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Review Article

Smart Materials and Smart Practice of Dentistry - A Review

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Abstract

The future pathways of dentistry will be greatly influenced by the development, evolution and integration of smart dental materials which have the capability to respond to diverse physiological and environmental stimuli which are present or develop in the oral cavity. Unlike conventional inert restorative materials, the smart ones can intelligently sense stimuli such as pH changes, mechanical stress, temperature changes, magnetic or electrical fields, moisture or bacterial activity and react in a manner which is beneficial to the individual who receives restorative treatment in the context of diagnostics and treatment. Smart materials can release fluoride, calcium, phosphate, or antimicrobial agents in response to cariogenic conditions and enhance remineralization and thereby reducing the possibilities of secondary caries. Shape memory alloys and smart polymers can generate controlled and adaptive responses which can bring in tremendous advancements in prosthodontic and orthodontic treatment. In regenerative dentistry, bioactive and biomimetic smart materials may support tissue engineering, pulp regeneration, and faster healing of oral tissues. Incorporation of nanotechnology, artificial intelligence and digital dentistry with smart biomaterials may further enable self-healing restorations, real-time monitoring of oral health and highly personalized treatment approaches. Research advancements will prove that dentistry is no more a reparative discipline but a predictive, preventive, regenerative clinical science which can improve the quality of life in the future days to come.

Keywords: Smart Materials; Dental Restorative Materials; Drug Delivery Vehicles; Nano Composites; Hydrogels; Shape Memory Alloys; Nickel Titanium Alloys; Nanoparticles of Amorphous Calcium Phosphate (NACP)

Introduction

Smart materials have become an integral part of modern life because of their ability to respond intelligently to changes in the surrounding environment. These materials can sense external stimuli such as temperature, stress, light, moisture, electric field, magnetic field, or pH and respond in a predictable and controlled manner by altering one or more of their properties.

A simple everyday example is that of a person who dislikes very hot coffee. Without touching the mug, the temperature can be estimated if a smart mug containing thermochromic pigments is used. These pigments change colour at specific temperatures, thereby providing a visual indication of heat. Similarly, smart windows coated with vanadium dioxide can regulate indoor temperature by controlling the transmission of heat and light, thereby improving energy efficiency during summer.

Photochromic lenses used in eyeglasses become dark in bright sunlight and return to a clear state indoors (Figure 1). Shape memory alloys such as nickel–titanium (NiTi), widely used in orthodontics, exhibit another remarkable smart behaviour. Orthodontic NiTi wires are manipulated and fixed to brackets in the softer martensitic phase at lower temperatures. At oral temperature, the alloy transforms into the austenitic phase and regains its original arch form, thereby exerting a continuous gentle force on teeth (Figure 2). This phenomenon is known as the shape memory effect. In other words, on heating the NiTi wire shrinks or shortens.

Figure 1: Photochromic lenses become dark against sun light.

https://us.jins.com/pages/photochromic-lenses?srsltid=

Figure 2: Nitinol arch wire which has shape memory.

https://www.xotmetals.com/blog/nitinol-archwire-in-orthodontic-treatment/

Hydrogels are another important group of smart materials. These materials absorb or release water in response to environmental conditions and are widely used in disposable hygiene products, contact lenses, drug delivery systems, and wound dressings (Figure 3). Phosphorescent pigments absorb light energy and release it slowly over time, allowing them to glow in darkness. Such materials are commonly used in road signs and emergency indicators, thereby improving safety during night travel.

Figure 3: Hydrogel wound dressing.

https://www.polarseal.net/blog/closer-look-at-hydrogels/

Smart fabrics can modify their properties in response to temperature or moisture changes. Certain fabrics increase pore size during sweating, thereby improving ventilation and comfort for the wearer. Thus, smart materials are encountered in various aspects of daily life and have become increasingly indispensable in modern technology and healthcare. This review explores the science of smart materials and analyses the related definitions [1].

Smart materials are defined as stimuli-responsive materials that react to external stimuli in a stable, reproducible, and controlled manner with noticeable changes in one or more physicochemical properties. In many cases, the response is reversible, allowing the material to function both as a sensor and an actuator [2].

Smart materials are classified into energy exchanging and property changing materials.

Energy exchanging materials

These materials convert one form of energy into another or in other words they act as energy converters. Piezoelectric materials generate electrical signals when subjected to mechanical stress and are commonly used as sensors. Photovoltaic materials, which convert light energy into electricity, are another example and are widely used in solar panels.

Property-changing materials undergo alterations in physical characteristics such as shape, colour, or viscosity without direct energy conversion. Shape memory alloys such as Nitinol can be deformed and later return to their original configuration upon heating. Photochromic materials that reversibly change between clear and dark shades in response to light also belong to this category.

Smart materials can be polymers, crystals, ceramics, metals, or composites. Polymers, gels, and liquid crystals are often referred to as soft smart materials because of their flexibility and responsiveness. Liquid-crystalline physical gels represent an important subgroup with significant biomedical applications [3].

Smart materials in dentistry

Smart dental materials indicate a radical shift in the concept and practice of dentistry. Traditionally dental materials were considered as passive and they just filled the specifically designed cavities of the teeth. If the material is passive it cannot respond to the oral environment characterized by temperature variations, pH changes and application of stress. The need for smart materials arose in this context. The identified characteristics of smartness can be further elaborated as follows: Stimulus responsiveness, self repair or remineralization capability, adaptability to oral environment, reversibility of response, biocompatibility and bioactivity.

pH responsive materials respond to changes in oral pH that can occur during cariogenic challenges. Glass ionomer cements (GIC) can release fluoride ions in response to the pH fall which happens during cariogenic activity. Fluoride ions help in remineralization and caries prevention. GIC is also capable of getting recharged when exposed to fluoride sources like mouth washes, tooth pastes and topically applied gels. In fact, GIC acts as a long term reservoir of fluoride and helps in preventing secondary caries [4,5].

Smart composite dental materials can sense and react to environmental stimuli such as pH or temperature changes and stress. These resins have clinical longevity, remineralization capability and can-do self-healing. They are capable of releasing Amorphous Calcium Phosphate (ACP) in response to pH <5.8. Fluoride ions are also released which can demineralize tooth structure. Self healing capability is obtained for these resins by incorporating resin filled micro capsule system which can release healing agents when micro cracks are developed. Another modification is monochromatic composites which can blend with the shade of the surrounding tooth structure. Resin modified glass ionomers show thermal responsiveness and fluoride recharge capability [6,7].

Thermo-responsive smart materials include alloys, polymers and hydrogels. Nickel-Titanium alloys are used in orthodontic treatment. When they are placed in the oral cavity as part of an appliance, the oral temperature makes them achieve a predefined shape thereby applying a constant force on teeth causing realignment. Nickel-Titanium alloys are used in root canal instruments which have high flexibility and super elasticity. Managing curved canals without permanent deformation is possible with NiTi instruments. The alloy is composed of 55% Nickel and 45% Titanium. On comparison NiTi instruments are two to three times more flexible than their stainless steel counterparts. NiTi instruments offer superior fatigue resistance, thereby avoiding fracture during the operations [8]. Thermo responsive hydrogels (Ex. Pluronic F 127) are in the sol state at the room temperature and in the oral temperature they get converted to gel form. They are used for sustained drug delivery system and serve as tissue engineering scaffolds [9].

Bioactive smart dental materials: are advanced restorative materials which are capable of promoting healing, regeneration and remineralization. In response to stimuli, they can release calcium, phosphate and fluoride ions to repair enamel and dentine. Some of the materials incorporate silver nano particles or antimicrobial peptides with a specific intention to reduce biofilm formation and secondary caries. Bioactive composites are highly durable because of the incorporation of rubberized component and glass ionomer fillers. Bio active materials provide restorative care and provides sealing against bacterial infiltration. They are also employed as sealants to prevent demineralization of enamel. In endodontics, bioactive cements are used for pulp capping and root perforation repair [10,11].

Smart ceramics in dentistry belong to an advanced class of biomaterials which represent a transformative shift from passive inert materials to active systems that can interact with the oral environment and can exhibit properties of bio activity, ion release, self-healing potential and mechanical adaptability. More than replacing the lost tooth structure, they can interact beneficially with surrounding tissues. Bio active glass ceramics and resin modified ceramics respond to external stimuli such as stress, temperature, pH changes and moisture. They can release essential ions such as calcium, phosphate, and fluoride and can promote the remineralization of surrounding tooth structure and effectively prevent secondary cavities. Smart ceramics obtain a therapeutic profile when they contribute to long term health and stability of the biological environment.

Zirconia based ceramics are considered as smart because of its property of transformation toughening mechanism which induces a phase transformation from tetragonal to monoclinic structure, leading to an expansion in volume and can resist crack propagation (smart mechanical behaviour). Zirconia gets significant fracture resistance (1000-2000N) and makes it fit for fixed prosthesis and to serve as implant abutments.

Piezoelectric properties are exhibited by certain ceramics – generating electrical charges against mechanical stress. These materials can stimulate bone and enhance osseointegration. Though in the experimental stage at present, they hold great promise for the future in the field of dental implantology.

Lithium disilicate and other glass ceramics can release ions like fluoride and calcium. They are having translucency and offer better aesthetics. Glass ceramics have remineralisation potential also. Lithium disilicate is commonly used in veneers, inlays and crowns. The material gets strength because of the crystalline phases present in it.

Self healing ceramics can repair microcracks through encapsulated healing agents, phase transformations and crack bridging mechanisms. Encapsulated healing agents in self-healing ceramics are typically liquid monomers or resin agents contained within microcapsules that when released by a crack, polymerize to bond and the crack is closed. Common encapsulated agents include epoxy resins, dicyclopentadiene (DCPD), or solvents designed to trigger healing.

Bioactive ceramics like hydroxy apatite and bioactive glass can bind chemically with dental tissues and bone. They are used in pulp capping, dental implant coatings and as bone grafts. In Prosthodontics, introduction of Zirconia made it possible to make fracture resistant prosthesis. Glass ceramics improves aesthetics and bioactive ceramics enhance implant integration. The advantages are longevity, strength, prevention of dental caries and improved interactions with oral tissues. Technique sensitivity, high cost and limited long term clinical data are some of the areas which requires updating [12-16].

Smart materials in endodontic practice: are capable of responding to environmental stimuli like temperature, stress and pH. Specifically, they exhibit shape memory, super elasticity and bioactivity. They mimic biological tissues, improve sealing, resist and reduce microbial load and promote tissue regeneration.

Nickel-Titanium rotary files are known for their smartness due to shape memory and super elasticity. Curved canals are efficiently negotiated and avoids errors like ledge formation and transportation (removal of dentin from the outer curve of root canal) (Figure 4). Recent introductions are M wire and CM wire. CM Wire is primarily in the martensite phase with superior flexibility while M wire contains mix of martensite, R-Phase and Austenite. These are manufactured through specific thermos mechanical process. Their flexibility reduces possible fracture of the instruments.

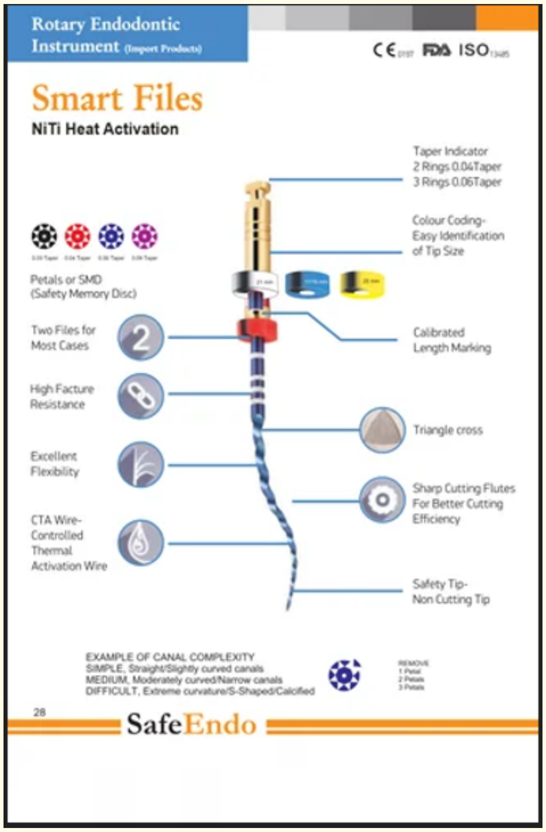

Figure 4: Smart rotary endo files.

https://www.indiamart.com/proddetail/safe-endo-smart-file-2859067642530.html

Self adjusting file system conforms to the canal anatomy and simultaneously provide irrigation and shaping. Smart burs are polymer based which can selectively remove infected dentin and preserve healthy tissue. On confronting healthy hard dentin, the bur gets softened or inactive, thereby preventing iatrogenic damage (Figure 5).

Smart bioceramic sealers exhibit bioactivity and gets converted to hydroxy apatite on setting. They are biocompatible and provides excellent sealing because they can respond to the moisture present in the dentinal tubules, further enhancing adaptation. As mentioned in other sections, Glass ionomer can release ions, gets recharged by the ions from external source, can respond to pH changes, can help in remineralisation and has a potential antibacterial action. Amorphous Calcium Phosphate materials also have remineralisation potential because of the calcium and phosphate ions released in acidic environment. Smart irrigants containing nanoparticles have antimicrobial properties, targeted bacterial elimination and demonstrate penetration into dentinal tubules.

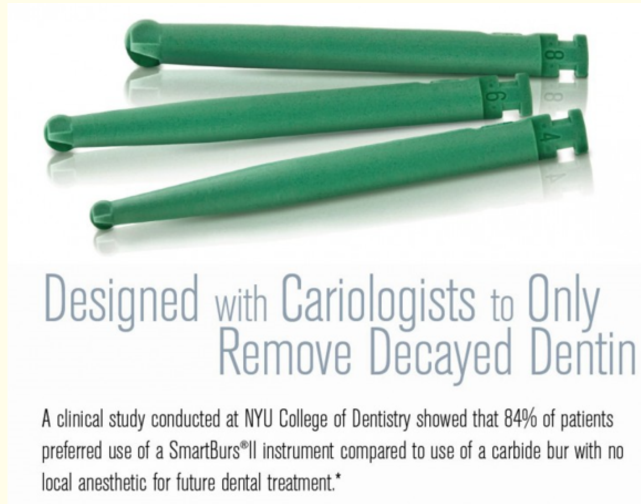

Figure 5: Smart bur selectively removes infected dentine.

https://dentistree.com/shop/home/37-smartburs-ii.html

Careful integration of smart instruments and materials in endodontics helps in the preservation of tooth structure, efficient shaping and cleaning of the root canal and enhanced sealing and regeneration. Duration of the treatment gets considerably reduced and the operator fatigue comes down because of the incorporation of smart instruments and materials. Future is very bright in the context of emerging technologies like nanorobotics in canal disinfection, stimuli responsive drug delivery system and self-healing materials. Integration of nanotechnology, tissue engineering and regenerative medicine will definitely add newer dimensions in clinical dentistry [17-20].

Smart materials and instruments in prosthodontics

Smart technologies have upgraded the status of Prosthodontics from a reactive discipline to a proactive (controlling a situation by making things happen rather than waiting for things to happen and then reacting to them) one. These materials can sense the changes that can happen in the environment of stimuli and responds in a controlled, predictable and reversible manner and enhances the clinical performance. Smart materials are capable of combating denture stomatitis and periimplantitis through their antimicrobial and antibiofilm action. Bioactive glass ceramics increase pH and control pathogens and PMMA dentures incorporated with silver nano particles can reduce streptococcus mutans and candida albicans. Smart coatings of dental implants ensure osseointegration through the release of calcium and phosphate ions.

Smartness introduced to the field of impressions has brought in remarkable changes. Poly vinyl siloxane (PVS) impression materials have been considered as gold standard but presently digital scanners provide better standards. Digital impressions show a deviation of 25µm whereas PVS impressions show a deviation up to 45µm. Digital impression is a 12 minute long process and impression with tray takes 20 minutes or more. Difficulties with breathing and gag reflex is not experienced by the patients with digital scanners [21,22].

Areas that influence and improve the practice of prosthodontics are printed prostheses which can adapt well in the mouth in response to temperature change and water; shape memory NiTi alloys and smart sutures made up of biodegradable thermoplastics which can get tightened when exposed to body temperature [23] (Figure 6).

Figure 6: Printed ceramic implants.

https://3dadept.com/lithoz-and-dr-jens-tartsch-partner-to-improve-the-production-of-3d-printed-dental-ceramics-implants/

Smart materials and instruments significantly upgrade prosthodontic treatment by introducing responsiveness, bioactivity, and adaptability into restorative systems. They enhance treatment precision, improve biological integration, and extend the lifespan of prostheses. As research advances, their integration with digital and nanotechnologies is expected to further revolutionize prosthodontic care [11,24,25].

Discussion and Conclusions

The term "smart materials" first appeared in the scientific literature during the 1980s. However, the emergence of the field was not accidental, as several products exhibiting smart behaviour, such as photochromic glasses and NiTi-based shape memory alloys, had already been in use since the 1960s. Since smart materials represent a relatively new and rapidly evolving area, a universally accepted definition has not yet been established. The National Aeronautics and Space Administration (NASA) defined smart materials as "materials that can remember different forms and reconcile with particular stimuli," or as "highly engineered materials capable of responding intelligently to environmental changes." Other researchers have described them as materials capable of regaining their original shape when exposed to external stimuli and producing a controllable smart response [26,27].

The Encyclopedia of Chemical Technology defines smart materials and structures as "objects that sense environmental events, process the sensory information, and subsequently act on the environment" [28]. Although the concept emerged several decades ago, significant scientific interest has developed only during the last decade due to advances in nanotechnology, biomaterials, tissue engineering, and regenerative sciences.

Several smart materials are currently in widespread use, including shape memory alloys and polymers, hydrogels, magnetorheological and electrorheological fluids, and self-healing materials. Among these, shape memory alloys such as Nitinol (nickel–titanium alloys) have contributed considerably to both medical and dental applications because of their superelasticity, corrosion resistance, and shape memory characteristics [29].

Globally, nearly 3.69 billion individuals are affected by major oral diseases such as untreated dental caries, severe periodontitis, edentulism, and associated conditions. Preventive measures including fluoride varnish applications and oral health education impose a substantial economic burden on healthcare systems [30,31]. Conventional restorative materials frequently fail to provide long-term success because of the highly dynamic and hostile oral environment characterized by thermal fluctuations, moisture, masticatory stress, pH alterations, and microbial activity. Traditionally, restorative materials were primarily expected to restore masticatory function and aesthetics while maintaining acceptable mechanical properties, adhesion, and biocompatibility. However, modern restorative dentistry increasingly demands materials with antibacterial, remineralizing, regenerative, and drug-delivery capabilities. Smart restorative materials capable of responding to environmental stimuli such as pH and temperature changes are therefore becoming highly relevant in contemporary dental practice [30,31].

Despite their clinical advantages, conventional restorative materials may produce adverse biological reactions. Residual monomer released from polymethyl methacrylate (PMMA) can induce allergic mucositis, burning sensation, and xerostomia. Nickel–titanium alloys may release nickel ions capable of triggering hypersensitivity reactions. Excessive fluoride exposure may cause mucosal irritation and dental fluorosis, while silicone-based materials have occasionally been associated with contact dermatitis [32,33]. These limitations emphasize the importance of developing biologically responsive smart materials with improved safety and compatibility profiles.

The oral cavity represents one of the most complex microbial ecosystems in the human body. Disturbance of the microbial balance can result in dental caries, periodontitis, peri-implantitis, and pulpal diseases. Secondary caries remains one of the most common causes of restoration failure, particularly at the tooth–restoration interface where bacterial colonization and biofilm formation frequently occur. Consequently, restorative materials with long-term antimicrobial and antibiofilm activity are highly desirable. Natural products such as tea polyphenols and curcumin have demonstrated promising effects in reducing bacterial adhesion and inhibiting extracellular polysaccharide synthesis associated with cariogenic biofilms [34,35]. Integration of such bioactive agents into restorative systems may significantly improve the biological environment of the oral cavity.

D.F. Williams, a pioneer in biomaterials science, defined biocompatibility as "the ability of a material to perform with an appropriate host response in a specific application" [36]. He further emphasized that biocompatibility is not an intrinsic property of a material but rather a context-dependent phenomenon influenced by the host environment and intended application. This concept transformed the understanding of biomaterials from passive inert substances to dynamic interactive systems. Smart dental materials align closely with this modern concept because they are bioactive and capable of sensing and responding to changes within the oral environment rather than functioning merely as passive restorative agents.

Sun., *et al*. classified smart dental restorative materials into seven major categories: nanocomposite materials, hydrogel-based materials, biomaterials, chemical materials, composite resins, smart carrier systems, and ceramic-based restorative materials [37]. Among these, nanomaterials have gained considerable importance in restorative dentistry. Bio nanocomposites containing pH-responsive nanoparticles can resist microbial adhesion and cariogenic biofilm formation. Nanotechnology has also enhanced the self-healing potential of restorative materials and bonding agents by promoting repair at the dentin–restoration interface, thereby reducing microleakage and increasing restoration longevity. In addition, chlorhexidine has been modified into pH-responsive systems that release the antimicrobial agent selectively in acidic cariogenic environments. Silver–metronidazole nanocomposites containing nano-hydroxyapatite have also been investigated as reinforcing fillers for periodontal disinfection systems [37].

Hydrogels constitute another important category of smart dental materials. They may be derived from natural sources such as polysaccharides and fibrous proteins or synthesized through cross-linking of polymers including polyacrylic acid derivatives. Hydrogels possess the ability to mimic natural tissues and therefore show considerable potential in tissue engineering and local drug delivery applications. In dentistry, hydrogels are being investigated for pulp regeneration, periodontal tissue repair, wound healing, and caries management through incorporation of antibacterial and remineralizing agents. Their responsiveness to pH, temperature, and light further enhances their smart behaviour [38,39]. Moreover, their biocompatibility and biodegradability make them suitable for long-term therapeutic applications. However, limited mechanical strength restricts their use in load-bearing areas.

Dental materials are therefore undergoing a major transformation from passive restorative fillers to multifunctional intelligent systems capable of antimicrobial activity, self-healing, regeneration, and remineralization. Future developments in smart dental materials are likely to involve advanced integration of nanotechnology, hydrogels, biosensors, and microencapsulation systems. Smart dental implants may eventually incorporate embedded sensors capable of monitoring occlusal stress, inflammatory changes, and microbial activity in real time. Such developments could substantially improve diagnosis, treatment outcomes, and long-term prognosis in dentistry.

India also possesses significant potential in the field of smart material research. According to a bibliometric analysis published in 2023, India ranked fourth globally in smart materials research output after China, the United States, and Germany, with major contributions from the Indian Institutes of Technology [40]. Continued interdisciplinary collaboration among material scientists, engineers, and dental researchers may enable substantial advancements in smart dental materials and their clinical applications in the coming decades. Overall, smart dental materials represent a major paradigm shift in restorative and regenerative dentistry. Their ability to interact dynamically with the oral environment offers significant advantages over conventional materials. Although several challenges related to long-term clinical performance, cost-effectiveness, and biological safety remain to be addressed, ongoing research indicates that smart materials are likely to play a transformative role in the future of dental treatment.

Conflict of Interest

The authors declare that they do not have any conflict of interest.

Author Contributions

Conceptualization-K. Chandrasekharan Nair, Review of articles-Pradeep Dathan; Viswanath Gurumurthy, T. Mohan kumar, Initial draft preparation: Hemalatha Konka, Viswanath Gurumurthy, Pradeep Dathan, Review and editing- K. Chandrasekharan Nair, Supervision-K. Chandrasekharan Nair.

All the authors have read and agreed to the published version of the manuscript.

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Bibliography

1. https://www.designtechguide.com/materials/examples-of-smart-materials-and-their-uses
2. Yin Y and Rogers JA. “Introduction: Smart Materials”. *Chemical Reviews* 122.5 (2022): 4885-4886.
3. Kato T., *et al*. “Liquid-crystalline physical gels”. *Chemical Society Reviews* 36.12 (2007): 1857-1867.
4. Nicholson J N., *et al*. “Fluoride exchange by glass-ionomer dental cements and its clinical effects: a review”. *Biomaterial Investigations in Dentistry* 10 (2023): 2244982.
5. Farahnaz Arbabzadeh-Zavareh., *et al*. *Dental Research* 9 (2012): 139-145.
6. Chaudhary., *et al*. “Smart composites — The new era in smart dentistry”. *Archives of Dental Research* 12.2 (2022): 69-75.
7. Artemis Kontiza Ioannis A Kartsonakis. “Smart Composite Materials with Self-Healing Properties: A Review on Design and Applications”. *Polymers* 16.15 (2024): 2115.
8. Asha K., *et al*. “NiTi rotary system in endodontics - An overview”. *IP Indian Journal of Conservative and Endodontics* 8 (2023): 128-133.
9. Keunhyuk Ryu., *et al*. “Thermoresponsive Hydrogels for the Construction of Smart Windows, Sensors, and Actuators”. *Material Research* 6 (2025): 379-392.
10. Olivia Lili Zhang., *et al*. “Bioactive Materials for Caries Management: A Literature Review”. *Dental Journal (Basel)* 11 (2023): 59.
11. Sethumadhavan J., *et al*. “Smart Biomaterials Shaping the Future of Dentistry: A Comprehensive Review”. *Cureus* 18 (2026): e101904.
12. Kan Yu., *et al*. “Smart Dental Materials Intelligently Responding to Oral pH to Combat Caries: A Literature Review”. *Polymers* 15 (2023): 2611.

13. Shetty P., *et al*. "Smart biomaterials shaping the future of dentistry: a comprehensive review". *Journal of Functional Biomaterials* 16.2 (2025): 85-101.

14. Zhang Y and Lawn BR. "Advances and challenges in zirconia-based materials for dental applications". *Advances in Ceram Material* 3.1 (2024): 12-29.

15. Jones JR. "Bioactive glass-ceramics: an essential biomaterial for dental restoration". *Research and Reviews: Journal of Dental Sciences* 7.3 (2019): 45-52.

16. Fasbinder DJ and Dennison JB. "State-of-the-art zirconia and glass-ceramic materials in restorative dentistry". *Applied Science (Basel)* 15.23 (2025): 12841.

17. Ved M., *et al*. "The impact of smart materials in restorative dentistry and endodontics: from innovation to application". *Cureus* 17.4 (2025): e82858.

18. Aggarwal T., *et al*. "Smart materials in endodontics". *International Journal of Applied Dental Sciences* 8.2 (2022): 524-529.

19. Zanza A., *et al*. "Nickel-titanium rotary instruments: mechanical and metallurgical characteristics". *Clinical Practice* 12.1 (2022): 94-96.

20. Maloo LM., *et al*. "Smart materials leading to restorative dentistry: an overview". *Cureus* 14.10 (2022): e30789.

21. Aftab Ahmed Khan. "Self-healing dental biomaterials: bioinspired pathways to sustainable dentistry". *Biomaterial Investigations in Dentistry* 12 (2025): 45229.

22. Amer Oussama Kanj and Abd El Hadi Usama Kanj. "Comparative Evaluation of Dimensional Accuracy Between Digital And Conventional Impression Techniques For Parallel Endosseous Dental Implants". *International Journal of Computational and Experimental Science and Engineering* 11.2 (2025).

23. Vasluianu RI., *et al*. "Innovative Smart Materials in Restorative Dentistry". *Journal of Functional Biomaterials* 16 (2025): 318.

24. Subramanian P., *et al*. "Smart material for smarter dentistry". *Journal of Pharmacy and Bioallied Sciences* 16.1 (2024): S17-S19.

25. Hamdy TM. "Highlights in contemporary smart dental materials: a review". *Current Oral Health Report* 10 (2023): 254-262.

26. Bogue R. "Smart materials: A review of capabilities and applications". *Assem Autom* 34 (2014): 16-22.

27. Addington DM and Schodek DL. Smart Materials and New Technologies: For the Architecture and Design Professions; Architectural Press: Amsterdam, The Netherlands; Boston, MA, USA (2005).

28. Pfenning A. "Encyclopedia of Chemical Technology". Vol. 4, 4th Edition. VonM. Howe-Grant (Ed.), John Wiley & Sons, New York (1992): 1117 S., zahlr. Abb. und Tab., £ 150.00. Chem. Ing. Tech. 65 (1993): 1381.

29. Copaci D., *et al*. "SMA Based Elbow Exoskeleton for Rehabilitation Therapy and Patient Evaluation". *IEEE Access* 7 (2019): 31473-31484.

30. E Bernabe., *et al*. "Trends in the global, regional, and national burden of oral conditions from 1990 to 2021: a systematic analysis for the global burden of disease study 2021". *Lancet* 405.10482 (2025): 897-910.

31. L Tang., *et al*. "Cost-effectiveness and cost-benefit analyses of fluoride varnish for caries prevention in Guangxi, China". *BMC Oral Health* 24 (2024): 534.

32. G Smidt., *et al*. "In vitro analysis of monomer leaching in modern dental materials: Cad milled, printed, traditional heat-processed, and auto-polymerizing denture base resins". *Journal of Prosthodontics* (2024).

33. F Di Spirito., *et al*. "Oral and extra-oral manifestations of hypersensitivity reactions in orthodontics: A comprehensive review". *Journal of Functional Biomaterials* 15 (2024): 175.

34. Y Chi., *et al*. "Natural products from traditional medicine as promising agents targeting at different stages of oral biofilm development". *Frontiers in Microbiology* 13 (2022): 955459.

35. Chandrasekharan Nair K., *et al*. "Relevance of Oral Microbiome - A Narrative Review". *Acta Scientific Dental Sciences* 10.2 (2026): 27-35.

36. DF Williams. "On the mechanisms of biocompatibility". *Biomaterials* 29.20 (2008) 2941-2953.

37. Sun J., *et al*. "Smart biomaterials in restorative dentistry: Recent advances and future perspectives". *Materials Today Bio* 35 (2025): 102349.

38. T Singh and R Singhal. "Poly (acrylic acid/acrylamide/sodium humate) super-absorbent hydrogels for metal ion/dye adsorption: Effect of sodium humate concentration". *Journal of Applied Polymer Science* 125.2 (2012): 1267-1283.

39. H Elnawam., *et al*. "Bovine pulp extracellular matrix hydrogel for regenerative endodontic applications: in vitro characterization and in vivo analysis in a necrotic tooth model". *Head Face Medicine* 20.1 (2024): 61.

40. Petras CU RM., *et al*. "Mapping Smart Materials' Literature: An Insight between 1990 and 2022". *Sustainability* 15 (2023): 15143.