

**Magic Materials for Mini Mouths: Smart Pediatric Dentistry – A Literature Review**

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**Abstract**

Smart materials have emerged as a major innovation in pediatric dentistry, offering adaptive solutions tailored to children’s evolving oral needs. These materials respond to external stimuli such as temperature, pH, stress, and moisture, enabling precise and effective interventions. Examples include shape memory alloys, self-healing composites, bioactive glasses and fluoride-releasing glass ionomers.

Their intelligent behavior supports applications ranging from temperature-responsive orthodontic appliances to remineralizing restoratives in acidic environments. Smart sealants and varnishes aid in long-term caries prevention. By reducing the need for repeated procedures, they enhance outcomes and cooperation. Advances in nanotechnology are further enabling personalized, preventive and biologically active pediatric dental care.

**Keywords:** ACP, biomaterials, Shape memory alloys, Smart materials

## Introduction

Pediatric dentistry is an age-specific dental specialty that provides both primary and comprehensive preventive and therapeutic oral health care for infants, children, and adolescents, including those with special health care needs. Due to the unique physiological, psychological, and behavioral characteristics of pediatric patients, specialized approaches and materials are required in dental treatment.<sup>1</sup> McCabe et al. defined "smart materials" as substances whose properties can be altered in a controlled manner by external stimuli such as stress, temperature, moisture, pH, electric or magnetic fields, or chemical agents. A defining characteristic of smart materials is their ability to return to their original state after the removal of the stimulus; hence they are also termed "responsive materials".<sup>1</sup>

The evolution of smart materials has shifted their function from being passive to active and multifunctional systems capable of structural and electronic responses.<sup>1</sup> The concept of "smart" or "intelligent" materials emerged in the 1980s in the United States. Traditionally, dental materials were developed to be passive, exhibiting minimal interaction with the oral environment.

However, as no single material fulfilled the criteria for an ideal restorative substance, the pursuit of smarter alternatives began. This has led to the development of innovative materials such as smart composites, smart ceramics, compomers, resin-modified glass ionomers and amorphous calcium phosphate (ACP)-releasing sealants. Other advancements include orthodontic shape memory alloys, smart impression materials, smart sutures and smart burs.<sup>4</sup>

These innovations have ushered in the era of "Smart Dentistry", which promises improved performance, longevity and patient comfort. These materials are capable of recognizing, adapting to, and even predicting

environmental changes. Properties like thermochromism, piezoelectricity, magnetorheology, shape memory, photochromism, biofilm response and pH sensitivity are among the intelligent features incorporated into modern dental materials. Their multifunctionality represents a significant leap toward biologically adaptive, minimally invasive pediatric dental care.<sup>5</sup>

## Requirements of Smart Materials in Dentistry

According to "David Franklyn Williams", smart materials can respond to an external stimulus in a specific, controlled way. Conventional filling materials fail because of the formation of secondary caries, fracture of restoration, fracture of tooth, marginal discrepancies, or wear. Materials developed are smart to reduce failures by adding additives to the materials.

### Smart materials responded by

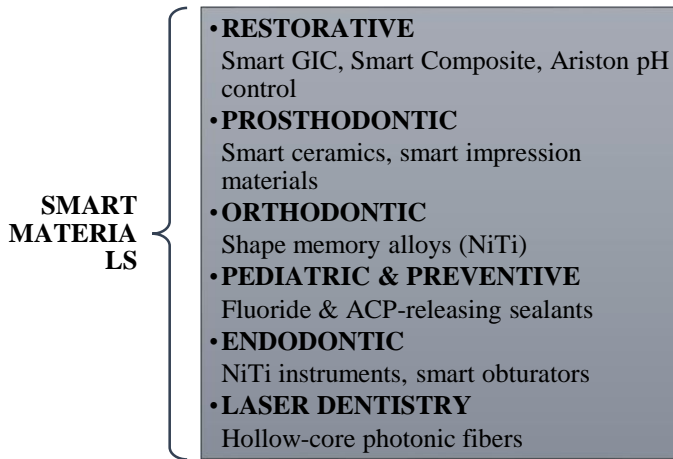
- Preventing secondary caries
- Preventing fracture of restoration
- Preventing fracture of tooth
- Providing a good marginal integrity
- Reducing wear
- Preventing marginal discrepancies
- Preventing wear.<sup>14</sup>

## Classification of Smart Materials

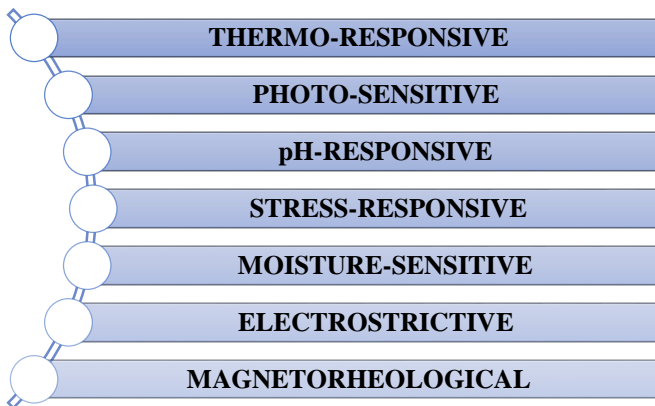
### A. Based on Nature

- Active Smart Materials: Respond via feedback mechanisms.  
e.g., GIC, Smart composites, ceramics, ACP sealants, self-healing composites, NiTi instruments, smart burs.
- Passive Smart Materials: React to environment without control.  
e.g., Conventional composites, GIC, RMGIC, compomers.<sup>6</sup>

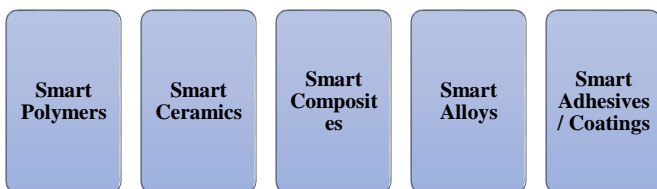
**B. Based on Dental Speciality<sup>3</sup>**



**C. Based on Stimulus-Response**



**D. Based on Composition**



**Properties of Smart Materials**

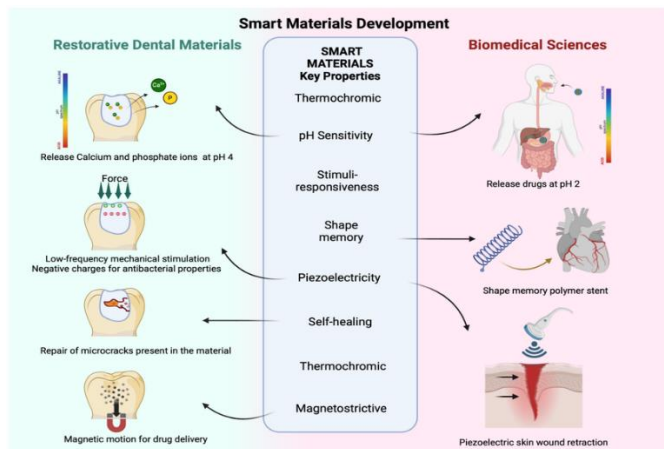
Smart materials undergo specific changes in response to environmental stimuli in a predictable way (Table 1). Smart materials respond predictably to changes like pH, temperature or stress. They enhance treatments by releasing fluoride, adapting shape (e.g., NiTi wires), or sealing gaps, improving durability and patient comfort (Fig 1)

Table 1: Properties of Smart Materials<sup>24</sup>

Properties	Description
Biofilm Responsive Materials	Alters surface-environment interaction due to biofilm presence.
Photochromic	Changes colour reversibly with light intensity.
Thermochromic	Changes colour reversibly with temperature.
Electrochromic	Change in colour or opacity with applied voltage.
Electrorheological	Fluids change viscosity when exposed to an electric field.
Magnetorheological	Becomes solid in magnetic field.
Conducting polymers	Conjugated polymers are organics with extended $\pi$ -orbitals enabling free electron movement along the chain.
Dielectric elastomers	Mechanical Strain under electric field.
Piezoelectric materials	Generates electric field under mechanical stress.
Polymer gels (pH-sensitive)	Reversibly Swells/shrinks with environmental changes.
Shape Memory Alloys (SMA)	Changes shape with temperature.
Electroluminescent	Emits light when electrically stimulated.
Fluorescent	Emits visible/invisible light under shorter wavelength exposure.

Phosphorescent	Emits visible or invisible light after exposure to shorter-wavelength light, detectable only once the source is removed.
Magnetostrictive	Changes length in magnetic field.
Electrostrictive	Deforms proportionally to square of applied voltage.
Thermoelectric	Function as heat pumps using coupled semiconductors.

Figure 1: Key Properties of Smart Materials



### Smart Glass Ionomer cement

Glass ionomer cement (GIC), introduced by Wilson and Kent in 1972, combines the fluoride release of silicate cement with the adhesive properties of polycarboxylate cement.<sup>24</sup> Davidson first described its smart behaviour, highlighting its ability to respond to environmental stimuli like temperature and moisture through water-mediated expansion or contraction, similar to dentin<sup>4,24,18</sup> GIC maintains marginal integrity under thermal stress, especially in moist conditions.<sup>18</sup> Its fluoride release and recharge capability further support its cariostatic effect, particularly valuable in pediatric dentistry for high caries-risk patients.<sup>24</sup> Smart traits are also observed in resin-modified GICs, compomers and giomers.<sup>3</sup> Commercially

available as Equia Forte, Fuji IX GP Extra, Ketac Universal, HY-BOND glasionomer cx-smart and Ionostar Plus.

### Smart Prep Burs

Smart Burs are polymer-based burs designed for selective caries removal, preserving affected but remineralizable dentin and preventing overcutting seen with conventional burs.<sup>4</sup> Made from polyether ketone ketone (PEKK), they possess hardness between infected (15–20 KHN) and healthy dentin (68 KHN), allowing removal of only soft, carious dentin.<sup>23</sup> Their shovel-like, paddle-shaped cutting blades deform on contact with harder dentin, becoming blunt and self-limiting, thus ideal for minimal intervention dentistry.<sup>18,23</sup> They work best with light pressure, from center to periphery, and are available in ISO sizes 0.10, 0.14, and 0.18 for single use only. Though slightly slower in caries removal, their ability to preserve healthy tissue offers significant benefits in pediatric care (Fig 2).<sup>24</sup> Commercially available as SS White.



Figure 2: Smart prep burs

### Smart Composites

Smart composites are advanced restorative materials incorporating light-activated components, alkaline agents, and nano-sized glass fillers. They release calcium, fluoride, and hydroxyl ions when oral pH falls below the critical 5.5 threshold, thereby preventing demineralization and enhancing remineralization.<sup>2,3</sup> Ariston pH Control (Ivoclar-Vivadent, Liechtenstein) is one such material, suitable for Class I and II cavities in

both deciduous and permanent teeth. It cures efficiently in bulk (up to 4 mm), does not require bonding agents and is used for posterior restorations due to its white shade.<sup>2,3,6,18</sup>

### Smart Memory Alloys

Shape memory alloys, particularly Nickel-Titanium (NiTi or Nitinol), exhibit superelasticity, shape memory, good resistance to fatigue and wear and good biocompatibility.<sup>7</sup> These alloys can revert to their original shape after deformation due to thermomechanical stimuli, undergoing phase transformation from martensite (low temperature/high stress) to austenite (high temperature/low stress) (Fig 3), this reversible transformation is responsible for their smart behavior. NiTi alloys were introduced in endodontics in 1988.<sup>17</sup> They revolutionized root canal treatment with their super-elasticity, allowing improved navigation of curved canals, reduced canal transportation and minimized procedural errors during instrumentation. Their stress-induced thermoelastic transformation enables controlled, safe canal shaping with minimal lateral force, marking a significant advancement in minimally invasive endodontic therapy.<sup>19</sup>

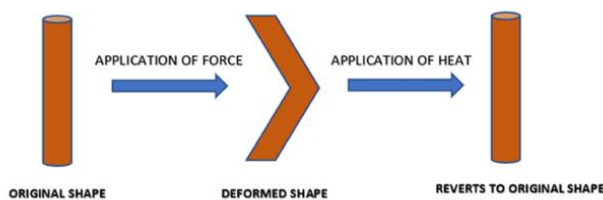


Figure 3: Nickel-titanium alloy showing property of shape memory

### Smart Ceramics

Ceramics, especially zirconia-based materials, are biocompatible, metal-free and lifelike restorations that closely mimic natural teeth.<sup>12,15</sup> The Cercon Zirconium Smart Ceramic System, developed after ETH Zurich's 1995 innovation, allows direct machining of all-ceramic

bridges without metal, enhancing strength and eliminating dark margins.<sup>4,13,15,18</sup> Zirconia's transformation toughening property—where tetragonal crystals shift to monoclinic upon crack formation—prevents crack propagation, enhancing durability. Yttrium-stabilized zirconia (YSZ) or tetragonal zirconia polycrystal (TZP) maintains this stable structure.<sup>24</sup> In pediatric dentistry, zirconia is commonly used for crowns due to its superior aesthetics, minimal wear to opposing dentition, and high fracture resistance (Fig 4). It is also employed in veneers, full-cast crowns, porcelain-fused-to-metal restorations and smart orthodontic brackets embedded with microchips that measure forces at the bracket-tooth interface, aiding in precision treatment.<sup>18</sup> Commercially available as **Cercon Zirconium Smart Ceramic System**

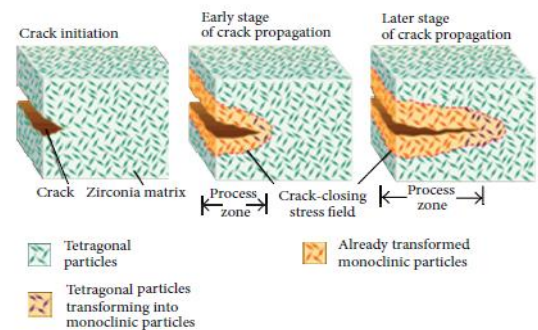


Figure 4: Phase transformation in zirconia

### Smart Healing composites

Most materials degrade over time due to physical, chemical, or biological stimuli such as mechanical forces, corrosion, erosion, or biodegradation, ultimately leading to failure.<sup>4</sup> Inspired by natural systems, self-healing materials have emerged as a key area of research. In biology, bone healing exemplifies self-repair and efforts are being made to mimic this in synthetic materials. The first self-healing resin-based material, developed by White et al., was an epoxy system containing microcapsules of dicyclopentadiene (DCPD) within a urea-formaldehyde shell. Upon cracking, the capsules

rupture, releasing resin that reacts with an embedded Grubbs catalyst, triggering polymerization and sealing the crack. This microcapsule-based healing system mirrors resin-based dental composites and may outperform traditional repair methods. Although concerns exist regarding the potential toxicity of the resin and catalyst, their low concentrations suggest acceptable biocompatibility levels, opening promising prospects for future dental applications.<sup>18</sup>

### Smart Impression Materials

Smart Impression materials exhibit enhanced properties that improve the accuracy and reliability of dental impressions. Their hydrophilic nature allows for void-free impressions, even in the presence of moisture. They demonstrate shape memory during elastic recovery, which helps resist distortion and ensures a more accurate impression. Their inherent toughness also provides resistance to tearing during removal. The snap-set behavior of these materials ensures a rapid transition from the working to the setting phase, minimizing distortion and resulting in precisely fitting restorations. Additionally, they reduce working and setting times by at least 33%, enhancing clinical efficiency. Their viscosity plays a crucial role—materials with lower viscosity exhibit higher flow, which helps in capturing fine surface details accurately and consistently.<sup>4,12</sup> Commercially available as Imprint™ 3 VPS, Impregim™, Aquasil ultra (3M ESPE Dental Products, USA).

### Smart Sutures

These sutures are composed of thermoplastic polymers that possess both shape memory and biodegradable properties. They are initially applied loosely in their temporary shape, with the ends fixed in place. When the temperature is raised above the material's thermal transition temperature typically, close to human body temperature the suture shrinks and tightens the knot,

applying optimal force. This temperature sensitivity is clinically significant, as it ensures proper tension and stress distribution during surgical procedures. Additionally, smart sutures made from plastic or silk threads coated with temperature sensors and microheaters have been developed. These advanced sutures can detect localized infections by monitoring temperature changes at the surgical site, enabling timely medical intervention.<sup>3,4</sup> Commercially available as Novel MIT Polymer (Aachen, Germany).



Figure 5: Novel MIT Polymer suture

### Smart antimicrobial peptide

Smart antimicrobial peptides (AMPs), particularly pheromone-guided ones, are designed to target *Streptococcus mutans*, the primary causative agent of dental caries.<sup>1,23</sup> Most AMPs are cationic, amphipathic peptides with  $\alpha$ -helical and  $\beta$ -sheet structures that disrupt microbial membranes or act intracellularly. Specifically targeted antimicrobial peptides (STAMPs) can be incorporated into oral care products like toothpaste, mouthwash, or floss to suppress cariogenic bacteria.<sup>24</sup> The BRAX-I gene, linked to enamel growth regulation, has also been identified.<sup>1,12,24</sup> These smart materials enhance tissue regeneration and restorative outcomes.<sup>12</sup> Commercially available as Pheromone guided “smart” antimicrobial peptide.

### Fluoride releasing pit and fissure sealant

Occlusal surfaces constitute only 12% of the tooth surface, they are eight times as vulnerable as smooth surfaces to caries.<sup>15</sup> Pit and fissure sealants are considered a minimally invasive method that seals pits and fissures to protect against tooth decay without causing harm to the tooth's structure. The use of fluoride sealants can also provide protection to neighboring areas through the release of fluoride.<sup>46</sup> The most appropriate period for the placement of occlusal sealants is soon after eruption of the permanent molars, because recently erupted teeth are less mineralized and teeth have also not undergone the benefits of post eruptive maturation of the enamel and may be thus more prone to acid attack.<sup>15</sup> It is recommended that pit and fissure sealants be applied at 3-4 years of age for primary molars, 6-7 years of age for the first permanent molar teeth and at 11-13 years of age for the second permanent molar and premolar teeth.<sup>46</sup>

Two common methods of fluoride incorporation into fissure sealant materials:

- The anion exchange system (organic fluoride compound chemically bound to the resin)
- Addition of fluoride salt to the un-polymerised resin. Commercially available as Fluoroshield and Deltonplus, contains sodium fluoride and release fluoride ions as the salt dissolves.<sup>15</sup>



Figure 6: Fluoride releasing pit and fissure sealant

### Amorphous Calcium Phosphate

Aaron S. Posner first described amorphous calcium phosphate (ACP) in 1963. ACP serves as a biological precursor to hydroxyapatite (HAP) and exhibits both preventive and restorative functions, making it ideal for use in cements, adhesives, sealants and composites.<sup>24</sup> Skrtic developed ACP-containing composites capable of sustained calcium and phosphate ion release, facilitating enamel repair.<sup>13</sup> At neutral pH, ACP remains stable, but when pH drops to 5.8 or below, it rapidly releases calcium and phosphate ions, forming a gel that crystallizes into HAP within minutes (fig 7).<sup>19</sup> This neutralizes acids and buffers local pH.<sup>12</sup> Commercially available as Enamel Pro Varnish.

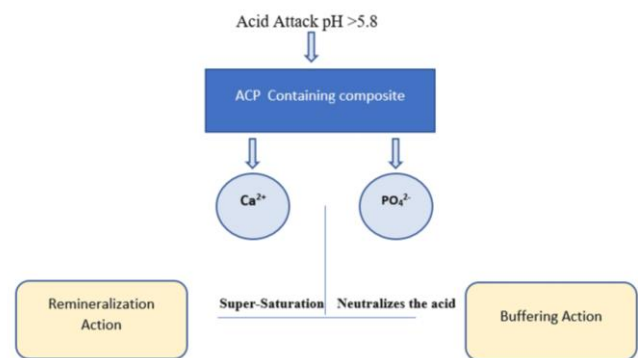


Figure 7: Conversion mechanism of ACP to Calcium and Phosphate

### Casein Phosphopeptide (CPP) – Amorphous calcium Phosphate (ACP) pit and fissure sealants

A milk derivative, in combination with ACP is used for the remineralisation of incipient white spot lesions in some dentifrices (under the name **ReCaldent**)<sup>19</sup>(Fig 8). Casein for caries prevention was addressed in the 1980s.<sup>18</sup> It has been shown to stabilize calcium and phosphate as nanoclusters together with fluoride ions, preserving them in an amorphous or soluble form. These can be combined with restorative materials to provide benefits of remineralisation as well as restoration in pediatric dentistry.<sup>18,24</sup> Aegis® is a light-cured sealant

that contains the smart material. The ACP filler is claimed to possess controlled flowability while also being resilient and flexible, resulting in a stronger and longer-lasting sealant. Unstabilized ACP, CPP stabilized ACP, and bioactive glass containing calcium sodium phosphosilicate are some of the systems available. They have both preventive and restorative properties, which justify their use in dental cements and adhesives, pit and fissure sealants and composites. CPP-ACP is available in dentifrice formulation, as a mouth rinse and as a non-sugar containing chewing gum.<sup>18</sup> Commercially available as GC tooth mousse plus® (The University of Melbourne, Victoria, Australia).



Figure 8: a) Recaldent



b) GC tooth mousse plus

### Smart Seal Obturation system

Obturation involves the three-dimensional filling of instrumented canals, accessory canals, and dead spaces to prevent reinfection and periapical disease. Gutta-percha, though commonly used, has limitations due to leakage between dentin, sealer and itself leading to treatment failure.<sup>6</sup> To overcome this, Smart Seal systems like the C Point system were developed. This system includes hydrophilic obturation points and a sealer. The C Point's core is made from nylon polymers Trogamid T and CX.<sup>4</sup> It enables controlled lateral expansion based on the prestress of the hydrophilic polymer.<sup>4</sup> This property allows the material to absorb moisture and expand, filling canal voids.<sup>6</sup> However, the use of an appropriate sealer remains essential. SmartSeal™ points are available in various sizes and tapers (table 2) for clinical adaptability.<sup>6</sup>

Table 2. Various Taper & Tip Sizes of SmartSeal™

Taper	Tip sizes
6% taper	ISO tip sizes 25-45
4% taper	ISO tip sizes 25-45
Protaper™	F1, F2, F3, F4 and F5
Sendoline™	S5-S2, S3 and S4

### Smart Local Drug Delivery System That Can Respond to pH

Advanced drug delivery systems have emerged as effective tools for sustained, controlled, and site-specific release of therapeutic agents in dentistry. Traditional systems ensure zero-order release and utilize carriers like hydrogels, micelles, and resins to protect encapsulated drugs from degradation. Recently, smart drug delivery systems have been developed that respond to environmental stimuli, particularly pH changes associated with dental caries. For instance, CHX-loaded nanomaterials using hydrogel carriers such as DMAEMA-co-2-HEMA selectively release CHX in

acidic environments created by cariogenic bacteria like *Streptococcus mutans*, showing strong antibacterial effects without disturbing healthy biofilms.

Similarly, farnesal-loaded systems and pH-sensitive chitosan nanoparticles release antimicrobial agents when plaque biofilm acidifies, preventing drug degradation at neutral saliva pH. These intelligent systems improve the precision and effectiveness of caries prevention by targeting only diseased sites. By responding to pH fluctuations, they ensure timely drug release, minimizing side effects and preserving beneficial oral microflora, making them a promising innovation in modern pediatric and preventive dentistry.<sup>42</sup>

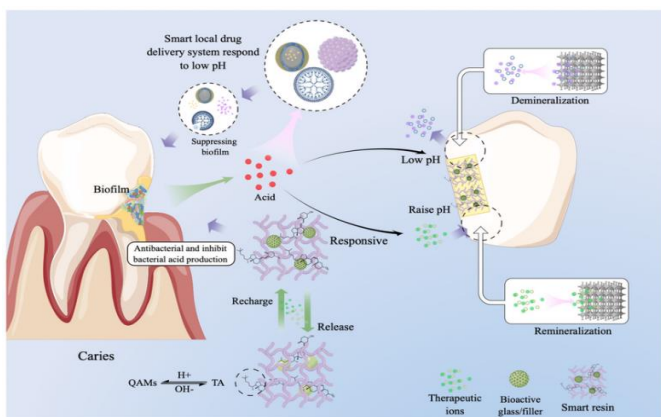


Figure 9: Smart local drug delivery system

## Discussion

Smart materials represent a new generation of materials with great potential for the future. Although they are still in the early stages of development, a great deal of material science research is needed. Smart materials encompass a diverse range of materials that exhibit adaptive responses to external stimuli such as temperature, pH, light or electrical/magnetic fields.<sup>1</sup> A material is said to be smart if it can support the remaining tooth structure to the extent that cavity preparation can be carried out in the most conservative way. Due to the interesting behaviour of smart materials, scientists have been encouraged to apply them in various fields, mostly

in biomedical science and dentistry.<sup>3</sup> Based on their capacity for recognition, analysis, and discrimination, these materials might be able to foresee problems in the near future. The superior biocompatibilities of smart materials, which have brought about a new generation of bio-smart dentistry, are a crucial component of their utilization in numerous dental applications. Smart materials may develop accidentally or may be intentionally built with intelligence. According to some scientists, no material can truly exhibit smart behaviour and these are merely responsive materials. They maintain that intelligence comprises concepts like adaptation and feedback in addition to just making a reaction in relation to a stimulus.<sup>7</sup>

Bio-smart restorative materials have been particularly impactful. Gandolfi et al. (2011) demonstrated that calcium-silicate hybrid materials can stimulate biomimetic remineralization of human dentin, restoring both functional and structural integrity.<sup>16</sup> In accordance with this, Basu (2023)<sup>8</sup> reported that ACTIVA BioACTIVE Restorative outperformed Cention N in clinical performance, maintaining superior marginal adaptation, resisting surface roughness and preserving aesthetics over a six-month follow-up.

Minimal intervention approaches have gained traction alongside these materials. Vishwanathaiah et al. (2025)<sup>10</sup> showed that SmartBurs, composed of polyether ketone (PEKK), selectively removed infected dentin while preserving remineralizable tissue, thereby reducing patient discomfort compared to carbide burs.<sup>10</sup> These findings align with the principles emphasized by Badami and Ahuja (2014)<sup>13</sup>, where tissue preservation is prioritized over aggressive caries excavation, especially in children. Similarly, Mohapatra and Mohandas (2024)<sup>9</sup> highlighted the role of Silver-Modified Atraumatic Restorative Treatment (SMART) in reducing secondary

caries risk and avoiding pulp exposure, further demonstrating how smart techniques complement smart materials in minimally invasive pediatric dentistry.

Glass ionomer cements (GICs) have also been enhanced through smart technology. Khoroushi and Keshani (2013)<sup>17</sup> described smart GICs exhibit coefficient of thermal expansion similar to dentin and maintain marginal integrity under thermal stress, while offering fluoride release and recharge capacity. These properties are especially relevant in pediatric settings, where moisture control is often challenging. Interestingly, in a study by Gupta (2018)<sup>4</sup> the development of resin-modified GICs and giomers has expanded the clinical versatility of these materials, combining fluoride release with improved mechanical properties and esthetics.

Preventive applications of smart materials extend into antimicrobial and remineralizing domains. Yu et al. (2023)<sup>42</sup> reviewed pH-responsive restorative systems that release antimicrobial agents such as chlorhexidine or fluoride in acidic environments created by *Streptococcus mutans*, allowing targeted suppression of cariogenic bacteria while preserving the beneficial oral microbiome. Montoya et al. (2023)<sup>33</sup> discussed smart antimicrobial peptides (AMPs), including pheromone-guided variants, that selectively bind to *S. mutans* cell surfaces, disrupting biofilm formation without affecting commensal flora—an advantage in maintaining microbial balance in the developing pediatric mouth.

Amorphous calcium phosphate (ACP)-containing materials and CPP-ACP sealants have further enriched the preventive toolkit. Azarpazhooh & Limeback (2008)<sup>45</sup> described that ACP serves as a hydroxyapatite precursor that rapidly releases calcium and phosphate in acidic conditions to promote remineralization. CPP stabilization improves ion bioavailability, allowing CPP-ACP products like GC Tooth Mousse Plus® to reverse

early enamel demineralization, making them ideal for post-orthodontic and high-risk pediatric cases. Taşan and Ceran (2024)<sup>46</sup> further reinforced the value of fluoride-releasing pit and fissure sealants, noting their capacity to protect vulnerable occlusal surfaces during the critical years following tooth eruption.

In the endodontic domain, the Smart Seal obturation system demonstrates the application of responsive technology beyond coronal restorations. As reported by Rathi et al. (2023)<sup>7</sup>, its hydrophilic obturation points expand laterally upon moisture absorption, filling canal irregularities more effectively than traditional gutta-percha—an especially valuable feature in the complex root morphology of immature permanent teeth in children.

Emerging research is also exploring smart polymers and nanotechnology-enhanced materials. Vasiliu et al. (2021)<sup>28</sup> and Alluhaidan et al. (2024)<sup>43</sup> highlighted the potential of smart nanoparticles and 3D-printed polymer systems to deliver real-time monitoring capabilities, antimicrobial effects and customized mechanical properties, indicating a future where restorative materials can adapt to both functional demands and microbial threats in real time.

Despite these advances, several limitations remain. Par et al. (2024)<sup>34</sup> emphasized that most current clinical data are based on short- to medium-term follow-up periods, and long-term studies are essential to validate durability, especially under the variable oral hygiene conditions seen in children. Cost factors, technique sensitivity and the need for comprehensive practitioner training are additional hurdles to widespread adoption. Furthermore, while laboratory performance of smart materials is promising, clinical success will ultimately depend on their behavior in vivo under pediatric-specific challenges

such as moisture contamination, patient cooperation and mixed dentition transitions.

### **Conclusion**

Smart materials are emerging as a transformative innovation in pediatric dentistry, offering intelligent and responsive solutions tailored to the unique and evolving needs of the developing dentition. Unlike conventional materials, which are passive and rely solely on mechanical properties, smart materials actively respond to environmental changes such as pH, temperature, moisture or mechanical stress. This dynamic behavior enables improved restorative outcomes, better caries management, and enhanced patient comfort. Conventional materials often require frequent replacement and offer limited biological interaction, whereas smart materials support minimally invasive dentistry by promoting tissue preservation, repair & adaptation. Their multifunctionality fosters a more preventive and biologically driven approach, aligning with modern principles of pediatric care. However, while their clinical promise is substantial, further long-term studies are necessary to establish their safety, durability and cost-effectiveness in children. Increased practitioner awareness, training and integration of evidence-based use are vital for successful adoption. As material science and pediatric dentistry continue to evolve together, smart materials are poised to play a central role in the future of child-focused oral healthcare, advancing beyond the limitations of traditional materials.

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