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Self-Adhesive Flowable Resin Composites—Are We Going Somewhere?

António H. S. Delgado[1,2] | Miguel Alves[1] | Inês Pires[1] | Marta Nunes Ferreira[1] | Carlos Enrique Cuevas-Suárez[3]

[1]Egas Moniz Center for Interdisciplinary Research (CiiEM), Almada, Portugal | [2]Division of Biomaterials and Tissue Engineering, UCL Eastman Dental Institute, London, UK | [3]Dental Materials Laboratory, Academic Area of Dentistry, Autonomous University of Hidalgo State, San Agustín Tlaxiaca, Hidalgo, Mexico

Correspondence: António H. S. Delgado (asalesdelgado@egasmoniz.edu.pt)

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ABSTRACT

Objective: To map laboratory/clinical evidence on self-adhesive flowable resin composites (SAFRCs), tracing their chemical evolution, performance, and behavior, and to identify gaps that must be addressed to drive their optimization.

Overview: A comprehensive literature search was performed in PubMed/MEDLINE, Scopus, and LILACS without language restrictions. To date, 11 commercial SAFRCs are available. These contain 5wt%–10wt% hydrophilic monomers and ≤55vol% fillers, as a flowable option, although susceptible to water sorption and color changes. Functional monomer trends shift from 4-META/GPDM to 10-MDP or phosphate-amide hybrids; meta-analytical and recent laboratory data confirm that μTBS to dentin is extremely low (rarely >10MPa). Inefficacy to bond/seal is the main reason for failure. Clinical evidence is scarce and short-term: RCTs suggest that small Class-I restorations survive comparably to controls at ≤24months, but failures are frequent. Emerging strategies such as alternative conditioning, collagen depletion, or incorporation of bio-interactive fillers may improve outcomes.

Conclusions: Current SAFRCs simplify placement and reduce technique sensitivity but are constrained by very low bond strengths, poor sealing, and high hygroscopicity. Until chemistry, paste acidity, and smear-layer interaction are co-optimized, their use should remain limited. Future research must couple novel chemical formulations and low-water-uptake matrices while validating performance in adequately powered RCTs.

1 | Introduction

Since their introduction in restorative dentistry, resin composites have undergone extensive developments and modifications to meet the evolving needs of both clinicians and patients [1]. Key advancements include several variations to the type, ratio, and mainly, size of filler particles [2, 3], which led to the filler size-based classification still used today, as described by Ferracane [4]. Further innovations introduced lower-shrinkage and hydrolysis-resistant monomers [3, 5], improved flexibility and biocompatibility [6], and updated photoinitiator systems aimed at enhancing polymerization efficiency [7]. As a result, resin composites with distinct applications and characteristics have been introduced to the market in recent years, including bulk-fill materials [8], fast-cure formulations [9, 10], composites with hybrid alkasite chemistry or claimed bioactivity [11, 12], and universal or one-shade systems [13, 14].

In this quest to further optimize restorative dental materials, a noticeable trend can be seen. The constant effort to simplify

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and streamline restorative procedures, by developing materials that are evermore simpler, quicker, and which offer versatile use [15, 16]. This shift in operative dentistry that has accompanied recent years, aims to reduce the technique sensitivity [17, 18] and operator variability [16, 19] that is characteristically inherent to resin-based restorative materials, while preserving their beneficial physico-chemical properties. As part of this trend, self-adhesive flowable resin composites (SAFRCs) reached the market over 15 years ago, in 2009 [20]. The goal of these materials was to eliminate the need for a separate adhesive, offering a more efficient and user-friendly solution without wanting to compromise performance. These resin-based materials featured the same acidic functional monomers present in self-etch/universal adhesives and self-adhesive resin cements, in the expectation that the composite itself could directly bond to enamel/dentin [21]. Given the diversity of formulations and the variability in laboratory and clinical outcomes, a focused synthesis is though needed to clarify where SAFRCs perform well, where they struggle, and what conditions influence those outcomes. Indeed, the desired expectation of these materials may not have yet been met, and such topic needs to be addressed [22–24]. These materials are currently only indicated for small class I/II retentive restorations, as bases/liners, and as pit and fissure sealants. Although meta-analyses of clinical trials indicate satisfactory short-term performance [25], robust long-term evidence is lacking, and additional low-risk-of-bias studies are required. This need is underscored by the consistently unfavorable in vitro findings [22, 26]. Laboratory investigations demonstrate low shear and tensile bond strengths to dentin [22], pronounced microleakage scores and deficient sealing [27, 28], and poor marginal, ultrastructural, and interfacial quality [26, 28]—all markedly inferior to outcomes achieved when a conventional adhesive is paired with a restorative resin composite. The theory and mechanisms behind these results should thus be addressed in an in-depth state of the art review.

Despite more than a decade and a half of investigation, the literature on SAFRCs remains highly compartmentalized and difficult to piece together. Existing systematic reviews have concentrated on singular outcomes—for instance, in vitro bond strength to enamel and dentin or the short-term clinical survival of occlusal restorations—while numerous primary studies separately address other parameters such as mechanical properties, degradation, bond strength, microleakage, marginal adaptation, or interfacial quality. To date, no evidence-based narrative that spans material chemistry, laboratory performance across physical and chemical properties, meta-analytical data, and clinical behavior has been produced. Therefore, the present paper aims to provide a comprehensive review of SAFRCs. This narrative review consolidates evidence on the chemistry, handling, adhesive performance (enamel/dentin), microleakage and interfacial quality, water sorption/solubility and aging, color stability, and mechanical behavior of SAFRCs. We highlight areas of convergent and divergent findings, identify sources of variability (e.g., smear-layer conditions, paste hydrophilicity, test methods), and outline practical indications/limitations. The goal is to provide clinicians and researchers with a clear, evidence-based map of what is currently known and where gaps remain.

2 | Methods

A comprehensive review was undertaken in PubMed/MEDLINE, Scopus, and LILACS (November 2, 2024–April 1, 2025) without language or date limits. A search strategy was defined to retrieve relevant papers concerning all commercial and/or experimental SAFRCs. The search string combined the core term "self-adhesive composite" with established lexical variants, using truncation and Boolean operators to maximize retrieval:

("self-adhesive resin composite" OR "self-adhesive composite resin" OR "self-adhering resin composite" OR "self-adhering composite resin" OR "self-bonding resin composite" OR "self-bonding composite resin" OR "self-adhesive flowable resin composite"). This review does not follow a systematic or scoping approach as it does not answer an interventive question but rather serves to map and gather all information, including laboratory, clinical, interventional, and systematic review studies concerning SAFRCs, ever since these materials were first launched in the dental market in 2009.

3 | History of SAFRCs

This brief historical context outlines key milestones that motivate current SAFRC formulations; mechanistic implications are analyzed in later sections.

A thorough history of self-adhesive composites must begin with the broader evolution of adhesive technology in restorative dentistry. Over a millennium ago, the Classic-period Maya used plant-based, low-pH cements for inlays, an early example of acid-mediated retention and antimicrobial effect exploitation [29]. By the late nineteenth century, zinc-phosphate cements were already in routine clinical use, illustrating that acid-mediated micromechanical retention predated the modern era [30]. The first intentional attempt to combine *chemical* adhesion with tooth conditioning is credited to Swiss chemist Oskar Hagger, who in 1949 introduced Sevriton Cavity Seal. This material contained glycerophosphate dimethacrylate (GPDM) —the earliest functional monomer capable of demineralizing hydroxyapatite while simultaneously forming ionic bonds to calcium [31]. Today, many other acidic monomers exist, but, to record, this was the first known functional monomer to be used in restorative dentistry [32]. This event marked the very beginning of self-adhesive technology in restorative dentistry, as shown in the timeline of Figure 1. The formulation developed by Hagger anticipated the self-etch principle by nearly four decades and provided the biochemical blueprint for contemporary adhesive dentistry. Without knowing, Hagger invented the first adhesive. Five years later, Buonocore popularized phosphoric-acid etching of enamel (1955), demonstrating that a roughened, high-surface-energy substrate dramatically improved resin retention [29]. This secured a bond between acrylate resin monomers and enamel [30], marking a breakthrough step responsible for scaling adhesive dentistry techniques.

Commercial development accelerated in 1978 when Kuraray launched CLEARFIL Bond System F, the first dentin/enamel bonding agent to combine mechanical retention with the

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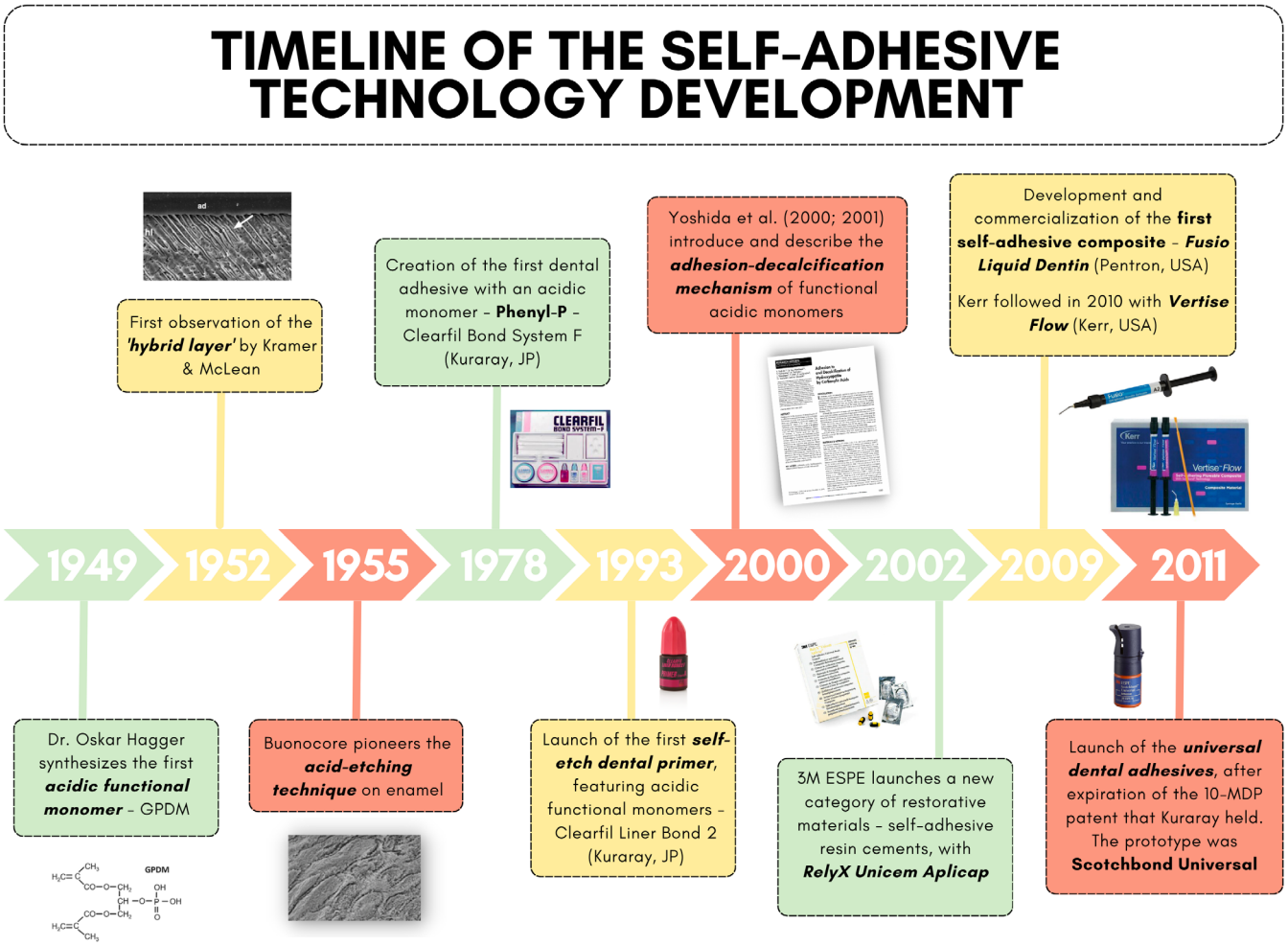

FIGURE 1 | Timeline showing the development of the self-adhesive technology, since the introduction of the first acidic functional monomer in dentistry, GPDM, until the launch of the self-adhesive composites, in 2009 and 2010, and the creation of universal adhesives in 2011.

phosphate monomer 2-methacryloxyethyl phenyl hydrogen phosphate (phenyl-P) [33]. This debut dovetailed with the "total-etch" concept proposed by Dr. Takao Fusayama, which at the time first validated simultaneous phosphoric-acid conditioning of enamel and dentin [34]. Kuraray extended the strategy in 1993 with CLEARFIL Liner Bond 2, inaugurating the self-etch adhesive category through a water-based primer containing the multifunctional monomer MDP. To rationalize the behavior of these acidic monomers, Yoshida et al. proposed the adhesion–decalcification (AD) concept in 2000 [32], positing that an acid will either form a stable ionic complex with hydroxyapatite (adhesion route) or decalcify it (decalcification route), resulting in a loss of Ca^{2+} ions to the surrounding medium [32, 35]. This depends upon the structure of the acid and its affinity for calcium. The AD concept remains a cornerstone for the design of today's universal and self-adhesive materials. The quest for ever-simpler protocols soon shifted from bonding agents to luting and restorative materials. In 2002, 3M introduced RelyX Unicem, the first self-adhesive resin cement, eliminating separate etching, priming, and bonding steps. Building directly on this philosophy, Pentron released Fusio Liquid Dentin in May 2009—the inaugural self-adhesive flowable resin composite—followed by Kerr's Vertise Flow in 2010.

4 | Rationale for SAFRCs

As explained above, SAFRCs are marketed as "one-step" restoratives because the acidic monomer that conditions enamel and dentin is built directly into the low-viscosity resin matrix. By suppressing the separate etch–prime–bond sequence, a typical adhesive step lasting 20 s active scrubbing + 15 s air thinning + 10–15 s light-cure (≈45 s) – and, in etch-and-rinse mode, an extra 15–30 s phosphoric-acid cycle (plus an additional 15–30 s of rinsing/drying) – is removed from every restoration. The replacement step for an SAFRC involves 15–20 s of active brushing, followed by 20 s of light-cure (≈35–40 s total). In other words, chairside working time is reduced by approximately one-third compared to procedures requiring phosphoric-acid etching, and by about 30%–50% even when using a self-etch adhesive.

Development of SAFRCs targets four practical issues: technique sensitivity, chair time, cost, and ease of use. Such factors are particularly crucial in specific clinical and resource-constrained scenarios. Collapsing the adhesive steps also reduces opportunities for contamination, solvent loss, and under-curing. Indeed, all of these advantages become decisive in clinical or logistical

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contexts where cooperation, time, equipment, or consumables are constrained.

In pediatric dentistry, managing young patients often requires minimizing chair time and procedural complexity due to the limited attention span of children and the likelihood of non-cooperative behavior. Thus, simplified techniques are needed [36]. Similarly, in geriatric dentistry, where patients may have physical or cognitive limitations, the ease of application and reduced procedural steps associated with self-adhesive composites are particularly beneficial. Frailty, xerostomia, or limited mouth opening makes meticulous isolation and restorative procedures difficult [37]. Simpler materials would ensure that effective restorations can be performed quickly and with minimal discomfort.

Furthermore, best-practice guidance from the American Academy of Pediatric Dentistry emphasizes minimizing clinical steps and appointment length for individuals with physical, cognitive, or behavioral impairments (patients with special health-care needs) [38]; SAFRCs intrinsically fulfill these recommendations by integrating conditioning, bonding, and the application of a restorative material in a single syringe.

In 2023, the World Health Organization (WHO) included resin-based composites in the Model List of Essential Medicines, citing their favorable cost-effectiveness and significance as mercury-free alternatives to amalgam in low- and middle-income countries. However, the WHO also acknowledges that "they require more specialized expertise and facilities for application" [39]. Single-bottle materials reduce the number of components required, such as bottles, applicators, and the time needed for dispensing and curing, thereby lowering both logistical burden and overall cost [40]. In constrained settings (e.g., mobile clinics or conflict zones), this simplicity is highly advantageous. Rotary instrumentation, multiple-step systems, or precise moisture control are impractical, and material access is severely limited [41]. Thus, single-syringe materials offer a practical solution. SAFRCs are particularly well-suited for underserved areas and contexts where economic and infrastructure barriers often restrict access to dental care.

5 | Commercial SAFRCs Available in the Market

Since their launch in 2009, SAFRCs have been making their way in the dental market, and several different options exist today, although only a few of these have laboratory and clinical data to support their use (Table 1).

The chemistry of SAFRCs has diversified over time but remains fundamentally hydrophilic. All formulations—from Fusio Liquid Dentin (2009) to SimpliShade (2024)—retain 5wt%–10 wt% of HEMA or analogous hydrophilic diluents. The compositional map also reflects the evolution of functional monomers paralleling developments in adhesive systems. Early products relied on 4-META (Fusio) or GPDM (Vertise/Dyad), whereas most formulations introduced since 2015 incorporate 10-MDP or phosphate-ester/amide hybrids (FIT SA, Fusion Flo SE, SimpliShade), in line with the superior calcium salt stability of MDP demonstrated in bonding studies.

Most SAFRCs maintain a moderate filler load (approximately 45vol%–55 vol%). In recent years, bioactive and radiopaque fillers have gained attention. Materials such as S-PRG (FIT SA) and MCPM/fluoro-aluminosilicate glasses are now included in newer formulations, indicating a shift toward ion-release and remineralizing capabilities aimed at expanding clinical indications beyond small, retentive cavities.

From Table 2A and 2B, some inferences regarding commercial SAFRCs can be drawn. Manufacturer instructions expose a consistent and deliberately conservative use profile for SAFRCs (2A). Across all brands, the recommended indications rarely extend beyond minimally invasive procedures: small, retentive Class I cavities, pit-and-fissure sealants, and use as liners or bases. Only Vertise Flow and SimpliShade Self-Adhesive Flow tentatively add small Class II restorations, while a few formulations (e.g., Beautifil Kids SA, Fusion Flo SE) accept cervical or root-surface lesions; none endorse bulk placement in large posterior cavities. Equally uniform is the prescribed handling: the material must be brushed or scrubbed as an ultrathin film—typically ≤0.5 mm—against every cavity wall for 10–20 s before light cure. This is likely intended to maximize wetting and diffusion of acidic functional monomers, with etching and chemical bonding capabilities into enamel and dentin. This is to expect a reliance on an intimate, micrometer-scale interfacial layer for adhesion. Manufacturers expressly discourage phosphoric-acid conditioning of dentin and allow only selective etching of enamel, underscoring that the self-etch chemistry must operate without external pretreatment. Taken together, these converging instructions portray current SAFRCs as niche materials whose success depends on conservative cavity design and meticulous, actively agitated placement rather than on bulk-fill capability or high occlusal durability—an implicit acknowledgement of the unresolved concerns about their long-term success.

5.1 | Laboratory Data

5.1.1 | Polymerization Kinetics

Current SAFRC formulations are flowable in nature, which impacts potential polymerization shrinkage and efficiency [42]. When compared to conventional composites, they generally have a lower filler load, making them reach lower levels of elasticity—and, consequently, a lower mechanical resistance—and greater polymerization shrinkage. Regarding the degree of conversion, SAFRCs such as Vertise Flow and Constic show acceptable to high conversion levels [43–45] in comparison to controls, while other materials achieve very low levels, such as Y Flow SA [43]. Vertise Flow required the longest light-cure interval (20 s) to reach its maximal density, whereas Herculite and OptiShade reached their respective plateaus at 10 s and 15 s. These results, found in the study of Iordache et al. [46], indicate that Vertise Flow needs the full 20 s manufacturer-recommended exposure to compensate for its delayed polymerization kinetics and that premature termination (≤15 s) may leave an under-converted, mechanically compromised surface layer.

Polymerization shrinkage has been assessed in the literature using a micro-CT technique. SAFRCs such as Vertise Flow have demonstrated greater volumetric shrinkage compared to other

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TABLE 1 | Characteristics of the SAFRCs that are currently commercially available in the dental restorative material market.

Composite and manufacturer	Launch date	Chemical composition	Functional monomer (wt%)	Lab/clinical data (Y/N)
FusioLiquid Dentin (Pentron, USA)	2009	Organic matrix (48 vol%): UDMA (N/A%) HEMA (5%–10%) TEGDMA (5%–10%) Inorganic matrix/filler phase (52 vol%): Glass fillers (N/A%) Amorphous silica (N/A%)	4-META (N/A%)	Laboratory and clinical data ✓
Dyad flow/Vertise flow (Kerr Corp, Orange, CA, USA)	2010	Organic matrix (30 wt%): BIS-GMA (N/A%) BIS-EMA (N/A%) HEMA (5%–10%) Inorganic matrix/filler phase (70 wt%): Ytteribium trifluoride (5%–10%) Glass fillers (N/A%) Amorphous silica (N/A%)	GPDM (N/A%)	Laboratory and clinical data ✓
Constic (DMG, Hamburg, Germany)	2015	Organic matrix (57 vol%): TEGDMA (< 45%) Bis-GMA (15%–35%) Inorganic matrix/filler phase (43 vol%): Barium aluminosilicate (0.02–2.3 μm)	10-MDP (N/A%)	Laboratory and clinical data ✓
Yflow SA (Yller Biomaterials, Brazil)	2018	Dimethacrylate monomers Acidic methacrylate monomers Dental glass particles	N/A	Data is unavailable
FIT SA (Shofu Dental Corporation, San Marcos, CA)	2019	Organic matrix (X%) UDMA (10%–30%) HEMA (5%–10%) Inorganic matrix/filler phase (X%): S-PRG filler based on fluoroboroaluminosilicate glass (N/A%) Glass powder (N/A%)	Phosphoric acid ester (N/A%)	Only laboratory data available
Oxford flow SE (First Scientific Dental Materials GmbH, Germany)	2020	Organic matrix (55 vol%) Dimethacrylates (N/A%) Inorganic matrix/filler phase (45 vol%): Dental glass (N/A%) Silicon dioxide (N/A%)	N/A	Data is unavailable

(Continues)

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TABLE 1 | (Continued)

Composite and manufacturer	Launch date	Chemical composition	Functional monomer (wt%)	Lab/clinical data (Y/N)
Profil Flow SE (Silmet, Or-Yehuda, Israel)	2020	Organic matrix (57 vol%) Dimethacrylates (< 45%) Bis-GMA (15%–35%) Inorganic matrix/filler phase (43 vol%): Glass fillers (N/A%) Amorphous silica (N/A%)	N/A	Data is unavailable
Beautifil kids SA (Shofu Dental Corporation, San Marcos, CA)	2021	Organic matrix (X%) UDMA (10%–30%) HEMA (5%–10%) Inorganic matrix/filler phase (X%): Silicon dioxide (10%–30%) Zirconium silicate (20%–30%) Glass powder (1%–5%) Ytterbium trifluoride (1%–10%)	Phosphoric acid ester (1%–5%)	Laboratory and clinical data ✓
FUSION FLO SE (Prevest DenPro Limited, Jammu, India)	2022	Organic matrix (30 wt%) Bis-GMA (< 20%) Bis-EMA (< 10%) TEGDMA (< 25%) HEMA (N/A%) Inorganic matrix/filler phase (70 wt%): Silanated barium glass powder (< 70%) Amorphous silica (< 5%)	10-MDP (N/A%)	Data is unavailable
NOVA COMPO SF (Imicryl, Anatolia, Turkey)	2023	Organic matrix (53 vol%) Aliphatic dimethacrylates (N/A%) Hydrophobic aliphatic dimethacrylates (N/A%) HEMA (5%–10%) Inorganic matrix/filler phase (47 vol%): Barium glass (N/A%) Fluoroaluminossilicate (N/A%) Glass powder (N/A%)	10-MDP 4-META (N/A%)	Data is unavailable

(Continues)

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TABLE 1 | (Continued)

Composite and manufacturer	Launch date	Chemical composition	Functional monomer (wt%)	Lab/clinical data (Y/N)
SimpliShade self-adhesive flow (Kerr Corp, Orange, CA, USA)	2024	Organic matrix (62 vol%): Bis-GMA (N/A%) Bis-EMA (N/A%) GDMA (N/A%) UDMA (3%–7%) HEMA (5%–10%) Inorganic matrix/filler phase (38 vol%): Ytteribium trifluoride (4%–12%) Fumed silica (0.5%–7%)	GPDM (2%–7%)	Data is unavailable

flowable control materials, exceeding 5.7 vol% [47]. Nakano et al. also reported higher volumetric shrinkage values, along with increased interfacial gap formation, when comparing Vertise Flow and Fusio Liquid Dentin to both bulk-fill and conventional flowable restoratives [48].

5.1.2 | Mechanical Properties

It is important to revise the mechanical properties of SAFRCs that have been studied in the literature. Properties such as flexural strength give an indication of the resistance of the material to bending stress and are clinically related to wear phenomena [49, 50]. In this context, Brewster and Roberts made a 12-month-long detailed investigation of flexural mechanical properties between conventional and SAFRCs. In these assays, it was noticed that SAFRCs exhibit lower values for flexural strength compared to conventional resin composites [51]. According to ISO 4049, which stipulates a minimum flexural strength of 80 MPa [52], several SAFRC materials did not meet this benchmark. The flexural strength of Constic fell beneath the ISO recommendation after 6 months of aging. Although Vertise Flow remained above 80 MPa initially, its flexural strength declined significantly at 1 and 3 months. While lower filler content can lead to diminished mechanical performance, the hydrophilic monomers in SAFRCs additionally facilitate water uptake, further compromising their mechanical properties. Incipient materials such as Beautifil Kids SA (Shofu), in very recent studies, show a reportedly higher flexural strength and elastic modulus than a universal flowable and a claimed to be bioactive bulk-fill restorative (Predicta Bioactive Bulk-Fill [Edgewood, NY, USA]) [53].

Regarding surface microhardness, it has been pointed out in some studies that SAFRCs exhibit lower microhardness values compared to other flowable composites or conventional packable composites [54–56]. Specifically, Vertise Flow demonstrated a lower hardness value than other flowable materials, with a more pronounced decrease in values after simulated brushing [57]. The same low results were verified in another report that tested microhardness in 2-mm thick samples, as a function of different light-curing times, comparing Vertise Flow to conventional flowable composites [46]. Contrastingly, other reports comparing Vertise Flow to other flowables demonstrated high reliability and good micromechanical and macromechanical properties, but for a 40 s curing time and 2-mm thickness [58].

Other properties, such as fracture toughness, which is clinically correlated to composite fracture in function, have also been the subject of research [50]. For instance, Vertise Flow showed lower values than conventional composites and some RMGICs [55], while in earlier reports, it surprisingly ranks higher than other flowable composites in elastic properties and hardness at different maximum loads [59].

5.1.3 | Water Sorption/Solubility

The chemical design of SAFRCs inevitably favors a high-water uptake. To achieve a syringeable viscosity, the filler load is

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TABLE 2A | Manufacturer-stated indications for SAFRCs.

Composite (Manufacturer)	Small class I	Small class II (retentive)	Class III	Class IV	Class V/ Cervical/ root	Liner/ base	Pit and fissure/ PRR	Other
Dyad flow/Vertise flow (Kerr)	✓	✓	—	—	—	✓	✓	—
Fusio liquid dentin (Pentron)	✓	—	—	—	—	✓	✓	—
Constic (DMG)	✓	—	—	—	—	✓	✓	*Extended fissure sealant*
Oxford flow SE (first scientific)	✓	—	—	—	—	✓	✓	—
Y-Flow SA (Yller)	✓	—	—	—	—	✓	✓	—
Profil flow SE (Silmet)	✓	—	—	—	—	✓	✓	—
Beautifil Kids SA (Shofu)	✓	—	—	—	—	—	✓	*Preventive Resin Restoration (PRR)*
Nova compo SF (Imicryl)	✓	—	✓	—	✓	✓	✓	*Undercut blocking; minor occlusal build-ups*
FIT SA (Shofu)	✓	—	✓	—	✓	✓	—	—
Fusion Flo SE (Prevest DenPro)	✓	—	✓	✓	✓	—	—	*Small posterior fillings*
SimpliShade Self-adhesive flow (Kerr)	✓	✓	—	—	—	✓	✓	*Porcelain repairs*

Note: Checkmarks denote indications explicitly listed in the instructions for use; blank cells indicate not stated/not recommended. "Small Class II (retentive)" refers to limited, retentive proximal lesions without extensive occlusal extension.
Abbreviation: PRR, preventive resin restoration.

reduced and replaced by low-molecular-weight, hydrophilic diluents such as HEMA, while the self-adhesive mechanism relies on acidic functional monomers (e.g., GPDM, 4-MET). Both sets of monomers possess polar, hydroxyl, phosphate- or carboxylate-containing groups that form strong hydrogen bonds with water, increasing the diffusion coefficient of the polymer network [60].

Wei et al. followed five composites through a 150-day water-immersion/desorption cycle and recorded the greatest hygroscopic dimensional change for Vertise Flow (4.82% at 90 days), more than twice that of conventional nano-hybrids and six times that of a silorane control; the authors further noted a post-desorption collapse of the GPDM-rich network, evidenced by dehydration shrinkage below the original dimensions [61]. Corroborating these dimensional data, Omrani et al. measured seven-day water sorption in artificial saliva and found Vertise Flow at 55.2 $\mu g\,mm^{-3}$, exceeding the ISO 4049 limit of 40 $\mu g\,mm^{-3}$, while Grandio Flow and Tetric-N Flow remained at 11–19 $\mu g\,mm^{-3}$; the difference was attributed to the hydrophilic GPDM/HEMA matrix and lower filler content of the self-adhesive formulation [62]. A hydrolytic degradation study by de Brito et al. extended the challenge to three solutions (distilled water, artificial saliva, lactic acid). Vertise Flow and Fusio Liquid Dentin again showed the highest sorption across all media and reached 22.2 $\mu g\,mm^{-3}$ solubility in distilled water, whereas bulk-fill and micro-hybrid controls stayed below 9 $\mu g\,mm^{-3}$ [63].

These studies show that SAFRCs absorb more water, expand hygroscopically, and leach more mass than conventional flowables. These effects are exacerbated by lower filler content and weakly bonded pre-polymerized fillers, which create additional diffusion pathways.

5.1.4 | Color Stability and Degradation

SAFRCs exhibit a color-stability profile that diverges from that of conventional, non-flowable composites. Because of the higher water sorption (see *Water sorption/solubility*), staining and ΔE shifts may be greater in some SAFRCs. Experimental SAFRC prototypes have shown significantly greater overall color change (ΔE) than control materials prepared with a separate adhesive layer [64]. Comparable findings have been reported for Vertise Flow, which displayed two- to three-fold higher ΔE values than a microhybrid composite after 7 days of coffee immersion [65]. Even so, Guler and Unel recorded a ΔE of 3.10 for Vertise Flow—below the widely accepted perceptibility threshold of 3.3 and on par with conventional flowables—after standardized aging procedures [66]. Accelerated shelf-life testing of Constic revealed a discoloration rate indistinguishable from that of Filtek Z250, indicating that long-term chromatic drift may be governed by degradation mechanisms common to both self-adhesive and traditional formulations [44]. More recent investigations likewise place Vertise Flow

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TABLE 2B | Manufacturer-stated application instructions (concise checkpoints).

Composite	Prep	Placement (thickness)	Activation	Cure	Build	Notes
Dyad/Vertise flow	Clean and isolate	Coat all walls (≤0.5 mm)	Brush 15–20 s	20 s	≤0.5 mm layers	—
Fusio liquid dentin	Clean and dry	Dispense directly	—	20 s	≤0.5 mm layers	—
Constic	Clean and dry	Apply; adapt	Instrument adapt	20 s	—	—
Oxford flow SE	Clean and dry	Apply; adapt	Instrument adapt	20 s	≤0.5 mm layers	—
Y-flow SA	Clean and dry	Apply; adapt	Instrument adapt	20 s	≤0.5 mm increments	—
Profil flow SE	Clean and isolate	Apply; adapt	Instrument adapt	20 s	≤0.5 mm layers	—
Beautifil kids SA	—	Thin layer < 0.5 mm	Leave 20 s; remove excess	— (per IFU)	—	PRR use emphasized
Nova compo SF	Rinse and air-dry; avoid contamination	Apply; spread	Wait 15 s	20 s (≥ 500 mW/cm^2)	—	—
FIT SA	—	Spread uniformly (< 0.5 mm)	Leave 20 s	20 s	—	Do not etch dentin
Fusion Flo SE	—	Apply and pre-contour (≤2 mm)	Wait 10 s	20–40 s	≤2 mm	Selective enamel etch recommended
SimpliShade Self-adhesive flow	—	Thin layer < 0.5 mm on walls/bevels	Brush 15–20 s	20 s	—	—

Note: Summarized steps from the instructions for use: Thin film (typically ≤0.5 mm), active brushing/adaptation (≈10–20 s) and light-curing (≈20 s), repeated in small increments as specified. Cells note product-specific deviations (e.g., wait times, max increment thickness, selective enamel etch guidance); phosphoric-acid etching of dentin is generally not recommended.
Abbreviations: IFU, instructions for use; mm, millimeters; s, seconds.

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and Y-Flow SA within clinically acceptable ΔE ranges following thermocycling and staining challenges [67]. Because many commercial SAFRCs remain untested, comprehensive color-stability assessments across the full product spectrum constitute an important direction for future research.

5.1.5 | Adhesive Performance, Sealing and Interfacial Quality

i. Interaction with the smear layer

During cavity preparation, rotary instruments leave a micrometer-scale smear layer composed of fragmented hydroxyapatite, collagen, and abrasive debris. Although this layer is only about 1–2 μm thick, densely packed smear plugs can penetrate 20–40 μm into dentinal tubules, blocking fluid flow but also hindering the passage of adhesive monomers. Because SAFRCs depend on the diffusion of comparatively mild acidic monomers (pH≈2–2.7) rather than on a separate phosphoric-acid etch, the integrity of this layer becomes a critical variable in their bonding performance. This concern has been the topic of interest in some studies over the years [26, 68, 69].

Latta and Radniecki created "thin" (600-grit) and "thick" (180-grit) smear layers on flat dentin and observed that all four tested self-adhesive restoratives—including Activa, Fuji II LC and Equia Forte—lost 30%–50% of their shear-bond strength when the thicker smear was present, whereas a universal adhesive used in self-etch mode was unaffected [68]. Brueckner and colleagues provided micromorphological support for this barrier effect: in Class V cavities restored with Vertise Flow or Fusio Liquid Dentin, scanning electron microscopy revealed only sparse (< 5 μm) resin tags penetrating the smear-covered dentin, and thermocycling produced micro-leakage along 75%–94% of the adhesive interface; post-aging shear-bond strengths fell by as much as 97% [70]. Mine et al. [26] used TEM to look inside those interfaces and found only a thin (≈100–200 nm) hybrid zone, with most smear debris and aprismatic enamel left intact—visual evidence that helps explain why self-adhesive flowables often underperform traditional adhesive protocols.

The advantage of removing or thinning the smear layer was also demonstrated by Sibai et al. [71] who reported that a 15 s phosphoric-acid pretreatment nearly doubled the bond strength of Fusio Liquid Dentin to dentin (26.6–49.4 MPa), although the use of acid pretreatment remains reserved. Consistent findings have been described for other self-adhesive composites in both permanent and primary dentin, where selective etching or fine-grit finishing produced bonds that approached those of two-step self-etch adhesives, whereas an intact smear layer led to markedly inferior values. To date, pH data are available only for Vertise Flow (≈1.9) [72]; the pH of other SAFRC pastes remains unreported, probably because accurate, reproducible measurement of paste pH is technically challenging.

The evidence indicates that SAFRC efficacy is highly dependent upon smear-layer thickness. Further long-term studies are warranted to determine how variations in smear composition and aging influence the durability of these simplified restorative materials.

ii. Enamel

Numerous studies have compared the adhesive performance of SAFRCs to adhesives and conventional composites, and meta-analytical laboratory data regarding the bond strength of these materials already exists [22]. Generally, with SAFRCs, bond strength to enamel is higher than to dentin, but altogether, it is still lower than with conventional dental adhesives. Thus, only studies that are posterior to the meta-analysis shown in [22] are worth reporting below.

In enamel, the main question is whether these materials do benefit from pre-treatment strategies such as the use of orthophosphoric acid etching. In a recent study, the bond strength to etched enamel was significantly greater than the bond strength achieved via normal application on both enamel and dentin [73]. In this study, the bond strength to dentin showed a difference to etched enamel larger than ten-fold. Nonetheless, the bond strength to etched enamel was still lower than values previously reported for composites used with a separate adhesive. A recent laboratory study also looked at pre-etching in bovine teeth and showed an increase of 14.1–15.1 MPa to 22.2–23.2 MPa for etched enamel, and also lower microleakage scores [74].

iii. Dentin

With regard to the bond strength of SAFRCs to dentin, several studies demonstrate that there is a deficient and unstable interaction between the incorporated functional monomers and the microstructure of dentin, possibly due to a very limited contact between a largely hydrophobic, viscous paste and the surface of dentin [69, 75, 76]. The most up-to-date meta-analytical data prove that bond strength to dentin is the main concern of SAFRCs, translating into very low bond strengths [22]. Other recent studies that have continued to explore the problem have still found lower bond strengths of these materials at 24 h and after aging when compared to traditional adhesive systems [77]. Öztürk and Baltacıoğlu subjected four SAFRCs to 6-month water-aging and found again low bond strengths: Nova Compo SF and EQUIA Forte lost significant bond strength (11.8 → 7.5 MPa and 8.5 → 3.5 MPa, respectively; $p < 0.05$); Vertise Flow and Fusio Liquid Dentin showed no statistical change yet remained with extremely low values (< 2 MPa after aging).

Successful dentin adhesion depends on intimate wetting of a hydrated, collagen-rich substrate, dissolution of the smear layer, and infiltration of low-viscosity monomers that polymerize into a micrometer-thick hybrid layer [15, 17, 78]. SAFRCs struggle at every step of this sequence. First, the resin phase of these materials is solvent-free and highly viscous. Transmission-electron microscopy (TEM) shows that, even when the smear layer is removed, Vertise Flow and an experimental SAFRC produce only a 100–200 nm "resin–smear complex" rather than a true hybrid layer [26, 79]. Resin tags are typically absent unless tubules are left smear-free by fracture. This viscous resin phase fails to envelop the exposed collagen network by itself and may rather make it collapse with the application pressure [80]. Limited penetration is mirrored by mechanical data (Table 3): micro-tensile bond strength

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TABLE 3 | Summary of mechanistic bond strength to dentin data gathered over the years, concerning the different commercial SAFRCs and the evidence available to date.

Commercial SAFRC	Test method/ aging	Reported range (MPa)[a]
Dyad flow/Vertise flow (Kerr)	μTBS to mid-coronal dentin, 24 h and 6 month	[1.8–32.66 MPa] (24 h) → [0–1.39 MPa] (6 month)
Fusio liquid dentin (Pentron)	μTBS to dentin, 24 h and 6 month	[14.34–22.2 MPa] (24 h) → [11.62 MPa] (6 month)
Constic (DMG)	μTBS to dentin, 24 h and 6 month	[1.3–10.64 MPa] (24 h) → [0.5–1.29 MPa] (6 month)
FIT SA (Shofu)	μTBS to dentin, 24 h and 6 month	[10.9–23.31 MPa] (24 h) → [14.09 MPa] (6 month)
Y-Flow SA (Yller)	μTBS to dentin, 24 h	3.8 MPa (24 h) → 6.5 MPa (6 month)
Nova compo SF (Imicryl)	μSBS to dentin, 24 h and 6 month	11.8 MPa (24 h) → 7.5 MPa (6 month)
Oxford flow SE (first scientific)	No peer-reviewed dentin–bond data located (to date).	—
Profil flow SE (Silmet)	Only manufacturer technical notes; no independent peer-reviewed bond-strength study yet.	—
Fusion Flo SE (Prevest DenPro)	No peer-reviewed dentin–bond data located (to date).	—
Beautifil kids SA (Shofu)	Reports same technology as FIT SA μSBS to dentin, 24 h	10.9 MPa
SimpliShade self-adhesive flow (Kerr)	Only manufacturer technical notes; no independent peer-reviewed bond-strength study yet.	—

Note: Reports include aging in water; no aging beyond 6 months was found in the literature. Note extremely high interval variability in the reported range of dyad flow/Vertise Flow.
[a]References: [43, 67, 69, 76, 77, 81].

to bur-cut dentin averages ≈2 MPa for Vertise Flow—with 45%–67% pre-testing failures—versus 18 MPa for Fusio Liquid Dentin and ≥ 25 MPa for one-step self-etch adhesives, while three-step etch-and-rinse controls exceed 40 MPa.

Second, acidity is too mild to consistently dissolve the smear layer. As discussed above, smear-layer thickness is a dominant variable; with thicker layers, bond strengths drop and hybridization is minimal. Third, functional-monomer bonding is limited. For example, GPDM in Vertise Flow behaves mainly as an ultra-mild etchant, producing ≈2 μm etch depths with little stable calcium-salt formation [82]. This is incompatible with durable ionic bonding. In Fusio Liquid Dentin, 4-MET may bond more effectively, but the viscosity reduction required to improve wetting often compromises mechanical integrity.

Finally, any bond that is achieved by SAFRCs degrades quickly. Vertise Flow shows a "remarkable decline" in shear strength after aging, while thermocycling of FIT SA cuts micro-shear values by ≈10% and increases the proportion of adhesive failures, changes attributed to hydrolytic swelling of the hydrophilic, HEMA-rich matrix and to the absence of a continuous, hydrophobic hybrid layer [75, 83]. El-Bouhi's simulated-pulpal-pressure study highlights the limitations of self-adhesive flowables when dentin is hydraulically active [1]. Under a constant intrapulpal pressure of 15 cm H_2O, Vertise Flow bonded with a mean micro-tensile strength of 8.9 MPa, the weakest of the six protocols tested and far below the 15.4 MPa achieved by a one-step self-etch adhesive and the 31.3 MPa recorded for a phosphoric-acid-etched, adhesive-plus-flowable strategy [84]. This confirms that dentin conditioning only partially mitigates the material's poor wetting and smear-layer resistance.

When microleakage and sealing were evaluated, Rengo et al. [85] pointed out that SAFRCs exhibit better sealing capacity at the dentin interface in class V cavities when applied solely than with pre-conditioning of the dentin with orthophosphoric acid at 37%. Not surprisingly, Bektas et al. concluded that self-adhering flowable composites used with an adhesive system provided stronger bond strength and better marginal seal than their individual use [86]. Another study by Celik et al. reported that SAFRCs had higher microleakage values when compared to three-step etch and rinse adhesives combined with flowable composites in enamel and dentin. Microleakage of these materials can be significantly reduced with enamel pretreatment; however, it is debatable whether or not the composite maintains its marginal sealing capacity over time [87]. Even in microleakage studies with different techniques, such as confocal laser scanning microscopy, SAFRCs show worse results in comparison to dental adhesives. Although in enamel, acid pretreatment may considerably reduce the microleakage of these materials [88], it is still open for question as to whether or not these materials maintain marginal sealing capabilities. Hala et al. examined Class V cavities restored with three materials: a conventional flowable composite, a self-adhesive flowable composite, and a nanohybrid composite. After 500 thermocycles, stereomicroscopic measurements showed that the self-adhesive flowable produced the widest occlusal and cervical

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marginal gaps, whereas the nanohybrid achieved the smallest; the differences at both margins were statistically significant [89]. Sengar et al. [90] compared cervical Class V restorations placed with a conventional etch-and-rinse technique (G-ænial Universal Flo + Adper Single Bond 2), a one-step self-etch adhesive (G-ænial Universal Flo + G-Bond), and the self-adhesive flowable composite Constic. Confocal laser scanning microscopy showed that Constic produced the highest dye penetration scores at both enamel and dentin margins, statistically greater than the self-etch and etch-and-rinse controls, while no group achieved a completely leakage-free seal. Confocal dye studies of Fit SA further revealed that the composite exhibited higher microleakage at both enamel and dentin margins, following the trend of other studies [91]. Most recently, Elraggal et al. also proved that SAFRCs are still inferior to composites and traditional adhesives in microleakage and with ultramorphological SEM imaging data [27]. Finally, Camatti and co-workers reported dye-penetration scores that did not differ statistically between Y-Flow SA and a conventional flowable placed with a universal adhesive after 24 h of water storage, but these results were observed in bovine teeth [92].

Only one study reports the results of nanoleakage expression at the interface concerning Fusio Liquid Dentin, and unexpectedly, the results of this material were significantly better, with less marked nanoleakage than when conventional dental adhesives and composites were used (before and after 50,000 cycles of occlusal cyclic loading) [93].

Alternative surface treatment methods such as laser preparation may be an interesting approach to aid the bonding of these materials to dentin [94]. Elkhaiat et al. pre-treated dentin with 50% dimethyl-sulfoxide (DMSO) for 60 s before placing Fusio Liquid Dentin and reported a six-fold jump in micro-tensile bond strength—from 7.2 ± 4.4 MPa to 31.6 ± 5.8 MPa—while the same pretreatment produced no statistically significant gain for a conventional flowable used with a self-etch adhesive (14.8 ± 2.7 MPa → 17.2 ± 4.9 MPa). The authors attributed the improvement to DMSO's ability to displace residual water, widen collagen microfibril spacing, and enhance monomer infiltration; failure analysis corroborated this, showing adhesive-type failures for the untreated self-adhesive composite but predominantly mixed failures when DMSO was applied. Collagen depletion methods have also been pointed out as an option on the horizon for these materials [95]. Figure 2 illustrates the main factors governing the bonding challenges of SAFRCs.

iv. To primary teeth

Similarly to what was found in permanent teeth, David et al. [22] in their meta-analytical data of laboratory studies reported that the bond strength of SAFRCs to primary enamel and dentin,

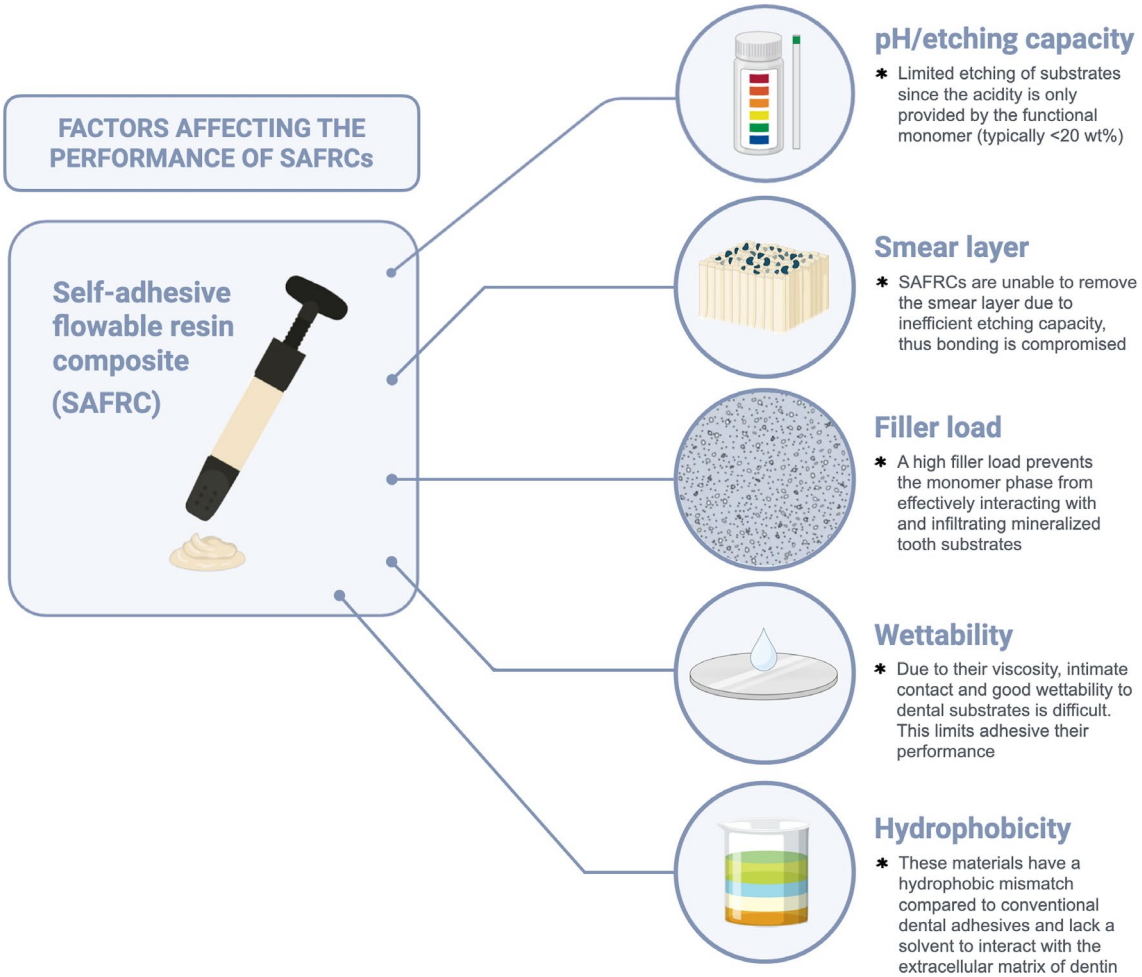

FIGURE 2 | Conceptual overview of the intrinsic and interfacial factors that govern the clinical performance of SAFRCs.

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regardless of the adhesive strategy used, is inferior. The use of an adhesive system combined with a conventional composite resin improved the bond strength to the substrate ($p < 0.001$) when compared to SAFRCs. Another systematic review that was published later compared the laboratory performance of SAFRCs to GICs and found no relevant differences, suggesting that these materials could be a replacement for current GIC restorations in primary teeth [96], although clinical data should be taken into account. This is in agreement with observations by Ghajari et al., who pointed out that the reduced mineral content and different microstructure of primary dentin result in a thicker hybrid layer and shorter resin tags, which reduce the bond strength when compared with that of permanent dentin [97]. Even with microleakage scores, the trend follows what is seen with permanent teeth—in class V cavities, SAFRCs do not seem to have an acceptable microleakage behavior [98].

5.1.6 | Biological Properties

Seldom studies have looked at the biocompatibility and potential toxicity of SAFRCs. Flowable SAFRCs such as Vertise Flow have been tested in direct contact tests, 24 h post-exposition in MTT assays, with results being similar to control groups and comparable to RMGICs [56]. Cell viability in accordance with ISO 10993-5/2009 has also been found acceptable, with proven biocompatibility in previous reports [43]. It is important, however, to take into account that SAFRCs are more prone to biodegradation phenomena, such as hydrolytic degradation, which increase their risk for toxicity over time [63]. This, however, is highly dependent upon the chemical composition. Particularly, Vertise Flow and Constic do not seem to have a higher monomer elution rate (tested in intervals of 1 h, 24 h, 4, 8, and 16 days) compared to other conventional flowables [99].

In a 12-month RCT on 90 non-carious cervical lesions, Peskersoy et al. [100] reported that Vertise Flow showed ≤10% USPHS failures and the most favorable periodontal profile—only a modest IL-1/IL-1β rise alongside the largest IL-10 increase. Nexcomp Flow induced the greatest gingival-crevicular-fluid expansion, the highest IL-1/IL-1β titres, and the poorest clinical scores, implying a fluoride-related inflammatory effect. Nova Compo SF displayed intermediate periodontal and clinical behavior.

5.2 | Clinical Data

5.2.1 | Clinical Studies in Adults

In 2023, important meta-analytical data regarding the clinical effectiveness of SAFRCs was published; however, it had many limitations. Firstly, this systematic review and meta-analysis only contemplated Class I occlusal cavities, leaving out Class II and Class V non-carious cervical lesion (NCCL) restorations, which make up a large amount of restorative cavity configurations in the clinical setting. Furthermore, only USPHS clinical criteria were assessed, and some studies used the FDI modified criteria to assess the clinical performance of restorations. Finally, only five studies were included. This is a very low number that does not allow any clinically informed decision. The meta-analysis suggests that, based on the five clinical trials, it seems that SAFRCs have a similar behavior to the conventional composite restoration with an adhesive system, although only one study reported follow-ups longer than 2 years (5 years maximum). At this point, it is not possible to make evidence-based recommendations for clinical practice. Mourão and Lowenstein [101] also published a commentary on the above systematic review and meta-analysis, highlighting the inadequate sample sizes, heterogeneity, and wide confidence intervals that, in the end, lack robustness and rigor to support the clinical use of SAFRCs. Further research is required.

Since then, other clinical trials have been published. Again, in Class I cavities at 18-month follow-up, Fusio Liquid Dentin shows comparable clinical performance to conventional protocols [102].

With regard to other clinical parameters, for instance, post-operative sensitivity, different studies have evaluated the clinical effectiveness of SAFRCs compared to conventional protocols. In one study, 46 patients with hypersensitive teeth were selected and put through a pain experience generated by a cold stimulus that was then evaluated with the use of a visual analog scale (VAS) of pain. Responses were recorded at baseline, after 1, 4, and 12 weeks. After 12 weeks, there was no significant difference, and all materials, including Vertise Flow, showed similar results in decreasing hypersensitivity [103]. Another randomized controlled clinical trial was conducted with the intention of evaluating the postoperative sensitivity of restorations after using a self-adhesive resin composite (Vertise Flow) in comparison with the use of a conventional resin composite with a self-etching adhesive. In another clinical trial, 27 volunteers, with third molars indicated for extraction, received two deep Class I restorations, including Vertise Flow versus conventional control, and then postoperative sensitivity was measured 24 h and 15 or 30 days after the restorative procedures using a visual analog scale. Results showed that both restorative materials presented a similar response in regard to postoperative sensitivity [104].

5.2.2 | Clinical Studies in Children

Compared to clinical trials in permanent teeth, studies on pediatric patients are notably fewer. The first clinical study to use SAFRCs in children was published in 2015, evaluating the clinical performance of Vertise Flow as a pit and fissure sealant [105]. The results of this study showed a retention rate of 62.9% for Vertise Flow, which was significantly lower than the other materials evaluated. Another study [106] evaluated 40 Class I restorations in primary molars of 20 children using a split-mouth design, comparing Fusio Liquid Dentin and Flow-It ALC. At 1 week, 3, 6, 9, and 12 months, restorations were assessed using the US Public Health Service modified Ryge criteria, with all restorations deemed acceptable at 12 months.

Another single-blind randomized clinical trial [107] compared Vertise Flow and Filtek Z250 with a two-step self-etch adhesive in Class I cavities of primary molars. Over a 12-month follow-up, no restoration exhibited retention loss, post-operative sensitivity, or significant differences in color match, marginal adaptation, secondary caries, or surface texture. A third trial

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compared Vertise Flow and Premise Flow in Class I primary molar cavities [108], focusing on hypersensitivity immediately post-restoration. Patients restored with conventional composites reported higher post-procedure pain frequency than those treated with flowable composites. Authors have acknowledged that SAFRCs reduce chair time and are desirable in pediatric clinical cases [109].

6 | Experimental SAFRCs

Up until this date, few research teams have published experimental development of SAFRCs. Laboratory studies strongly suggest that the interaction between SAFRCs and the dental substrate—particularly dentin—is limited, exhibiting minimal micromechanical retention and poor marginal sealing. These deficiencies are associated with high and clinically undesirable failure rates [28, 79]. In experimental SAFRCs formulated with 3% 4-META, Delgado et al. [79] showed that these materials are incapable of forming a hybrid layer when compared to conventional adhesives. This was further strengthened by investigating the same interfacial quality with commercial materials, confirming that indeed SAFRCs do not form true hybrid layers [110]. When Vertise Flow was released, TEM analysis of experimental SAFRCs supplied by 3M revealed that, even on smear-free dentin, the material produced only a sub-micron "nano-interaction zone" made up of partially infiltrated collagen and scattered hydroxyapatite crystals; on bur-cut surfaces, the smear layer remained largely intact, and silver tracer studies exposed reticular nanoleakage throughout the interface [111]. These ultra-structural observations confirm that the mildly acidic, high-viscosity chemistry characteristic of current SAFRCs is unable to create a continuous, resin-reinforced hybrid layer—a limitation that explains the low μTBS values reported for GPDM-based products. In 2021, Nunes Ferreira et al. proved that the addition of functional monomers is not enough to grant these materials a self-adhesive capacity, and that the restriction to etch, infiltrate, and guarantee micromechanical retention is further responsible for catastrophic sealing results, even when the chemical composition (namely, the functional monomer) varies [28].

Attempts at developing composites with other properties other than self-adhesiveness have also been made. Panpisut et al. [112, 113] pursued a bio-interactive route, incorporating calcium-phosphate glass and the antimicrobial peptide nisin into dual-cure experimental SAFRCs. The formulations met ISO flexural strength and conversion targets and even nucleated apatite-like crystals after simulated body fluid aging, but dentin SBS still hovered between 2 and 6 MPa—lower than Vertise Flow—underscoring that remineralising additives do not compensate for deficient interfacial chemistry. A more radical chemical redesign was attempted by Shimizu et al. [114], who combined 10-MDP with a hydrophilic amide monomer in SA-100R. Initial μTBS to dentin reached 28.8 MPa—substantially higher than Constic (19.7 MPa) and within the lower clinical range—but 60% of specimens still failed adhesively, indicating that even enhanced functional monomer blends cannot fully overcome smear layer impedance and water-rich collagen porosity.

Following this trend, Cocco et al. [115] pursued a chemotherapeutic strategy by incorporating metallic monomers—zinc methacrylate and di-n-butyl-dimethacrylate-tin—into self-adhesive pit and fissure sealants. While all experimental formulations met mechanical and esthetic requirements, only SnM 5% demonstrated potent anti-biofilm activity, achieving > 70% CFU reduction and neutral pH stabilization against *Streptococcus mutans–Candida albicans* dual-species biofilms. Importantly, this effect occurred without compromising flexural strength or inducing cytotoxicity, yet bond strength to enamel remained modest (< 16 MPa), reinforcing the view that anti-biofilm function alone does not resolve interfacial limitations inherent to self-adhesive systems.

Regarding polymerization kinetics, the monomer ratios, specifically, monomers that are functional and that act as co-solvents, that is, HEMA, are responsible for guiding kinetics and controlling final conversion levels [28, 116]. Due to reported acidic instability, camphorquinone coinitiators may not be indicated in SAFRCs. In 2013, Munchow et al. looked at replacing it with 1,2-diethyl-2-thiobarbituric acid as an alternative co-initiator with good results. However, using a UDMA-PPGDMA system with 1 wt% camphorquinone has been established in the literature as a very good approach, with optimal kinetic results, for experimental SAFRCs [6, 112, 116, 117]. Bertolo et al. systematically replaced the traditional camphorquinone/amine photoinitiator in model SAFRCs with TPO and BAPO, showing that bis-acyl-phosphine oxide (BAPO) doubled the degree of conversion and polymerization rate relative to CQ/amine, yet simultaneously intensified yellowing and—critically—inflated 30-day water sorption to the highest levels recorded in the study, underscoring the trade-off between cure efficiency and hydrolytic stability in these hydrophilic, acidic matrices [118].

More recently, Oliveira et al. reported that a new self-adhesive composite (DF) displayed sorption and solubility values of 0.54 and 1.70 $\mu g\,mm^{-3}$, respectively—well inside ISO tolerances yet still higher than a Bis-GMA/UDMA bulk-fill comparator—highlighting the persistent impact of acidic and hydrophilic monomers on diffusion-controlled degradation [65].

Finally, compositional tuning of the acidic monomer itself can shift performance but not eliminate the dentin barrier. Costa et al. formulated orthodontic SAFRCs containing either GDMA-P or MDP. The MDP version achieved an immediate enamel bond (≈7 MPa) statistically equivalent to a three-step control and maintained mixed failures after thermocycling, whereas the GDMA-P analogue and an acid-free negative control remained dominated by adhesive failures; both experimental resins nonetheless suffered significant drops in conversion compared with the amine-free control [119].

7 | Summary and SWOT Analysis

SAFRCs offer several notable advantages that streamline restorative procedures. The integration of adhesive properties within their composite matrix simplifies clinical application, reducing chair-time and mitigating technique sensitivity. This is particularly important under suboptimal conditions such as saliva contamination, absence of rubber dam isolation, or uncooperative

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patients [36]. The handling/flow characteristics are advantageous for small, low-stress restorations. Their solvent-free, higher filler-loaded composition makes them less susceptible to hydrolytic and enzymatic degradation compared to conventional adhesives. These practical strengths explain the continued clinical interest in SAFRCs.

At the same time, the dominant limitation remains dentin adhesion. Smear-layer impedance, ultra-mild acidity, and hydrophilic formulations are typically yielding a thin interfacial zone rather than a proper hybrid layer [26, 79, 120], which helps explain consistently higher microleakage versus standard adhesive controls. These materials exhibit consistently low bond strengths in self-adhesive mode, failing to reliably offset polymerization shrinkage stress without adjunctive strategies such as selective etching or additional adhesive layers [22, 80]. Hydrophilicity, as seen in *water sorption/solubility* increases both of these outcomes, surpassing that of conventional resin composites and potentially compromising long-term stability [61]. In turn, the flowable consistency and lower filler loads contribute to higher polymerization shrinkage and generally inferior mechanical properties relative to conventional, higher-viscosity composites [58]. Color stability concerns have likewise been reported.

Future advances in SAFRC technology must therefore address these compositional and rheological constraints to realize their clinical potential fully.

Figure 3 depicts a strengths–weaknesses–opportunities–threats (SWOT) analysis for the implementation of SAFRCs in current practice, especially considering the advantages and challenges of the present day.

8 | Future Directions

Future formulations are converging on a multifunctional design that may tackle chemistry, polymerization, and substrate conditioning. Regarding chemistry, one promise may be the development of polymerizable poly-acids and other amphiphilic oligomers that merge the cross-linking capacity of dimethacrylates with the self-etch adhesion typical of glass-ionomer polyacids [121, 122]. The challenge is to create water-resistant networks that can both demineralize and bond. Complementing this, advanced curing schemes now integrate a peroxide/amine redox pair [123] (e.g., persulfate with a barbiturate or tertiary amine) alongside camphorquinone; dual-cure bulk-fill restorative options such as Surefil One are able to polymerize in shadowed

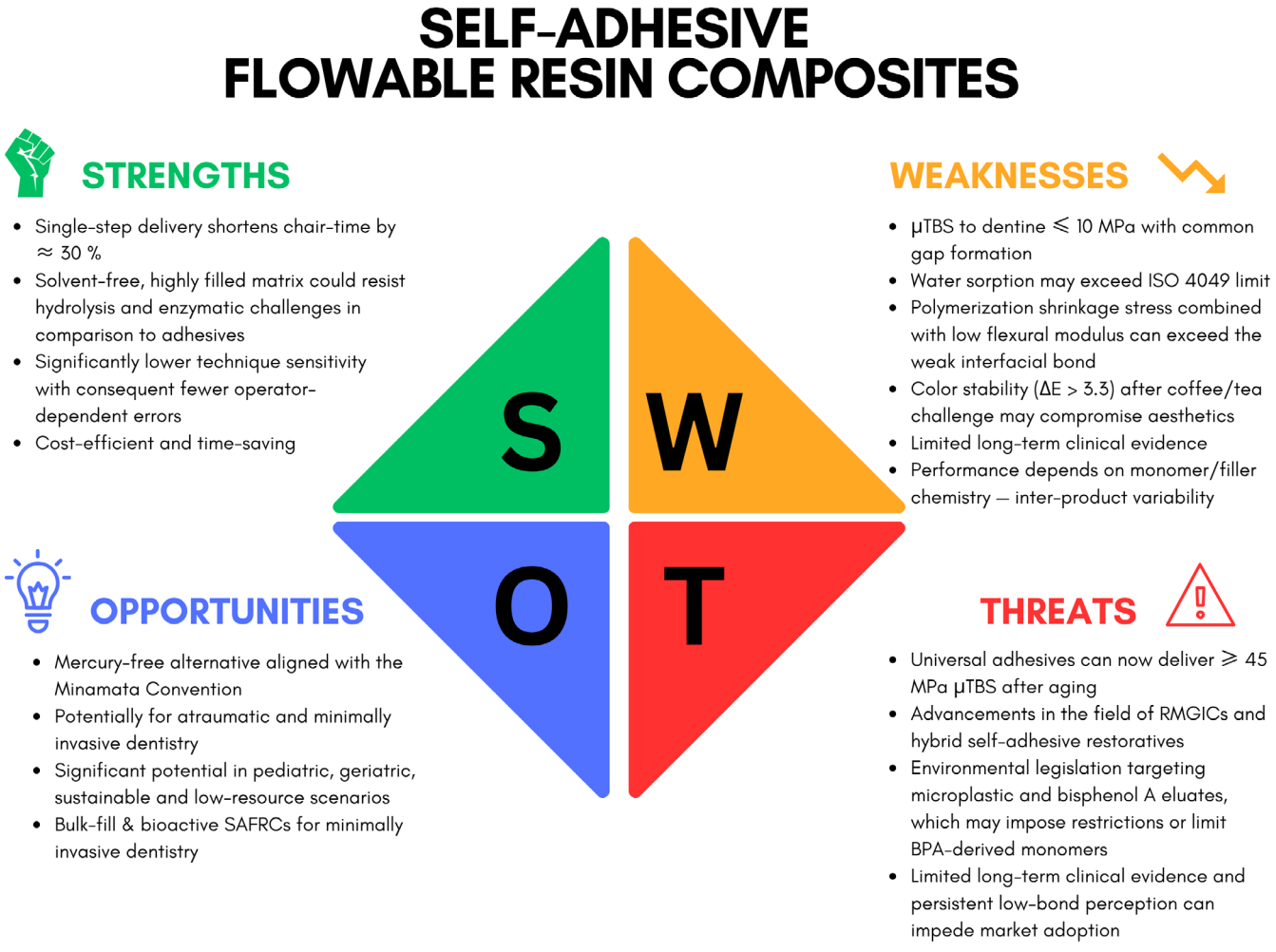

FIGURE 3 | SWOT analysis that frames the strengths, weaknesses, opportunities, and threats for the implementation of SAFRCs in clinical practice.

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areas, although future work must balance rapid self-cure with acceptable working time, final polymerization extent values, and shelf stability.

Functionalisation is also moving into the domain [124]. Silica nanocapsules and halloysite nanotubes loaded with remineralising ions, antimicrobial drugs, or protease inhibitors are being embedded in the resin matrix to provide a therapeutic reserve that can seal micro-gaps, eventually reharden demineralized affected dentin, or suppress biofilm over the lifetime of a restoration [125]. In parallel, nanostructured fillers such as S-PRG particles and calcium-silicate nanosheets supply fluoride, calcium, and phosphate under acidic challenge, thereby protecting the tooth–restoration interface.

Tailoring the chemical composition of next-generation SAFRCs is an approach that is already underway [28], however, it may not be enough. It seems that to make clinical translation of these materials possible, it may also be necessary to revise their application technique and determine whether a different substrate preparation is required [95]. Material innovation is thus being paired with substrate-level optimisation. Brief EDTA or DMSO pretreatments that thin the smear layer and expand collagen nano-channels have been shown to double chemical infiltration of low-viscosity. Specifically, dentin calls for alternative preparation techniques that are able to increase the surface free energy and simultaneously remove the need to interact with the exposed collagen network, post-etching, and water-bound non-collagenous proteins that hinder the penetration and infiltration of a viscous, hydrophobic-rich resin layer. Techniques such as substrate deproteinization [126, 127], collagen-depletion [95], or selective extrafibrillar demineralization [128, 129] may all be effective in guaranteeing adhesion of subsequent hydrophobic resin layers.

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Disclosure

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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