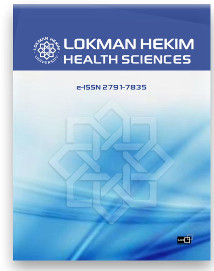
LOKMAN HEKIM HEALTH SCIENCES

DOI: 10.14744/lhhs.2026.93149
Lokman Hekim Health Sci 2026;6(3):545–553



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REVIEW

Dental Fiber Post Systems: A Literature Review

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Abstract

Endodontically treated teeth (ETT) with significant tissue loss commonly require intraradicular post systems to support the coronal restoration and restore function and esthetics. These posts, which are placed within the root canal, have been manufactured from various materials and in different designs throughout history. Today, fiber posts are favored because of their physical properties similar to dentin, esthetic advantages, ease of use, and compatibility with adhesive techniques. This review aims to evaluate the general characteristics of currently used fiber post systems for the restoration of ETT, examine clinically observed failures and their causes, and discuss application principles alongside recent clinical studies.

Keywords: Glass fiber post; Post core systems; Survival

The long-term survival of endodontically treated teeth (ETT) largely depends on the success of the coronal restoration, which prevents microbial leakage and restores function and esthetics by replacing lost tooth structure.[1,2] In cases where coronal walls are absent, intraradicular posts are required to retain the coronal restoration.[3]

Metal post systems were widely utilized; however, due to disadvantages such as susceptibility to corrosion and high elastic modulus, the clinical use of metal posts has declined.[4,5] To overcome these limitations, fiber-reinforced posts have been widely adopted in dentistry.[6] These posts demonstrate a modulus of elasticity comparable to that of dentin, which enables more uniform distribution of occlusal forces along the root structure and reduces the risk of catastrophic root fracture.[7] The most common failure mode of metal posts is root fracture, whereas that of fiber posts is loss of retention. Factors such as limited isolation control, accumulation of secondary dentin or cement, and the passive fit of fiber posts reduce their ability to bond effectively to the root dentin.[8]

Unlike previous reviews focused on traditional fiber or metal post systems, this paper integrates recent literature published between 2017 and 2025. It highlights emerging technologies such as computer-aided design/computer-aided manufacturing (CAD/CAM) and 3D-printed post systems. It also synthesizes clinical determinants, mechanical properties, and failure mechanisms to establish a modern and clinically oriented framework for post selection and performance evaluation.

This review aims to provide a comprehensive and up-to-date overview of dental fiber post systems, focusing on mechanical properties, clinical indications, failure patterns, and advances such as CAD/CAM-fabricated and 3D-printed posts. A comprehensive literature search was conducted to ensure an evidence-based narrative.

Cite this article as: *Kuşçu Baran E. Dental Fiber Post Systems: A Literature Review. Lokman Hekim Health Sci 2026;6(3):545–553.*

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Submitted: 20.05.2025 **Revised:** 02.01.2026 **Accepted:** 03.01.2026 **Available Online:** 06.08.2026

Review Methodology

A comprehensive literature search was conducted in PubMed, Scopus, and Web of Science databases for articles published between 2017 and 2024. The following keywords were used: "fiber post," "dental post system," "glass fiber post," "CAD/CAM post," "3D printed post," "mechanical properties," "failure modes," and "clinical performance."

Inclusion Criteria

- Peer-reviewed articles published in English between 2017 and 2024
- Studies evaluating mechanical properties, clinical behavior, or survival outcomes of fiber, metal, CAD/CAM, or 3D-printed post systems.

Exclusion Criteria

- Non-English publications
- Abstracts without full text
- Case reports, conference proceedings, and letters to the editor
- Studies unrelated to post-endodontic or indirect restorations.

Titles and abstracts were screened for relevance, and full texts of those meeting the inclusion criteria were evaluated. In addition, reference lists of included articles were reviewed to identify further relevant studies.

As this was a narrative review, no quantitative synthesis or meta-analysis was performed; instead, selected studies were qualitatively analyzed and organized into key thematic areas, including material composition, mechanical performance, and clinical applications.

History of Dental Fiber Posts

The history of dental fiber posts dates back to 1989 with the clinical introduction of the first carbon fiber post, the Composi Post (RTD, Meylan, France). The first published article on fiber posts was written by Duret et al.[9] in 1990. The early incorporation of fiber posts into clinical dentistry provided an alternative to the metal post systems used at that time.[5] The initial fiber post systems were fabricated from carbon or graphite fibers. They exhibited favorable mechanical properties, including high stiffness and tensile strength, as well as an elastic modulus comparable to that of dentin.[9,10] However, first-generation carbon fiber posts had esthetic disadvantages due to their dark coloration and lack of radiopacity, making them difficult to mask under all-ceramic or composite restorations.[9] To overcome this limitation, radiopaque quartz and glass fiber posts (GFPs) were developed, offering more esthetic and clinically acceptable alternatives.

GFPs

The limitations of earlier post systems led to the development of glass fiber–reinforced post systems, first introduced in 1992. GFPs are composed of unidirectional glass fibers embedded in a resin matrix and are available in white, translucent, and opaque shades, offering superior esthetic outcomes. The resin-based composition of GFPs provides strong adhesion to resin cements.[11] With a low modulus of elasticity and biomechanical behavior similar to that of dentin, these posts closely mimic the natural flexural properties of tooth structure. Translucent variants enable light transmission, further enhancing their esthetic potential.[12] The dentin-like bending capacity allows for harmonious flexing under functional forces, thereby facilitating effective stress distribution over a broader surface area.[12] In addition to high bonding capacity with tooth structures, composite resins, and resin cements, GFPs demonstrate excellent biocompatibility and corrosion resistance. Post length can be adjusted during clinical application, and removal from the canal can be performed using a rotary bur. However, the most significant drawback of GFPs is the reduced stability when exposed to moisture.[13]

Clinical Determinants of Fiber Post Outcomes

The success and longevity of fiber post restorations depend on several key clinical factors:[14]

- Remaining tooth structure and the presence of a ferrule,
- Tooth type and location (anterior/posterior; maxillary/mandibular),
- Anatomical variability of the root canal system,
- Type of luting cement,
- Type of final restoration (direct or indirect),
- Presence of proximal contacts.

Tooth type, location, and remaining tooth structure (i.e., the number of residual coronal walls) are key determinants of tooth longevity. Survival rates of ETT are higher in molars compared to pre-molars and anterior teeth, and teeth with one or fewer remaining coronal walls show increased failure rates.[15]

Final restoration type also influences the long-term success of ETT. Direct restorations designed to protect occlusal cusps have been shown to improve survival rates. In addition, sufficient remaining tooth structure and the presence of a ferrule have a greater impact on durability than the post type.[16] Moreover, self-adhesive resin cements have demonstrated superior bond strength to conventional cements.[17]

Studies have shown that horizontal occlusal loads increase stress concentration and that teeth without proximal contacts have a threefold higher failure rate. The presence of adjacent contacts helps distribute stress among teeth, thereby reducing stress concentration on a single tooth.[18]

Types of Failure in Dental Fiber Post Systems

Post Retention Loss

Retention refers to the ability of a dental post to resist vertical displacing forces and represents the most frequently observed failure mode in post-restored teeth.[19] Retention is influenced by multiple factors, including post diameter, taper, length, luting cement type, and whether the post design is active or passive. Increasing post length generally enhances retention, whereas parallel-sided posts provide superior retention to tapered designs. Active post designs demonstrate greater retention than passive posts due to their threaded or mechanically interlocking features.[19] Post diameter has a relatively smaller impact on overall retention compared to other design and cementation factors.[20] Although increasing diameter may slightly improve retention, excessive dentin removal compromises the structural integrity of the root; therefore, increasing post diameter solely to improve retention is not recommended.[20]

Marginal leakage between tooth structure and restoration contributes to post retention loss. Advancements in adhesive systems and posts with dentin-like elasticity have improved overall retention; however, cement systems are effective only when used with well-designed posts and cannot compensate for the deficiencies in poorly designed ones.[21] Combining adhesive techniques is essential to maximize retention and preserve tooth structure.[22]

Pre-cementation cleaning of the post surface improves retention and may involve ethanol rinsing, air abrasion, or phosphoric acid application. Applying cement simultaneously to both the post surface and root canal enhances retention more effectively than applying it to either alone.[23]

Deformation of the Post

Post deformations primarily depend on the material properties and diameter. Posts with smaller diameters are prone to deformation under masticatory forces. The post diameter should provide adequate resistance against deformation while minimizing unnecessary removal of remaining dental tissue.[24] Pre-fabricated posts fracture more frequently than cast posts, although these failures are generally restorable.[25,26]

Root Fractures

Root fractures represent irreversible failures that often necessitate tooth extraction.[27] They occur most frequently in the maxillary anterior region, due to horizontal functional loads, making the presence of a ferrule particularly critical in this area.[28]

Excessive removal of tooth structure during post space preparation weakens the tooth and increases fracture risk. The high modulus of elasticity of metal posts prevents uniform stress distribution within the root, whereas the widespread use of fiber posts whose modulus of elasticity is similar to that of dentin has been associated with a reduced incidence of fractures. Reported root fracture frequencies in teeth restored with posts range from 0% to 10%,[18] with approximately 7% in tapered posts, 3% apically tapered posts, and 1% in parallel posts.[4]

Root Perforation

Placement of posts with dimensions that do not correspond to the root canal anatomy may result in root perforation. This complication most frequently occurs during post space preparation but may also arise during endodontic treatment or when post removal becomes necessary. This type of failure may not be apparent during post placement. Therefore, radiographic control must be performed, and the anatomy of the root should be well understood.[4] The use of parallel-sided posts may further increase the risk of perforation during root preparation.

Failure in Root Canal Treatment

Apical periodontitis presents with radiographic changes, percussion sensitivity, or a periapical abscess.[29] Such failures result from inadequate asepsis or bacterial contamination, often due to prolonged temporary restorations or microleakage.[22,30] In cases of reinfection, post removal and retreatment are indicated, whereas preserving at least 3 mm of apical gutta-percha to prevent apical leakage.[31]

Crown Retention Loss

If a ferrule effect is not established in a tooth restored with a post core system, crown retention depends entirely on the retention of the post. Crown loss can be caused by cement failure or caries developing in the dentin.[31] Advances in dentin bonding have enabled integrated tooth–post–crown restorations, which tend to fail in a more reparable manner.[31]

Secondary Caries

Secondary caries may develop due to inadequate oral hygiene or errors in the post core system. Stress generated at the post–crown interface, particularly with flexible posts, can cause microleakage and subsequent caries formation. Such lesions may remain clinically undetected, especially in bridge abutments where prosthetic support delays diagnosis.[22]

Allergy

Allergic reactions are primarily associated with posts made from base metal alloys. Such reactions have been reported with modern post systems due to their biocompatibility.[32]

Corrosion

Corrosion weakens the post–canal interface and may cause root and gingival discoloration; this issue, common with base metal alloys, has largely been eliminated with modern GFPs.

Esthetic Problems

Metal or carbon fiber posts placed under all-ceramic crowns can cause cervical discoloration and compromise esthetics, an issue largely resolved with the development of GFPs.[24]

Sarkis-Onofre et al.[30] classified post-related failures as absolute or relative. Absolute failures were defined as those requiring tooth extraction, whereas relative failures included cases of post decementation that could be managed by re-cementation or repair. Accordingly, success refers to the absence of both absolute and relative failures, whereas survival denotes the absence of absolute failures only.

Resin-Based Luting Cements

The adhesive system used for bonding fiber posts to dentin is critical for post retention and long-term clinical success. Total-etch systems provide strong micromechanical bonding and the highest retention; however, their effectiveness depends on acid concentration, application time, and proper rinsing and drying procedures, making them technique-sensitive and prone to operator errors.[11] Self-etch systems combine the etching and priming steps into a single application, simplifying the procedure, reducing technique sensitivity, and yielding retention values comparable to those of total-etch systems.[21] Clinically, self-etch adhesives demonstrate more consistent results in the root canal environment, especially in deep regions where rinsing and drying control are difficult, thereby reducing post-operative sensitivity and improving marginal adaptation.[21,29]

Self-adhesive resin cements eliminate the need for tooth surface pre-treatment, offering ease of use but demonstrating weaker chemical bonding to dentin and lower retention values. Although self-adhesive systems reduce chair time and the risk of contamination during cementation, *in vivo* and *ex vivo* studies report higher rates of post debonding and marginal leakage compared with total-etch and self-etch protocols.[21,24]

Recent clinical evidence suggests that dual-cure and self-adhesive cements perform adequately for fiber post retention in the short term, but long-term performance may be compromised by hydrolytic degradation and incomplete polymerization in deeper canal areas.[29,33] Therefore, adhesive selection should be based on post design, canal anatomy, and isolation control.

Retention values also vary by dentin regions, with higher retention generally observed apically than coronally, underscoring the influence of adhesive choice and clinical protocol on cementation outcomes.[33]

What Should Be Considered in Post Applications?

Indication for post placement requires an assessment of the amount of remaining dentin and the overall clinical situation.[29] Before post placement, the quality of endodontic treatment should be thoroughly evaluated. Periapical or lateral lesions must be examined radiographically, and retreatment of the root canal should be performed before post placement.[29]

During post space preparation, preservation of coronal and radicular dentin is essential.[32] Sound cervical dentin is critical for maintaining tooth structure and achieving a ferrule effect, thereby optimizing biomechanical performance.[32] The ferrule effect – derived from the Latin words ferrum (iron) and viriola (bracelet) — was first introduced by Rosen in 1961 and refers to the crown's ability to encircle the underlying tooth structure in a ring-like manner.[34]

The ferrule consists of a tooth structure extending coronally from the preparation margin and functions to distribute occlusal stresses, counteract wedging forces generated by posts, and reduce lateral functional loads.[34] Although the ideal ferrule height remains debated, most authors recommend a continuous circumferential ferrule of 1–2 mm. Increasing ferrule height beyond 2 mm does not appear to improve fracture resistance further.[3,34] When an adequate ferrule cannot be obtained, orthodontic or surgical extrusion or gingivectomy may be considered.

The diameter and length of a post influence both its retention and longevity. Optimal post length is as long as possible without compromising the apical seal or risking the integrity of the remaining root structure.[4] Excessive post space preparation increases the risk of root perforation and reduces apical gutta-percha, potentially leading to periapical pathology, whereas insufficient post length results in inadequate retention.[4,35]

The following criteria should be considered when determining post length:[35]

- The post length should be equal to the length of the clinical crown
- The post length should be between one-half and two-thirds of the root length
- The post should extend to at least one-half of the portion of the root surrounded by bone.

Root length and morphology are the primary determinants of post length, followed by the quality of the apical seal.[35] Periapical lesions are more frequent when apical gutta-percha is <3 mm. Optimal post length maximizes retention without compromising apical sealing or integrity of the remaining root structure, whereas excessive post preparation increases the risk of perforation and periapical pathology.[4]

Increasing post diameter raises stress within the tooth, whereas smaller diameters may compromise retention.[21] When a gap exists between the post, gutta-percha, and the root canal walls, a hermetic seal is not achieved, thereby increasing the likelihood of periapical lesion formation.[29]

Post design also affects the retention and resistance of the restoration. Parallel-sided posts provide greater retention but require more dentin removal in thinner root regions, increasing fracture risk, whereas tapered posts preserve dentin but may concentrate stress apically due to a wedging effect.[23,29]

According to surface retention mechanisms, posts are classified into two types: Active (screw-retained) and passive (cemented).[36] Active posts generated stress concentrations that may lead to root fractures.[36] Screw-retained posts are generally recommended for short roots requiring maximum retention.[37] Another post design includes threaded posts with macro-retentive features that enhance mechanical retention between the post and cement. However, these features reduce flexural strength by decreasing post diameter.

Tooth's position within the arch is a key factor in restorative planning for ETT, as it influences occlusal force direction and magnitude. Research has shown that horizontal occlusal loads increase stress concentration.[38] Furthermore, a prospective clinical study with a 39-month follow-up by Naumann et al.[39] found that restorations on canines and incisors failed 3 times more frequently than those on premolars and molars. Adjacent teeth influence failure risk in teeth restored with intraradicular posts, with Naumann et al.[39] reporting a threefold higher failure rate in the absence of proximal contacts. Proximal contacts help distribute stress among adjacent teeth, thereby reducing stress concentration on any single tooth.

Regardless of post space preparation, it is essential to avoid damaging the periodontal ligaments. Improper use of rotary instruments, including Peeso reamers, may significantly increase root surface temperature.[22] Therefore, Peeso reamers or Gates–Glidden drills should be operated at low speeds and used intermittently under copious irrigation.

For optimal outcomes in fiber post applications, rubber dam isolation is recommended during both endodontic treatment and post placement to prevent bacterial contamination. Laboratory tests have demonstrated that water contact reduces the bending strength of fiber posts.[32] Because temporary sealing of post spaces can compromise isolation, immediate post placement followed by core build-up is recommended.[22]

A systematic review and meta-analysis by Dos Reis-Prado et al. (2021)[38] demonstrated that delayed post space preparation compromises apical sealing, whereas immediate post placement is associated with reduced leakage. This study also recommends an ideal post space preparation interval between 24 h and 7 days after the completion of root canal filling, showing that preparation within this period minimizes apical leakage and preserves the sealing integrity of the filling.

Based on these findings, a simplified decision-making framework was developed to guide clinicians in selecting the most appropriate post system for different clinical scenarios. The main characteristics, clinical indications, and common failure modes of currently available post systems are summarized in Table 1. This framework is based on four key clinical criteria:

- Remaining coronal dentin (presence of a ferrule)
- Root canal anatomy (narrow, flared, or irregular canal morphology)
- Esthetic requirements and tooth position (anterior or posterior region)
- Functional load and occlusal stress.

Table 1. Comparative summary of different post systems (fiber, metal, CAD/CAM, and 3D-printed)

Post type	Composition	Elastic modulus	Clinical indications	Common failure modes
Fiber (Glass/Quartz)	Glass/quartz fibers in resin matrix	Similar to dentin (low-to-moderate)	Esthetic zones; moderate coronal loss; desire to reduce root fractures	Loss of retention/ debonding; post-dislodgement
Metal (Pre-fabricate-CAST)	Stainless steel, titanium, cast alloys	High (>>dentin)	Extensive coronal loss; posterior teeth	Root fracture; corrosion; esthetic issues
Ceramic	Zirconia or alumina-based ceramics	Very high (rigid)	High esthetic demand with ceramic crowns	Root fracture; loss of retention (adhesion challenges)
CAD/CAM (Customized)	Milled Fiber-reinforced composite blocks (customized post core)	Low-to-moderate	Flared/weakened canals; need for thin, uniform cement layer	Debonding if bonding suboptimal; marginal gap
3D-Printed	Photopolymer/resin-based reinforced composites (custom)	Closer to dentin (material-dependent)	Personalized design; complex anatomies	Surface defects; adhesion/printing accuracy limits

CAD: Computer-aided design; CAM: Computer-aided manufacturing.

Table 2. Post design types

Design type	Mechanical behavior	Advantages	Disadvantages	Clinical recommendations
Parallel-sided	More uniform stress distribution; high cemented retention	High retention	More dentin removal apical/middle third; potential perforation risk if anatomy is not respected	Prefer when root length and dentin bulk are adequate
Tapered	Mimics root anatomy but may increase apical stress concentration (wedging effect)	Conserves dentin; better for narrow/ tapered canals	Lower retention versus parallel; stress concentration apically (wedging effect)	Use in thin/narrow roots to preserve dentin; maintain optimal post length to avoid excessive apical stress
Active (screw-retained)	Threads engage dentin mechanically	High primary retention (especially in short roots)	Higher risk of root fracture due to stress concentration	Use cautiously; generally avoid in thin roots; consider only when maximum retention is needed
Passive (cemented, smooth)	Relies on adhesive cementation; lower mechanical interlock	Lower stress on the root; compatible with adhesive strategies	Lower primary retention than active designs	Preferred with fiber posts and adhesive cements; prioritize ferrule and isolation

Fiber posts are preferred in cases with an adequate ferrule and esthetic demands. Metal posts may be considered for posterior teeth with high occlusal stress and low esthetic demand. For teeth with flared or irregular root canals, customized fiber posts or CAD/CAM- or 3D-printed post systems are recommended to achieve optimal adaptation. Post placement is unnecessary when three or more sound coronal walls and a sufficient ferrule can be achieved with direct or indirect restorations. The characteristics, advantages, disadvantages, and clinical recommendations of different post designs are summarized in Table 2.

Restorations of ETT

Restoration of ETT aims to:

1. Preserve the remaining tooth structure and prevent fracture,
2. Prevent reinfection of the root canal system,
3. Replace lost tooth structure.[30]

ETT differ structurally and in restorative treatment requirements compared with vital teeth.[35] Loss of structural integrity, reduced moisture, increased brittleness, cavity preparation procedures, and dentin removal during caries excavation contribute to the higher fractures incidence in ETT.[35] Access cavities preparation weakens teeth and increases the risk of cusp fractures. The amount of remaining hard tissue is critical for tooth stability. Access cavity and root canal procedures reduce durability and rigidity by about 5%, whereas a three-surface mesio-occluso-distal preparation reduces them by about 63%.[37] Insufficient remaining tooth structure predisposes weakened cusps to fracture under normal functional loads. Such fractures may occur at the enamel-dentin junction or extend into the root.[39] Therefore, the restorative approach should ensure both esthetic appearance and structural reinforcement. Restoration of ETT is a challenging phase of dental treatment with multiple therapeutic options.[22] Post placement is primarily indicated by the amount of remaining tooth structure and functional requirements.[22]

Clinical Studies on Fiber Posts

Sarkis-Onofre et al. compared the clinical performance of GFPs and cast metal posts placed in ETT without ferrules.[30] The annual failure rate for both types of posts was reported as 1.5% after 5 years. When evaluated individually, the annual failure rate was 1.2% for cast metal posts and 1.7% for GFPs. Most failures (16/23) occurred in posterior teeth, including 10 root fractures and 5 post dislodgement.

In their first long-term randomized controlled trial (2017), Naumann et al.[39] compared GFPs systems with rigid titanium post (TP) systems in ETT with two or fewer remaining walls. After 132 months, survival rates were 58.7% for GFP and 74.2% for TPs. Failures in the GFP group included root fractures (n=4), crown fractures (n=1), secondary caries (n=1), failed endodontic treatment (n=2), and extraction due to mobility (n=1). In the TP group, failures were mainly due to failed endodontic treatment (n=5) and root fracture (n=1), and survival rates decreased markedly after 8 years in both groups.

Bruhnke et al.[40] conducted a prospective clinical study to investigate the survival of ETT restored with GFPs and TPs. The primary outcome for the 128 included patients was restoration survival. Clinical and radiographic assessments were performed at 6, 12, and 24 months, with continued follow-up to 178 months. After 178 months, cumulative survival was 57.1% for GFP I, 56.5% for GFP II, and 71.8% for TP, with no significant effect of post system on tooth survival.

Van Landuyt et al.[20] conducted a 15-year randomized controlled trial comparing GFP and metal posts in single-crowned ETT. Among 182 restorations, survival rates were 68.5% for pre-fabricated GFPs and 53.6% for metal posts, whereas success rates were 59.2% and 48.0%, respectively. Metal posts failed more frequently due to root fractures, whereas GFPs showed fewer catastrophic failures, although the difference was not statistically significant.

Linnemann et al.[25] conducted a multicenter prospective study evaluating the success and survival of post-restored ETT during a 3–15-year follow-up. A total of 195 teeth restored with posts were evaluated. The study defined success as cases where the post and initially placed final restoration remained intact during follow-up, including restoration replacement or re-cementation, post or crown dislodgement, root fracture, or post fracture. If the post was still functioning at the final follow-up without any clinical or radiographic signs of technical failure, even after re-cementation of the post or crown, the restoration was considered to have survived. Conversely, post replacement or tooth extraction was considered a survival failure. The annual failure rates were 6.0% for success and 3.3% for survival.

Cloet et al.[2] conducted a prospective study comparing 5-year outcomes of 203 ETT restored with GFPs and cast posts. The mean follow-up period was 5.8 years, and failures were classified as absolute or relative. Irreparable fractures requiring tooth extraction were classified as absolute failures. Failures manageable by re-cementing of the post and crown were classified as relative failures. Success required the absence of both absolute and relative failures, whereas survival required the absence of absolute failure. After 5 years, success and survival probabilities were 85.2% and 91.5%, respectively, with no significant difference between groups.

New Approaches: Customized Fiber Post Systems

In flared root canals, where extensive tissue loss makes post adaptation difficult, pre-fabricated GFPs often fail to conform to the canal shape and size, requiring a thicker cement layer for luting.[27] A thick cement layer is associated with inadequate polymerization, reduced mechanical strength, and void formation.[28] To overcome these limitations, CAD/CAM and 3D printing technologies enable the fabrication of anatomically customized, monolithic GFPs that allow placement with a thin, uniform cement layer.[28] These approaches improve adaptation and mechanical performance, reducing fracture risk, particularly in flared or weakened root canals.[29] 3D printing offers design flexibility and rapid production, enabling highly individualized solutions.[27] These digital techniques provide precise adaptation and potentially enhanced long-term outcomes; however, further clinical validation is required.

Conclusion

Fiber posts are essential for restoring teeth with extensive coronal damage and should be placed based on thorough clinical and radiographic evaluation of the remaining dentin. This review outlines current principles of fiber post application and common cases of failure. Future research should establish standardized clinical protocols for CAD/CAM and 3D-printed customized post systems to ensure predictable outcomes. Long-term prospective randomized clinical studies are needed to evaluate their survival rates, mechanical performance, and failure patterns under functional conditions. The development of novel biomaterials with enhanced bonding potential, biomechanical compatibility, and resistance to hydrolytic degradation should be encouraged. Integrating digital design tools, AI–assisted analysis, and patient-specific risk assessment may further reduce failures and enhance treatment durability.

Ethics Committee Approval: Ethical approval was not required for this study since this is a review article.

Conflict of Interest: None declared.

Financial Disclosure: The author declared that this study has received no financial support.

Use of AI for Writing Assistance: Not declared.

Peer-review: Double blind peer-reviewed.

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