

## Smart dental implants in modern Dentistry: A comprehensive review

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### Abstract

Smart dental implants (SDIs) are transforming the field of oral healthcare by integrating advanced materials, sensors, and energy harvesting technology. These smart, innovative implants overcome key challenges like implant failure and peri-implantitis through antimicrobial materials, built-in photo-biomodulation therapy, and real-time health monitoring. The piezoelectric nanoparticles in SDIs generate electricity from natural oral motions such as chewing and brushing, eliminating the need for external power sources. This renewable energy powers LEDs for light therapy, which promotes healing and reduces inflammation. Additionally, embedded micro-sensors wirelessly transmit oral health data, allowing for early detection of potential complications.

**Keywords:** Photo-biomodulation therapy, piezoelectric nanoparticles, micro-sensors

### Introduction

Dental implants are widely used to replace missing teeth in the oral cavity. They not only restore dentition but also improve phonetics, speech, and masticatory functions, while preventing alveolar bone loss, supra-eruption of opposing teeth, and drifting of adjacent teeth, thereby enhancing patient outcomes and overall quality of life [1, 2]. Despite their high success rates, conventional implants face limitations, including peri-implantitis, bacterial infections, and eventual failure [3]. Following tooth extraction, remnants of the periodontal ligament degenerate, leading to the loss of mechanoreceptive feedback essential for detecting occlusal forces during mastication. This deficit contributes to mechanical complications and prosthetic failures [2, 4]. These complications negatively impact clinical outcomes and increase healthcare costs due to repeated interventions [5].

Accurate implant placement begins with a precise diagnosis and treatment plan. Although panoramic and periapical radiographs were traditionally used, cone-beam computed tomography (CBCT) is now essential, offering three-dimensional imaging, cross-sectional views, and DICOM data for virtual planning, surgical guide fabrication, and preoperative prosthetic design [6, 7]. The growing adoption of dental implants is supported by innovations in design, material science, and digital workflows, alongside extensive research into their clinical performance [8].

Smart Dental Implants (SDIs) have emerged to address these limitations by integrating advanced biomaterials, energy-harvesting technologies, and embedded sensors [9]. SDIs utilize piezoelectric nanoparticles that convert oral motion into electrical energy, powering embedded LEDs used for phototherapy to promote healing and prevent infections [10]. Additionally, SDIs are equipped with

microsensors that monitor key oral health parameters such as pH, temperature, and bacterial load, transmitting this data wirelessly to healthcare providers for real-time monitoring and proactive care [11].

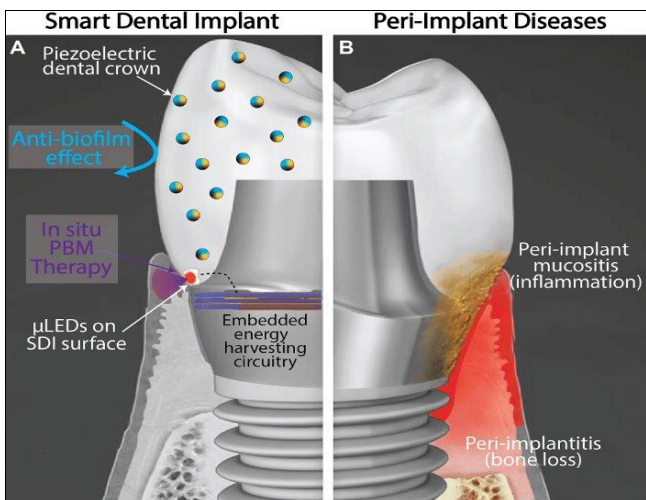
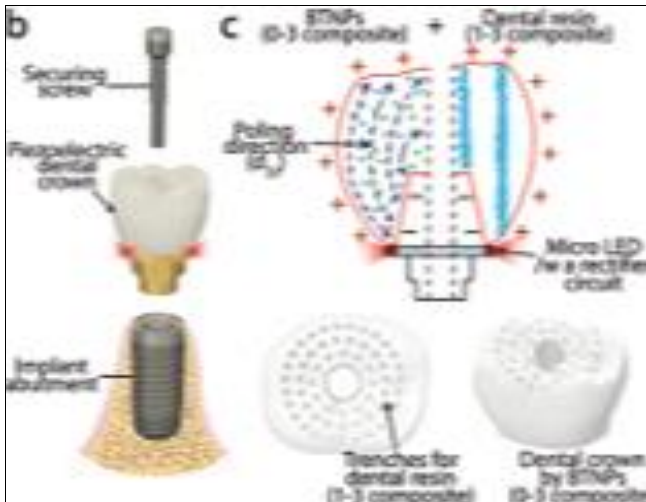
This review explores the components, materials, applications, challenges, and future prospects of SDIs, highlighting their potential to revolutionize implant dentistry.

### Discussion

A smart dental implant is a next-generation prosthesis embedded with biosensors and digital components enabling real-time monitoring of peri-implant health parameters such as bone integration, pH, temperature, and bacterial activity. This innovation allows early detection of complications and therapeutic responses while maintaining the mechanical strength of traditional implants [12, 13].

The need for smart implants arises from limitations in conventional implantology—particularly the rising incidence of peri-implantitis and implant failure [14]. Traditional techniques like radiographs or resonance frequency analysis often detect issues only at later stages. Smart implants aim to overcome this with real-time monitoring of osseointegration, mechanical loading, and biofilm formation using embedded sensors [13, 15].

In addition to diagnostic functions, SDIs offer controlled local drug delivery of antimicrobials or anti-inflammatory agents [16], and even promise systemic health insights by analysing saliva biomarkers [17]. They also support predictive maintenance via remote data transmission, aligning with the broader goals of tele dentistry and personalized care [15, 18].



**Fig 1:** Components of Smart Dental Implants

(image was modified from the source <http://www.deardocor.com/articles/peri-implantitis-can-cause-implant-failure/>).

**The SDI system includes**

- Implant abutment and piezoelectric crown prosthesis
- Securing screw
- Energy-harvesting circuit
- Embedded micro-LEDs

**1. Piezoelectric Material**

The crown prosthesis incorporates barium titanate nanoparticles (BTNPs)—a lead-free piezoelectric compound that generates electrical energy from masticatory forces [19]. This energy powers LED therapy and sensor functions, eliminating the need for batteries.

**2. Two-Phase Composite Crown Design**

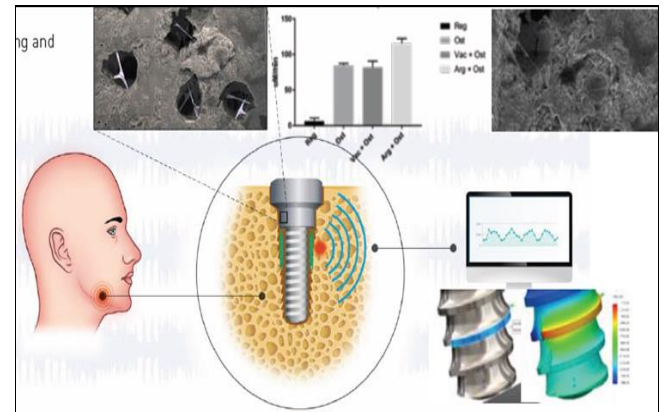
- **0-3 composite:** 0D BTNPs dispersed in a 3D matrix enhance energy harvesting from chewing.
- **1-3 composite:** 1D resin pillars embedded in a 3D matrix improve mechanical integrity during mastication.

**Customized Fabrication**

These crowns are fabricated using paste extrusion 3D printing for anatomical accuracy and functional performance [20]. LEDs are embedded near the cervical third

of the crown to provide targeted photo-biomodulation therapy (PBMT)—a light-based therapy known to reduce inflammation and promote healing [21].

**Integrated Micro-Sensors**



**Fig 2:** Integrated sensors in SDI

(<https://me.engin.umich.edu/news-events/news/toward-smart-dental-implants/>)

Embedded micro-sensors continuously track:

- pH (linked to bacterial activity)
- Temperature (indicating inflammation)
- Bacterial metabolites [13, 16]

These metrics are wirelessly transmitted to clinicians via mobile or desktop apps, enabling real-time interventions [13, 18].

**Photo-biomodulation Therapy (PBMT)**

Powered by the energy harvested during chewing, PBMT emits blue light (405–470 nm) via implanted LEDs. The benefits include:

- Antibacterial effects by disrupting biofilm formation [12, 21]
- Anti-inflammatory responses by modulating immune signaling
- Enhanced healing through stimulation of collagen synthesis and angiogenesis [21]

A 2023 study demonstrated that implantable LED systems can perform non-invasive disinfection, reducing biofilm burden and promoting peri-implant health [12].

**Energy Harvesting from Oral Motions**

BTNPs produce electricity from:

- Chewing (200 N, 1–5 Hz)
- Brushing (15–70 N)
- Harvested energy density: up to 0.77 μJ/cm<sup>2</sup>/s at 5 Hz [19]

This energy supports LED activation, data transmission, and sensor operations, making the system self-sustaining.

**Antimicrobial Coatings**

BTNPs in the implant surface may also function as antimicrobial coatings, discouraging bacterial adhesion and biofilm formation—a major cause of peri-implantitis [16,17].

**Integration: PBMT + Sensor Synergy**

When sensors detect early signs of infection or inflammation, PBMT activates to provide preventive or

therapeutic intervention, forming a feedback-controlled oral ecosystem [12,15].

Feature	Conventional Implants	Smart Dental Implants (SDIs)
Primary Function	Passive tooth replacement	Active diagnostic and therapeutic tool
Monitoring	Periodic clinical and radiographic check-ups	Real-time monitoring via embedded biosensors
Disease Detection	Often detected in late stages	Early detection through pH, temperature, and bacterial activity data
Drug Delivery	Not applicable	Localized, controlled therapeutic release
Technological Integration	Stand-alone, analog system	Integrated with digital dentistry platforms (e.g., tele-dentistry)

**Applications Beyond Dentistry**

Technologies in SDIs—such as energy harvesting, wireless data, and biosensors—are adaptable to orthopaedic implants, catheters, and cardiovascular stents for infection control and healing surveillance [17].

Smart dental implants enable early identification of peri-implant complications through continuous, real-time monitoring. This facilitates prompt treatment and reduces the risk of implant failure. Predictive maintenance features support proactive management of implant health, minimizing emergency interventions. Additionally, remote monitoring enhances patient oversight while decreasing the need for frequent clinic visits.

For patients, ongoing health tracking leads to fewer complications and reduces the frequency of appointments. The implants allow for tailored treatment plans that improve both safety and comfort. Overall, they promote efficient, minimally invasive, and lasting oral healthcare.

**Challenges**

SDIs provide several benefits, but they also confront considerable hurdles. These include expensive material and manufacturing costs, assuring long-term biocompatibility, and navigating complex regulatory approval routes. Furthermore, incorporating various technologies into a single implant necessitates precise engineering and rigorous testing to ensure durability.

**Future Scope**

Advances in materials science and production techniques will improve their functionality and durability. Furthermore, the ideas of SDIs could be applied to various medical applications, revolutionising healthcare in a variety of sectors.

**Conclusion**

Smart dental implants have the ability to change implantology from a passive prosthetic to an active diagnostic and therapeutic tool. By combining sensors, medicine administration, and digital connectivity, they improve implant survival and personalise patient care. They also serve as guides for dentists, helping them make day-to-day clinical decisions. Further *in vivo* studies and clinical trials are required to evaluate the benefits and advance this promising technology.

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