ± 14.0[a]	35 (28.2%)	8 (6.5%)	78 (62.9%)	3 (2.4%)
PEDS/NaOCl	58.2 ± 16.0[a]	45 (34.6%)	7 (5.4%)	75 (57.7%)	3 (2.3%)
PEDS/NaOCl/EDTA	57.9 ± 16.0[a]	33 (29.7%)	8 (7.2%)	67 (60.4%)	3 (2.7%)
PEDS/NaOCl/EDTA/CHX	59.5 ± 13.4[a]	46 (37.1%)	19 (15.3%)	59 (47.6%)	0 (0.0%)
PEDS/NaOCl/HEDP	58.9 ± 13.9[a]	51 (38.6%)	11 (8.3%)	69 (52.3%)	1 (0.8%)

Note: Microtensile bond strength is expressed in MPa. Fracture pattern is expressed in absolute frequency (relative frequency).
Abbreviations: μTBS, microtensile bond strength; A, adhesive; CD, cohesive in dentin; CR, cohesive in composite resin; M, mixed; SD, standard deviation.

2.10 | Scanning Electron Microscopy ($n = 2$)

Two randomly selected teeth from each experimental group were longitudinally sectioned using a low-speed saw (3000 rpm at 0.05 mm/s) water-cooled diamond (Accutom-5; Struers, Ballerup, Denmark) to produce 450-μm thick sections for examining adhesive interface ultramorphology via scanning electron microscopy (SEM). Each section was polished with ascending grit silicon carbide (SiC) abrasive paper (1000, 1200, and 2500-grit) and treated with 6 mol/L hydrochloric acid for 30 s, rinsed with distilled water for 30 s, immersed in 5.25% NaOCl for 10 min, rinsed with distilled water for 30 s, dehydrated in ascending ethanol solutions (25%, 50%, 75% [20 min each], 95% [30 min] and 100% [30 min two times]), immersed in hexamethyldisilane for 10 min, and, lastly, air-dried. In addition, two debonded specimens representative of each fracture pattern were selected and dehydrated in ascending ethanol solutions (25%, 50%, 75% [20 min each], 95% [30 min] and 100% [30 min two times]). The specimens were then mounted on aluminum stubs using carbon adhesive (Leit-C; Sigma-Aldrich Chemie GmbH, Steinheim, Germany) and sputter-coated with gold–palladium for SEM observation (SU-70; Hitachi, Tokyo, Japan) at 15.0 kV under 100× to 5000× magnifications.

2.11 | Statistical Analysis

The bond strength of each study group was described using the mean and standard deviation. A mixed linear regression model was employed to compare bond strength between the groups. This model was selected due to the structure of the data, where the specimens originated from the same teeth, albeit different teeth across groups. Groups were treated as fixed effects, while individual teeth were treated as random effects. Specifically, a linear mixed model with random intercepts and slopes was utilized. Correction for multiple comparisons was performed using the Benjamini–Hochberg method, with a false discovery rate (FDR) set at 5%.

The robustness of the findings was evaluated by calculating the achieved statistical power using the *simr* package within the R environment.

Fracture type analysis was conducted in two stages. First, fractures within each group were described in terms of absolute and relative frequencies. Subsequently, the association between fracture type and group was examined using the chi-squared test implemented through a Monte Carlo simulation scheme with 10.000 samples.

The statistical analysis was carried out in the R environment (version 4.1.2) using the *lme4* and *lmerTest* packages for linear mixed models and the *simr* package for power calculations. The IBM SPSS v28 platform was also used. A significance level of 0.05 was adopted for all analyses.

3 | Results

The results for microtensile bond strength and fracture pattern are summarized in Table 3. A statistical power of 100% (95% CI [88%, 100%]) was achieved. Pre-test failures occurred exclusively in the PEA/NaOCl/EDTA and PEA/NaOCl/HEDP groups (5 and 11 pre-test failures, respectively). PEDS groups exhibited the highest mean bond strength values, ranging from 57.4 to 59.5 MPa. In contrast, bond strength in the PEA groups varied between 33.3 and 56.5 MPa. No significant differences were observed in bond strength between the PEA/Control and all PEDS groups ($p > 0.05$), with these groups showing significantly higher bond strength compared to all PEA/NaOCl, PEA/NaOCl/EDTA, PEA/NaOCl/EDTA/CHX, and PEA/NaOCl/

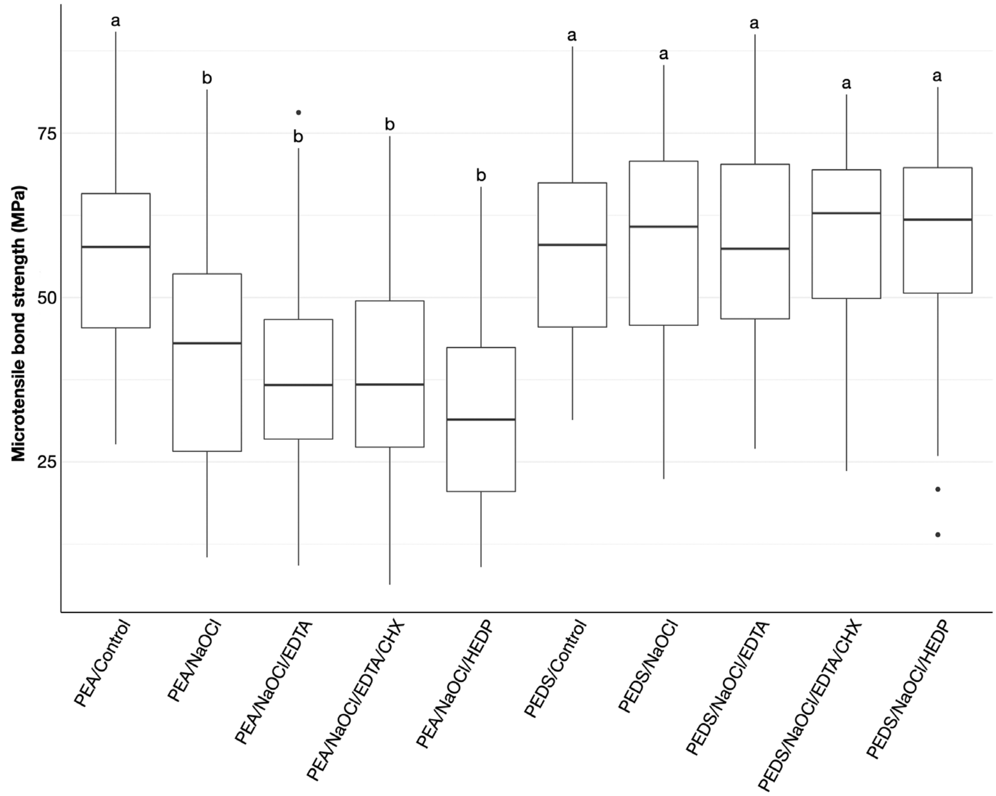

FIGURE 3 | Box plots illustrate microtensile bond strength distribution for each study group. Identical letters indicate groups with no statistically significant differences ($p > 0.05$) according to the mixed linear regression model adjusted for multiple comparisons using the Benjamini–Hochberg method.

HEDP groups ($p < 0.001$) – Figure 3. Furthermore, PEA/NaOCl, PEA/NaOCl/EDTA, PEA/NaOCl/EDTA/CHX, and PEA/NaOCl/HEDP groups produced the lowest mean bond strength values, with no intergroup statistically significant differences ($p > 0.05$) (Table S1).

Figure 4 displays the absolute frequencies of fracture pattern distribution within each experimental group. A statistically significant association was observed between the group and fracture type ($p < 0.001$). Adhesive fractures were predominantly detected in PEA groups, with the PEA/Control group being an exception. In contrast, cohesive fractures within the composite resin were primarily associated with the PEA/Control and PEDS groups. Cohesive within dentin fractures were also more frequently observed in the PEDS and PEA/Control groups. Mixed failures were present across several experimental groups, with no discernible trend. Figure 5 displays representative SEM images of the observed fracture patterns.

Low-magnification SEM images depict PEDS and PEA restorative interfaces, emphasizing the adequate thickness of the resin coating (Figure 6). The PEDS groups demonstrated adhesive interfaces that were consistent across all experimental groups, with no significant variation in depth, thickness, or the quantity of resin tags (Figure 7). Similarly, the PEA/Control group, where the adhesive procedure was conducted on dentin without prior exposure to endodontic irrigants, exhibited resin tag distribution and morphology comparable to those observed in PEDS groups. In contrast, PEA groups treated with endodontic solutions exhibited significant variations in the resin-dentin interfaces. Notably, the PEA/NaOCl group displayed a markedly thinner hybrid layer compared to the other groups (Figure 7E,F). PEA groups exposed to chelating agents showed enhanced patency of the dentinal tubules, resulting in a significant increase in both the length and number of resin tags, along with the formation of multiple lateral branches. These lateral branches were especially prominent in groups treated with EDTA, a strong chelator (Figure 7J,N). One of the most notable findings from this SEM analysis was the frequent occurrence of interfacial gaps between the resin and dentin, as observed in Figure 7J. These gaps were exclusively identified in the PEA/NaOCl, PEA/NaOCl/EDTA, PEA/NaOCl/EDTA/CHX, and PEA/NaOCl/HEDP groups (data not shown).

4 | Discussion

This is the first study to compare bond strength to coronal dentin subjected to clinically relevant endodontic irrigation protocols, with or without the application of the immediate dentin sealing (IDS) technique.

The first research hypothesis was partially confirmed. While all endodontic irrigation protocols yielded significantly different bond strength outcomes depending on the restorative treatment approach (PEDS > PEA), the distilled water irrigation group (control) rendered similar bond strength for both PEDS and PEA. The second research hypothesis was also partially confirmed. Within the PEA groups, all endodontic irrigation protocols rendered similar bond strength values, but these were

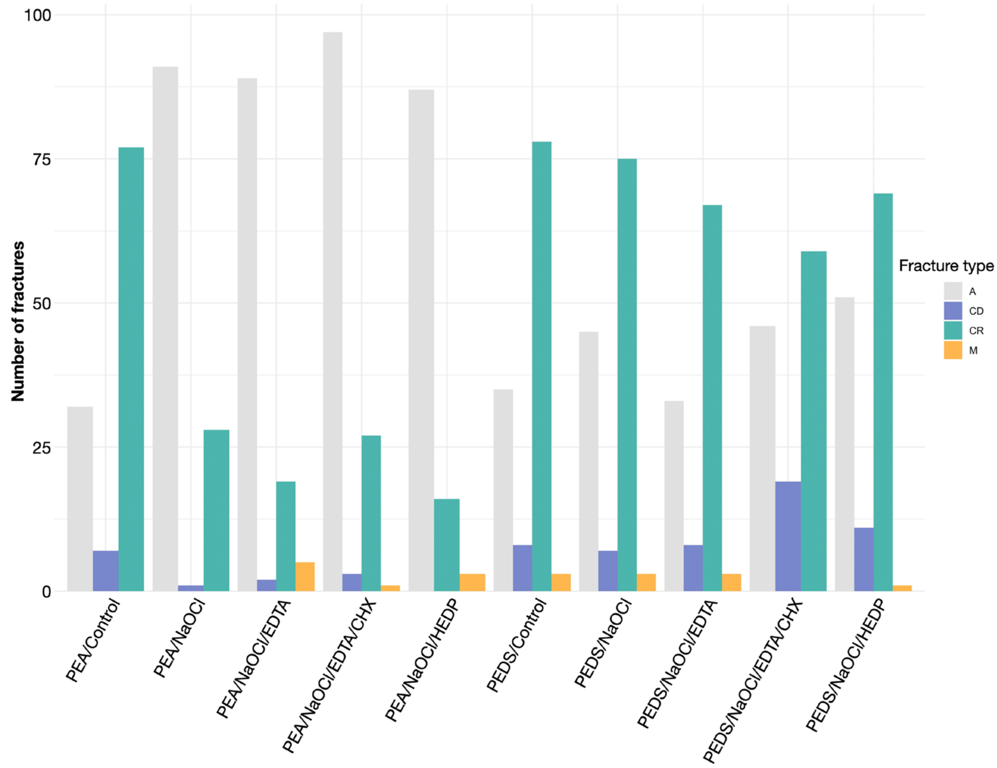

FIGURE 4 | Bar plot of fracture pattern distribution within each group. A, adhesive; CD, cohesive in dentin; CR, cohesive in composite resin; M, mixed.

significantly lower than those of the control group ($p<0.001$). In contrast, all PEDS groups produced comparable bond strength values ($p>0.05$).

The microtensile bond strength test is widely regarded as a valuable method for assessing the adhesive performance of restorative materials on a microscale (approximately 1 mm^2 areas), minimizing variability and promoting uniform stress distribution across the specimen [54, 55]. Armstrong et al. [54] recommended the microtensile bond strength test, particularly when specimens are exposed to durability challenges, as the most reliable surrogate measure for predicting the retention of dental composite restorations.

Irrigation is a *sine qua non* step for the success of nonsurgical endodontic treatment [2]. However, the unavoidable use of irrigation solutions during endodontic procedures induces significant ultrastructural and compositional alterations in coronal dentin, potentially affecting its interaction with restorative materials and ultimately impairing adhesive performance [3, 17, 18, 20, 22, 24, 25, 28–31, 33, 38, 40, 47–49].

Resin-dentin bond strength appears to be differently affected by distinct endodontic irrigants. While a few studies [5, 26, 27, 29, 31, 32, 56–59] have reported no alteration or even an increase in bond strength following endodontic irrigation—either with the exclusive use of NaOCl or in combination with chelating agents—the majority of the literature reports a decrease in bond strength [5, 17, 18, 21, 22, 24–26, 28–31, 33, 38, 47, 48, 59]. The frequently heterogeneous bond strength results may be attributed to (1) dentinal substrate variations (e.g., human versus animal, regional differences within human dentin—coronal versus root dentin, superficial versus deep dentin—as well as the age of the dentin source); (2) specimen storage conditions; (3) variation in irrigation parameters (e.g., concentration, contact time, temperature, agitation method); (4) bond strength testing methodology; (5) adhesive strategy (etch-and-rinse versus self-etch approaches) and, the most frequently referred, (6) the adhesive system chemistry [17, 18, 21].

The current preference for dentin bonding involves a two-step self-etch adhesive strategy. Among the available adhesive systems, Clearfil SE Bond (CSE) is considered the gold standard, making it the logical choice for the initial study of this research line. CSE is a two-step self-etch adhesive system that synergistically combines micromechanical and chemical bonding, with the latter being key for reliable and durable bonding [16, 19, 60]. Its clinical long-term success is attributed to the mild pH of the priming solution, which facilitates micromechanical retention, the presence of the functional monomer 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP), which forms stable ionic bonds with hydroxyapatite calcium through its phosphate group, and the presence of a separate hydrophobic bonding layer [16].

Our findings align with the majority of the literature, as all tested endodontic irrigation protocols resulted in a significant decrease in bond strength compared to the control group ($p<0.001$) in the absence of dentin pre-sealing (PEA groups). Bond strength values ranged from 33.3 to 40.8 MPa, with no statistically significant differences ($p>0.05$) among the tested irrigation protocols (NaOCl, NaOCl/EDTA, NaOCl/EDTA/CHX, and NaOCl/HEDP). This indicates that no preferential protocol could be

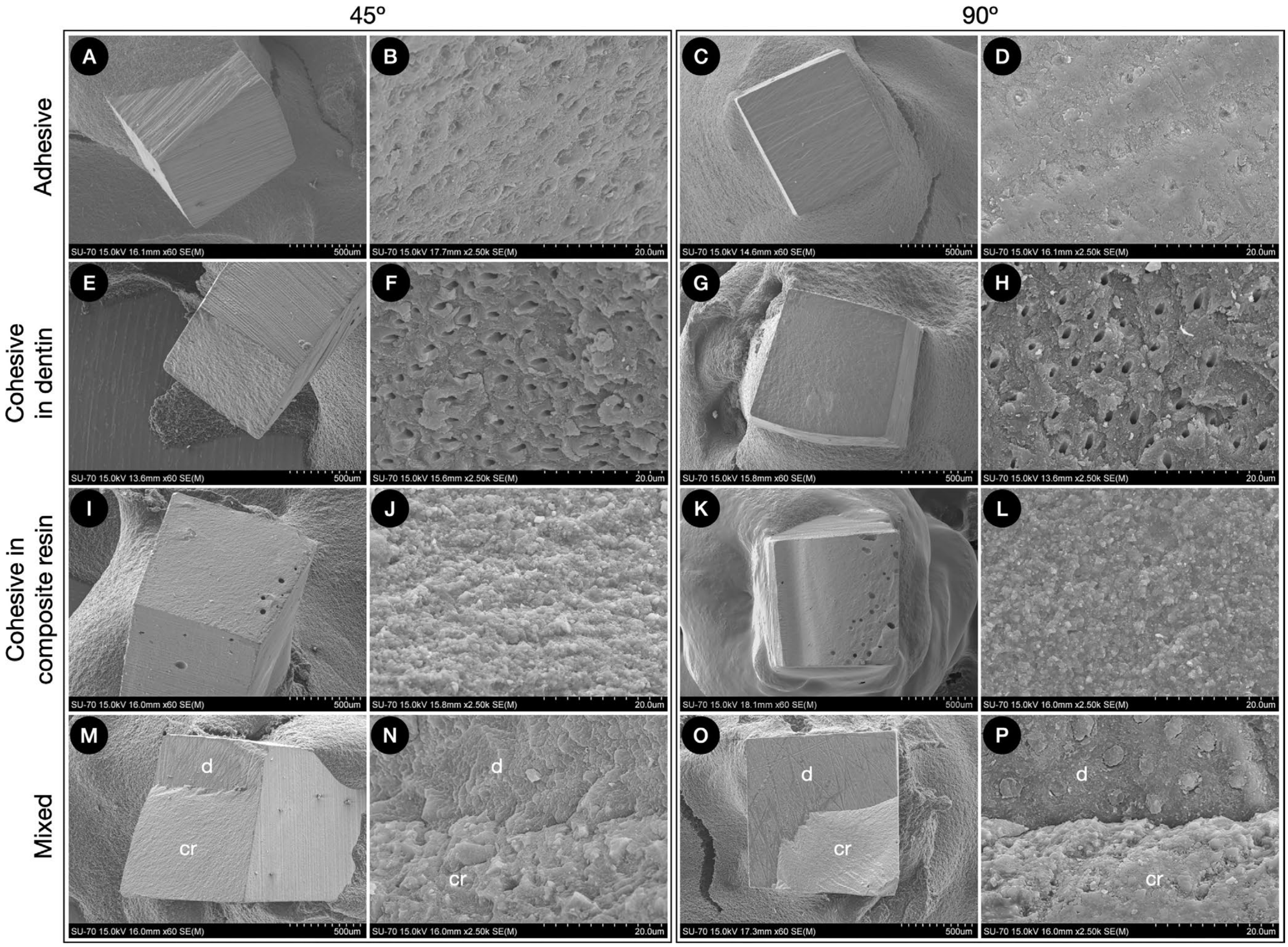

FIGURE 5 | Representative SEM images of debonded surfaces at 60× magnification (A, C, E, G, I, K, M, O) and 2500× magnification (B, D, F, H, J, L, N, P). High-magnification images in the second and fourth columns (B, D, F, H, J, L, N, P) correspond to the same-row images in the first and third columns, respectively, providing detailed views of the fracture surfaces. (A–D) Adhesive fractures; (E–H) cohesive fractures in dentin; (I–L) cohesive fractures in composite resin; (M–P) mixed fractures. cr = composite resin; d = dentin.

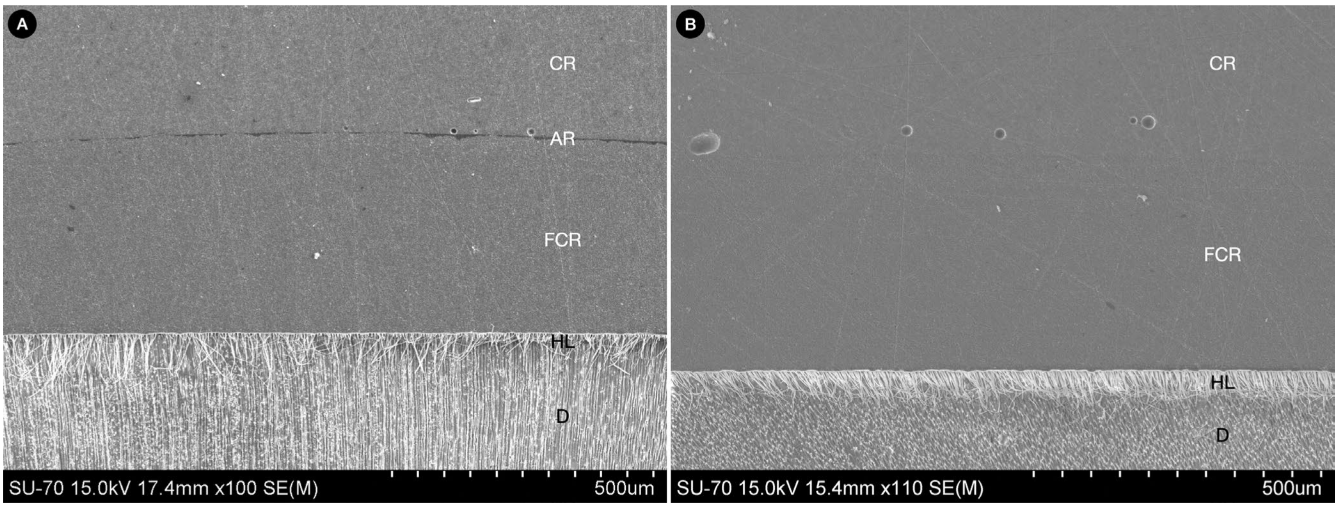

FIGURE 6 | Representative SEM images of restorative interfaces for (A) PEDS at 100× magnification and (B) PEA at 110× magnification, illustrating the adequate resin coating thickness (0.3–0.5 mm). AR = adhesive resin; CR = medium-consistency composite resin; D = dentin; FCR = flowable composite resin; HL = hybrid layer.

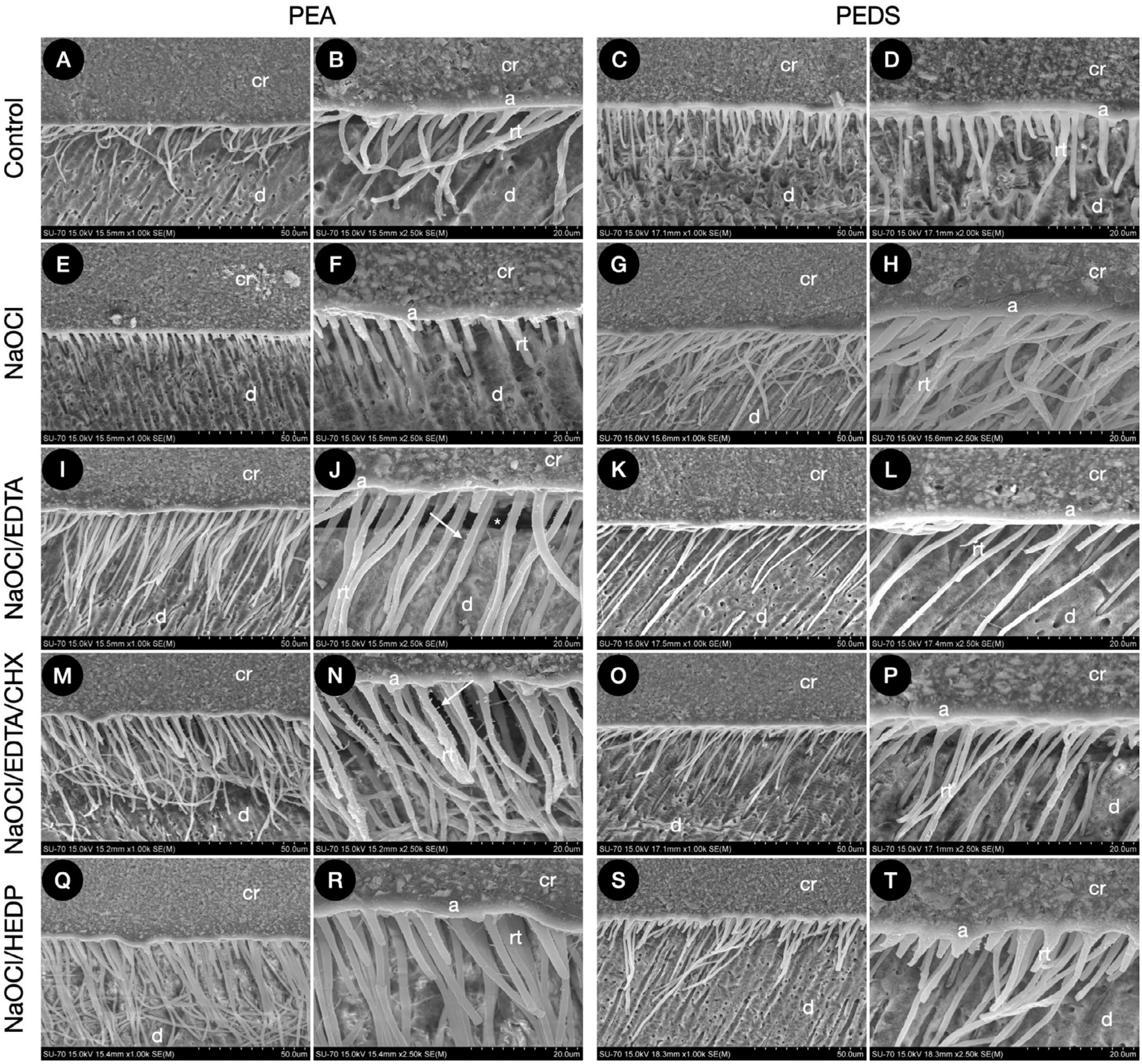

FIGURE 7 | Representative SEM images of adhesive interfaces. PEA/Control: (A) 1000× and (B) 2500×. PEDS/Control: (C) 1000× and (D) 2000×. PEA/NaOCl: (E) 1000× and (F) 2500×. PEDS/NaOCl: (G) 1000× and (H) 2500×. PEA/NaOCl/EDTA: (I) 1000× and (J) 2500×. PEDS/NaOCl/EDTA: (K) 1000× and (L) 2500×. PEA/NaOCl/EDTA/CHX: (M) 1000× and (N) 2500×. PEDS/NaOCl/EDTA/CHX: (O) 1000× and (P) 2500×. PEA/NaOCl/HEDP: (Q) 1000× and (R) 2500×. PEDS/NaOCl/HEDP: (S) 1000× and (T) 2500×. Arrows indicate evident lateral branches. Asterisk indicates interfacial gap. a = adhesive system; cr = composite resin; d = dentin; rt. = resin tags.

identified, as all similarly and significantly reduced adhesion compared to the control ($p < 0.001$). Despite the substantial differences in dentin structure, composition, and smear layer patterns produced by these clinically relevant irrigation protocols –as demonstrated in Part I of this publication series [20], they all resulted in a comparable reduction in bond strength. In contrast, bond strength values were significantly higher and uniform across all PEDS groups, including the control ($p > 0.05$), ranging from 57.4 to 59.5 MPa. Regardless of the endodontic irrigation sequence, the use of endodontic irrigants prior to bonding (PEA) left the dentin substrate less receptive to adhesion. However, the PEDS technique effectively mitigated this effect, maintaining high and consistent bond strength across all conditions.

Previous studies reported that NaOCl, whether combined or not with chelating agents, adversely affects the microtensile bond strength of CSE to dentin [17, 22, 33]. In agreement with our results, Santos et al. [22] and Farina et al. [33] demonstrated that irrigation with EDTA failed to restore the bond strength of NaOCl-treated dentin. It has also been hypothesized that chelators could enhance bond strength by facilitating greater penetration of the bonding agent into the dentinal tubules [33]. However, previous research has shown that superior bond strength is achieved with calcified dentin rather than decalcified dentin, emphasizing the critical role of calcium in dentin adhesion [61]. The SEM images of the adhesive interfaces in PEA groups corroborate our preceding study, which showed dentinal surfaces with opened/partially opened dentinal tubules only in the EDTA and HEDP-treated groups, thus explaining the higher number of resin tags observed in these groups [20]. Despite the SEM images of PEA groups showing a clearly greater bonding system penetration with more and longer resin tags in the chelator-treated groups, this did not translate into improved bond strength. Thus, the use of chelators proved ineffective in improving bond strength.

Consistent with our findings, Arslan et al. [40] reported no significant differences in bond strength between 2.5% NaOCl and 2.5% NaOCl-17% EDTA treatments. However, contrary to our results, HEDP-treated dentin rendered significantly lower resin-dentin bond strength compared to both NaOCl and NaOCl-EDTA groups [40]. The authors attributed this reduction in all HEDP-treated groups to concurrent collagen degradation/demineralization, irrigation remnants on dentin tubules, and HEDP precipitates, which collectively may prevent adequate bonding agent diffusion, polymerization, and hybrid layer formation [40]. Additionally, according to Carvalho et al. [56], the bonding performance of CSE was not influenced by any endodontic irrigation protocol (5% NaOCl-17% EDTA or 2% CHX gel-17% EDTA). We hypothesize the discrepancies between the results of the present study and those of Arslan et al. [40] and Carvalho et al. [56] may stem from differences in testing methodologies (microtensile versus microshear).

Par et al. [5] also investigated the effects of various endodontic irrigation regimens involving NaOCl, EDTA, Dual Rinse HEDP, and saline solution on the microtensile bond strength of CSE (self-etch) and Optibond FL (etch-and-rinse) adhesives. The highest bond strength was achieved using the NaOCl-EDTA-NaOCl protocol in combination with CSE, with no significant differences among the remaining study groups when this self-etch adhesive system was employed. In the present study, we opted not to test the alternate exposure of NaOCl and EDTA, as it leads to erosion enhancement and should, therefore, be reconsidered [3]. In contrast to our findings, Par et al. [5] reported similar bond strength across all control, NaOCl, NaOCl/EDTA, and NaOCl/HEDP groups. This discrepancy may be attributed to differences in study design, such as our evaluation of long-term microtensile bond strength versus their focus on immediate results. Additionally, their protocol did not include the renewal of NaOCl or the NaOCl/HEDP mixture [5]. Finally, our study tested deep dentin to simulate clinical endodontic scenarios, whereas their investigation evaluated superficial dentin [5].

Other studies have assessed the impact of NaOCl irrigation and the NaOCl-EDTA sequence on the bond strength to coronal dentin. However, differences in adhesive systems preclude direct comparison of results [29, 31, 58, 59].

The use of CHX as an endodontic irrigant has gained prominence over time [22]. To our knowledge, no studies evaluated the effect of the NaOCl-EDTA-CHX sequence on bond strength to coronal dentin, preventing direct comparisons with the literature. In the present study, final irrigation with 2% CHX did not significantly increase long-term bond strength (36.9 ± 13.3 MPa for PEA/NaOCl/EDTA and 37.4 ± 14.3 MPa for PEA/NaOCl/EDTA/CHX). Nevertheless, from an endodontic perspective, CHX may be beneficial for a final disinfection boost. From a restorative standpoint, its matrix metalloproteinases (MMPs) inhibitory effect could potentially be advantageous, though this effect diminishes over time and is not consistently supported by long-term clinical studies [2, 4, 9, 16].

SEM images corroborate the bond strength findings, revealing areas of discontinuity along the adhesive interface in the PEA/NaOCl, PEA/NaOCl/EDTA, PEA/NaOCl/EDTA/CHX, and PEA/HEDP groups. These interfacial gaps may account for the lower bond strength results (or conversely, the reduced bond strength may contribute to the formation of these gaps) as they were exclusively observed in these experimental groups. Although such gaps could potentially result from SEM specimen processing, observations in this study confirmed that they only occurred in the presence of an impaired hybrid layer [17]. Similar findings were reported by De Rose et al. [50], who demonstrated interfacial gaps in bonded interfaces during comparisons of immediate and delayed endodontic sealing approaches. In their study, irrigation was performed using 3% NaOCl, followed by 17% EDTA and 3% NaOCl, before or after dentin sealing [50]. Consistent with our results, the immediate endodontic sealing approach led to significantly better internal adaptation than the conventional delayed endodontic sealing [50]. A different study also reported a continuous resin–dentin interface when immediate pre-endodontic dentin sealing was performed, in contrast to the interrupted interface observed in study groups subjected to late dentin hybridization [51]. In accordance with our findings, Carvalho et al. [51] further demonstrated that early dentin hybridization before exposure to endodontic chemical substances significantly improves microtensile bond strength. Nevertheless, certain methodological limitations of this study must be acknowledged: a small sample size ($n = 5$), with no prior sample size calculation; the questionable clinical relevance of the tested irrigation protocol (reduced NaOCl exposure time); and the exclusive evaluation of immediate bond strengths (24 h), which may restrict its clinical extrapolation [51].

The evidence that the irrigation solutions used in endodontic procedures are the cause of decreased adhesion forces is further supported by the fact that the PEA/Control group demonstrated bond strength comparable to all PEDS groups and was statistically superior to all other PEA groups involving NaOCl, whether alone, in combination with chelating agents, or with CHX as a final irrigant. This is most likely because distilled water, a neutral and inert solution, does not alter the dentin substrate during the PEA protocol, thereby resembling adhesion to freshly cut dentin, as in the PEDS protocol.

Interestingly, the PEDS and PEA/Control groups consistently exhibited substantially lower standard deviations relative to their mean bond strengths compared to the PEA groups. In the PEA/NaOCl, PEA/NaOCl/EDTA, PEA/NaOCl/EDTA/CHX, and PEA/NaOCl/HEDP groups, the standard deviation represented 43.6%, 36.0%, 38.2%, and 43.8% of the mean value, respectively. In contrast, in the PEA/Control, PEDS/Control, PEDS/NaOCl, PEDS/NaOCl/EDTA, PEDS/NaOCl/EDTA/CHX, and PEDS/NaOCl/HEDP groups, the standard deviation represented 24.6%, 24.4%, 27.5%, 27.6%, 22.5%, and 23.6% of the mean value, respectively. These findings reflect greater predictability in bond strength outcomes when bonding to freshly exposed dentin or dentin irrigated with distilled water, compared to the greater unpredictability observed when bonding to dentin previously treated with endodontic irrigants. This trend is further supported by the uniform hybrid layer patterns observed in SEM images of PEDS groups, underscoring the homogeneity and predictability of adhesion to non-treated dentin and highlighting the efficacy of PEDS in preserving dentin integrity. Similarly, adhesive interfaces in the PEA/Control group, where bonding was performed on dentin without prior exposure to endodontic irrigants, displayed comparable integrity, further underscoring the negative impact of irrigation solutions on dentin adhesion.

The fracture pattern analysis closely aligned with the bond strength results, as a higher incidence of adhesive fractures was observed in the groups with significantly lower mean bond strength values (PEA/NaOCl, PEA/NaOCl/EDTA, PEA/NaOCl/EDTA/CHX, and PEA/NaOCl/HEDP). In contrast, cohesive fractures within the composite resin and within dentin were more frequently observed in the PEDS and PEA/Control groups. The predominance of cohesive fractures in these groups reflects stronger adhesion forces, suggesting that the resin-dentin bonds exceeded the cohesive strength of both the dentin and the composite resin. Our findings regarding failure mode are corroborated by previous research [23, 25, 30, 32].

4.1 | Limitations and Future Perspectives

The American Association of Endodontists (AAE) defines endodontic treatment as procedures involving the pulp and periradicular tissues, distinguishing them from restorative procedures such as coronal dentin sealing. However, this perspective has evolved over the years, as restorative procedures play a crucial role in ensuring endodontic treatment success [11–15]. In the present study, we extend this concept by demonstrating that not only is proper coronal restoration essential for endodontic success, but that the endodontic treatment itself—particularly irrigation protocols and the interaction of irrigants with the restorative substrate (coronal dentin)—significantly influences bonding quality and, potentially, the overall prognosis of the combined restoration and endodontic treatment.

This in vitro study aimed to simulate the clinical scenario of a single-session root canal treatment. Considering that the effects of endodontic irrigants on dentin are influenced by both their concentration and exposure duration, we hypothesize that PEDS may play an even more crucial role in preserving bond strength for cases requiring multiple treatment sessions [3]. Furthermore, in multi-session treatments, the interaction of provisional materials and intracanal medication (if used) with the dentinal surface can also negatively impact adhesion, further emphasizing the benefits of PEDS [14, 42, 44, 46]. In clinical practice, regardless of whether a single-session or multi-session root canal treatment is performed, the use of endodontic sealers is inevitable. These sealers interact with coronal dentin and may impair adhesion quality [14, 45]. Moreover, various methods of NaOCl activation are routinely employed, which can enhance the irrigant's effect on bonding. PEDS effectively mitigates these adverse effects by bonding to freshly cut, uncontaminated dentin, thereby adhering to the *primum non nocere* maxim. In addition, combining PEDS with a pre-endodontic adhesive restoration may offer structural advantages by preventing early fatigue and reinforcing weakened cusps between endodontic sessions and until the final restoration. These benefits underscore the broader clinical implications of PEDS as a strategy not only for optimizing dentin bond strength but also for enhancing the overall structural resilience of endodontically treated teeth.

Similar to previous research [5, 17, 18, 22–24, 29–33, 40, 48, 56, 58, 59], our study design intentionally controlled variables to specifically assess the effect of endodontic irrigants on bond strength. Introducing additional factors, such as sealer remnants or provisional materials, would have made it difficult to pinpoint the precise impact of irrigation on adhesion. However, future research should gradually expand the experimental model to incorporate these clinical variables, ultimately including fully endodontically treated teeth. Additionally, while the present study employed static immersion of dentin in irrigating solutions, future studies should aim to replicate the dynamic flow of irrigants as it occurs in vivo to better reflect clinical conditions. These refinements are necessary to further validate the clinical relevance of PEDS and provide a more comprehensive understanding of its long-term benefits. Importantly, the findings of this study should not be generalized to intra-radicular adhesion, as the present investigation focused exclusively on coronal dentin, the primary substrate for adhesive restorations in endodontically treated teeth.

Future research should also explore alternative approaches to PEDS that aim to optimize adhesion to irrigated dentin, particularly treatments with the potential to remove the affected superficial dentin, such as airborne-particle abrasion with aluminum oxide and other surface modification strategies. While the literature suggests that airborne-particle abrasion does not necessarily improve the bond strength of dentin previously exposed to endodontic irrigants, methodological variability across studies warrants further investigation to clarify its actual impact [51, 62]. Additionally, other strategies, such as acid etching or alternative abrasive treatments, may be promising and should be evaluated in future studies.

As noted, previous studies have shown that varying adhesive strategies and bonding agents can produce different adhesion outcomes following endodontic irrigation. Par et al. [5] reported that the use of phosphoric acid may neutralize the effects of irrigation solutions. Thus, further research should focus on evaluating alternative adhesive systems, particularly Optibond FL, which is regarded as the gold standard among etch-and-rinse adhesives for dentin bonding.

In the present study, only immediate restoration was evaluated for the PEA groups. Although Spicciarelli et al. [57] suggested that delaying the adhesive procedure could mitigate the negative influence of NaOCl, the advantages of immediate restoration remain well established. Immediate restoration effectively prevents coronal leakage during the provisional phase and promotes structural reinforcement [52, 63]. Furthermore, while the use of antioxidants has been proposed to restore bond strength to NaOCl-treated dentin and enable immediate restoration, this approach has notable limitations: it is time-consuming (requiring 5 to 10 min), does not fully address collagen matrix degradation, and may cause tooth discoloration, posing significant drawbacks [30, 52, 64–66]. Therefore, although delayed restoration should be explored in future studies to evaluate its potential for improving bond strength, immediate restoration remains the preferable clinical approach due to its practicality and established benefits.

The importance of aging in studies evaluating bond strength is undeniable, as previous studies have emphasized that immediate dentin bond strength values do not always correlate with long-term bond stability [60]. Although the present study assessed long-term bond strength after aging microspecimens in water at 37°C [54], incorporating an aging method that includes dynamic thermomechanical loading in a subsequent study would be invaluable to better simulate the oral cavity aging process.

In future stages, clinical data evaluating the long-term survival of root-filled teeth restored using the PEDS technique is essential.

4.2 | Final Remarks

The results of this study demonstrate that performing adhesive procedures after endodontic irrigation (PEA) significantly impairs the microtensile bond strength, while PEDS achieves bond strength comparable to the control. Significantly higher mean bond strength values were observed across all PEDS groups, regardless of the chosen endodontic irrigation protocol. This finding suggests that the PEDS approach enables clinicians to tailor the irrigation sequence according to the specific clinical scenario without compromising adhesive performance. By ensuring that bond strength outcomes remain independent of the irrigation protocol, the PEDS technique offers greater predictability and the potential to improve the overall prognosis. These insights are pivotal for clinical practice, as they support the preservation of tooth structure and function, facilitate the effective management of endodontic infections, and enhance long-term adhesion to coronal dentin. Thus, building on the findings of the present study, the integration of PEDS into the routine endodontic-restorative workflow of root canal treated teeth is recommended.

5 | Conclusion

Within the limitations of this in vitro study, the following conclusions were drawn:

1. The PEDS approach yielded significantly higher long-term microtensile bond strength to coronal dentin compared to the PEA approach across all tested endodontic irrigation protocols.
2. Endodontic irrigation protocols involving NaOCl, with or without chelating agents or chlorhexidine, significantly reduced bond strength in the PEA groups compared to the control group. No differences in bond strength were observed among the PEA groups treated with endodontic irrigants.
3. Within the PEDS approach, all irrigation protocols resulted in similar bond strength values, indicating that this strategy mitigates the impact of endodontic irrigation on adhesion.

These findings highlight the potential of the PEDS technique to improve adhesive performance and enhance the predictability of outcomes, regardless of the endodontic irrigation protocol employed.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.