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Mini Review

Smart Materials in Dentistry: A Paradigm Shift Toward Responsive Dentistry

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Abstract

Dentistry has changed drastically in recent years thanks to the development of smart materials. These are special types of dental materials that can sense changes in their surroundings like temperature, moisture, pressure, or pH and respond accordingly. Due to this, they're often called intelligent or responsive materials. With the help of new technologies like nanotechnology, digital tools, etc., smart materials are now being used in all the specialisations of dentistry. They have improved the quality of treatments by making them more precise, personalised, and long-lasting. This review looks at the evolution of smart materials, their mechanism of action, classification, properties, advantages, disadvantages, and recent advances to highlight their importance in modern dentistry. Smart materials are expected to become a key part of contemporary dentistry, offering better care and outcomes for patients.

Keywords: *Smart materials, dentistry, stimulus, responsive.*

INTRODUCTION

With the rapid advancements in the field of dental materials in the past decades, there has been a rapid development of smart materials in dentistry. These materials are engineered such that they can respond adaptively to the changes in the surrounding environment. In dentistry, smart materials, also called intelligent materials, play an important role. These materials actively interact to the stimuli, such as temperature, moisture, stress, pH, and electric or magnetic fields, and respond to the changes. Hence, they are also called responsive materials.[1] They provide benefits like precise drug dispersal, accelerated osseointegration, and enhanced structural integrity. With the invention of these materials, there has been a marked paradigm shift from passive restoration to active participation in biological regeneration and immune support. [2]

Smart materials now enable unprecedented precision, personalisation, and biological compatibility in restorative and regenerative procedures due to advancements in nanotechnology, biomimetics, and digital fabrication techniques. As a result, smart materials are reshaping areas like implantology, restorative dentistry, and regenerative therapies by engaging in biologically active roles such as tissue regeneration, remineralisation, and host defence.

In this review, we explore the latest advancements in smart dental materials, which collectively suggest that smart materials will soon become the gold standard in modern dental practice.

TIMELINE OF SMART MATERIALS [3-7]

1960's - Clauser first proposed the idea of smart structures in 1968.
1960's-1970's- Development of Nitinol (nickel-titanium alloy) showcasing shape memory effect.
1980's- Piezoelectric devices were first used.
1990's-Rapid growth in the research of smart materials for biomedical use.
2000's-Electrochromic and thermochromic materials gained popularity.
2010's-Self-healing polymers & responsive hydrogels were developed.
2020's 4D Printing & Bioinspired Smart Materials gained usage.

CLASSIFICATION [8-11]

Smart materials in dentistry can be classified as follows:

A. Based on responsiveness

Passive smart materials respond to environmental changes without external control. Examples: Glass ionomer cements, Resin-modified GICs, Compomers.

Active smart materials react selectively and reversibly to stimuli like pH, temperature, and stress. Example: Smart composites, shape-memory alloys, piezoelectric scaffolds

B. Based on the type of stimulus and the behaviour exhibited

Mechanical stimulus leading to piezoelectric response. Example: Barium titanate scaffolds.
Temperature changes cause a shape memory effect. Example: NiTi orthodontic wires, smart toothbrushes.
pH changes release ions for remineralisation or buffering. Example: ACP-releasing sealants, bioactive composites.
Light stimulus causing photochromic colour adaptation. Example: monochromatic composites.
Moisture can cause swelling or contraction. Example: hydrogels, smart impression materials.

C. Based on Clinical Application

Prosthodontics—Smart impression materials for accuracy and hydrophilicity.
Endodontics – NiTi rotary instruments for flexible shaping of the root canals and reduced risk of fracture.
Orthodontics—Shape memory alloys, as they are self-adjusting wires with reduced risk of fracture.
Restorative Dentistry – Smart composites and smart ceramics help in remineralisation and aesthetic adaptation.
Oral surgery—Smart sutures and antimicrobial peptides help in controlled healing and superior infection control.
Paediatric dentistry – Fluoride and ACP-releasing pit and fissure sealants are used to prevent caries.
Periodontics—Smart fibres, particularly hollow-core photonic fibres, deliver high-energy laser pulses for procedures such as tooth ablation and tissue treatment.

MECHANISM OF ACTION [12-16]

The mechanism of action of smart dental materials depends upon the type of stimulus they are engineered to detect and respond to.

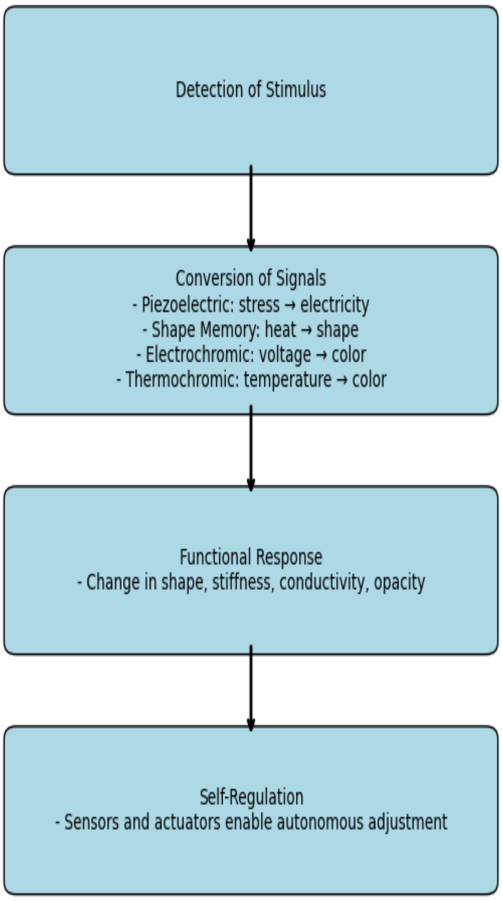

Table 1. Flow chart of mechanism of action of smart dental materials.

Detection of stimulus – Changes in the surroundings such as temperature, pH, light, magnetic fields, or mechanical stress are detected.

Conversion of signals: The detected changes are converted into physical, chemical or electrical signals by an internal component. For example, piezoelectric materials convert mechanical stress to electrical signals, shape memory alloys revert to their original shape on heating, electrochromic materials change their colour or transparency in response to electrical voltage, and thermochromic materials change their colour in response to a change in temperature.

Functional response: The material alters its behaviour, like a change in shape, stiffness, conductivity or opacity, in an efficient and reversible manner.

Self-regulation: These materials have sensors and actuators that help them interact, adjust and function optimally without any external guidance**.**

PROPERTIES OF SMART DENTAL MATERIALS [17-28]

Smart dental material possesses the unique ability to respond dynamically to environmental stimuli due to its properties.

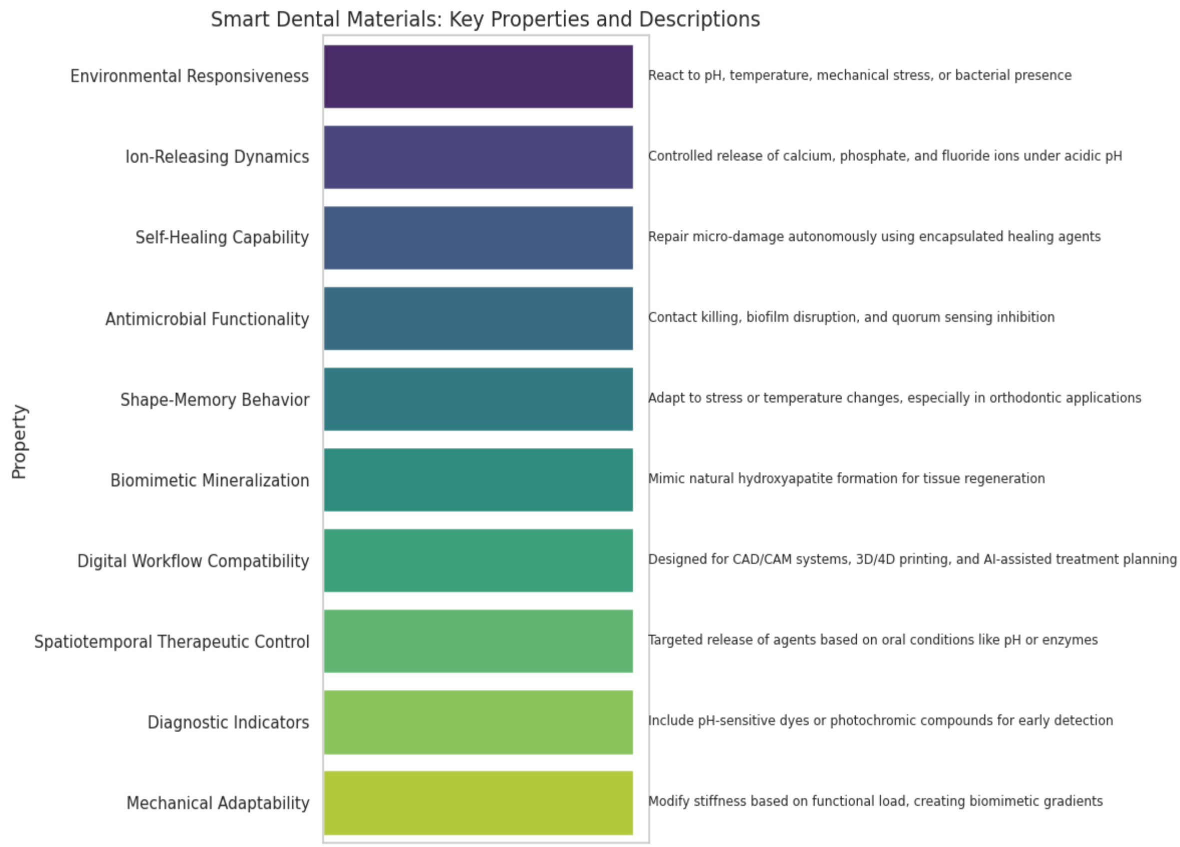

Table 2. Properties of smart dental materials**.**

Environmental responsiveness: This property enables smart dental materials to dynamically interact with the changes in the oral environment, such as pH, mechanical stress, temperature, etc., to improve the durability and biocompatibility. This results in prevention of secondary caries and tissue regeneration, thus providing effective, minimally invasive, and personalised dental care.

Ion releasing dynamics: Controlled release of therapeutic ions such as fluoride (F^-), calcium (Ca^{2+}), phosphate (PO_4^{3-}), and hydroxyl (OH^-) ions in response to oral environmental stimuli—most notably pH changes. These dynamics are critical to the materials' ability to promote tooth remineralisation, inhibit caries development, neutralise acids, and support overall oral health.

Self-healing capability: It is the intrinsic ability to autonomously repair microcracks or damage that occur during or after placement in the oral cavity using encapsulated healing agents, thereby extending the lifespan and effectiveness of dental restorations.

Antimicrobial functionality: It refers to the ability to inhibit or reduce the growth of harmful oral bacteria and biofilms, thereby preventing dental infections, secondary caries, and periodontal disease. This is due to mechanisms like contact killing, biofilm disruption and quantum sensing inhibition.

Shape memory behaviour: Shape memory alloys (SMAs), like nickel-titanium, have a unique ability to undergo deformation in response to a stimulus that is generally stress and temperature and then return to their original, pre-deformed shape. This property is used in orthodontics for teeth alignment.

Biomimetic mineralisation: It is the process of mimicking natural biological mineralisation mechanisms to restore or regenerate dental hard tissues like enamel and dentin to improve durability, integration, and resistance to decay of the tooth.

Digital workflow compatibility: These materials integrate with digital technologies used in modern dentistry, such as intraoral scanning, CAD/CAM design, and 3D printing, rendering seamless data transfer, precise manufacturing, and efficient clinical workflows from diagnosis through treatment.

Spatiotemporal therapeutic control: This property helps in the precise and sophisticated regulation of the delivery and activation of therapeutic agents with both spatial and temporal specificity within the oral environment. It aims to provide personalised, effective, and minimally invasive dental treatment.

Diagnostic indicators: It is the property that allows these materials to detect, signal, or provide information about the condition of the tooth or oral environment, often facilitating early diagnosis and intervention. They enhance preventive and minimally invasive dentistry by providing early warnings of pathological changes, reducing unnecessary tissue removal, and improving patient outcomes through timely intervention.

Mechanical adaptability: It is their ability to dynamically adjust their mechanical properties, such as stiffness, elasticity, or flexibility, in response to changing conditions in the oral environment.

ADVANTAGES OF SMART MATERIALS [15, 16, 29, 30]

Adaptive behaviour: These materials respond to external stimuli and bring about desired changes to improve the efficiency of the procedure and reduce the chairside time by enhancing the properties of a material. Example: shape memory NITI wires.

Enhanced therapeutic function: They support remineralisation by release of fluorides, targeted drug delivery, tissue healing, etc., without invasive intervention. They work at a localised site, thus reducing the need for systemic medications. Example: pH-sensitive composites releasing antimicrobial agents

Improved mechanical properties: They exhibit good mechanical properties like resistance to fatigue, wear and fracture. Furthermore, these materials have excellent self-healing properties. Hence, these materials prolong the life of the restoration. Example: Fatigue-resistant rotary files with smart flexibility.

Bioactivity & hygiene optimisation: They interact with saliva and tissues to provide a biologically supportive microenvironment that helps in reducing the risk of secondary infections and improves mucosal compatibility. Example: antimicrobial sealants and fluoride-releasing varnishes.

Geriatric-friendly: They are great to use for geriatric patients, as the denture liners provide superior cushioning, flexibility and adhesion. Example: Cushioning liners.

Digital workflow integration: These materials integrate with CAD/CAM workflow that improves the predictability and personalisation of the prosthesis. Example: 3D-printed smart crowns customised to patient anatomy.

Long-term performance & durability: These materials are minimally invasive in nature and provide long-term performance that helps promote the preservation of healthy tooth structures.

DISADVANTAGES [31-35]

Cost and Accessibility: Since these materials require advanced fabrication techniques, rendering them more expensive than conventional materials.

Technique sensitive: These materials require specific conditions for handling. Skill and training for the operator are critical for effective management of these materials.

Limited clinical evidence: Since these materials are still in the experimental stage, long-term data is required to establish their efficacy, safety and durability.

Structural deterioration: Over usage of this material for an extended period can lead to material fatigue and degradation, leading to loss of smart function.

RECENT ADVANCES [36-39]

Recent advances in smart dental materials have led to the development of highly responsive systems.

- Smart composites, glass ionomer cements, and thermochromic sealants sense changes in pH, temperature, moisture, and stress to adapt for better treatment outcomes and longevity.
- Bioactive and regenerative composites release calcium, phosphate and fluoride ions to promote remineralisation and tissue regeneration.
- Antibacterial nanocomposites prevent the formation of biofilm, thereby reducing the risk of caries.
- Nanotechnology-based systems like nano sensors and smart dental probes detect early signs of decay or chemical changes in enamel. Nanoparticles such as nano-hydroxyapatite, nano-silica, and graphene reinforce the restorative materials, thereby improving their mechanical strength, wear resistance, and surface polishability.
- CAD/CAM-compatible smart composites, 3D/4D printable smart polymers, digital impression-compatible smart ceramics, sensor-integrated smart materials, and bioactive CAD/CAM blocks are the smart materials used in digital dentistry.
- Self-Healing Dental Materials – Acrylate-based composites and Strontium fluor aluminosilicate systems are some of the self-healing smart dental materials that are designed to repair any kind of structural damage without external intervention.
- Magnetically responsive smart materials respond to magnetic fields to bring about desired action. For example, neodymium-iron-boron magnets are used to secure prostheses; cobalt-samarium alloys are used in orthodontics to assist in tooth movement without wires; and magnetic scaffolds promote stem cell differentiation.
- Electrically responsive smart materials respond to electrical stimuli. Example Piezoelectric ceramics generate electric signals under mechanical stress to monitor bite forces; electroactive polymers change stiffness or vibration in response to electrical input for canal shaping; cement-based piezoelectric composites. These materials mimic the behaviour of enamel and dentin when responding to chewing forces.

CONCLUSION

Smart dental materials have greatly modernised dentistry, paving the way for a new era of adaptive, multifunctional, and patient-specific treatments. Advancements in technology have led to the development of superior dental materials and tools that outperform traditional materials in terms of biocompatibility, mechanical strength, and clinical functionality. Overall, the dynamic field of smart dental materials is ever-growing and promising. It has shifted the entire focus towards more adaptive, robust, and patient-centric dental care. In this ever-changing field of dentistry, it becomes essential to upgrade technology that can help in newer innovations and foster interdisciplinary research. This will contribute to achieving the ultimate goal of enhancing oral health and improving the quality of life for patients worldwide.

Author contributions:

Eram Perwez- Concept, Design, Definition of intellectual content, Literature search, Manuscript preparation.
Shabina Sachdeva-Literature search, Manuscript editing, Manuscript review.
Uzair Rehman- -Literature search, Manuscript review.

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