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Application of nanowire technology in dentistry: A narrative review

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ABSTRACT

Nanowire technology utilizes one-dimensional wire-like structures (nanowires) to create materials with a high aspect ratio and tunable surface chemistry. These nanowires can be synthesized from diverse material classes, including metallic, bioceramic, semiconductor, and polymer systems, each offering distinct structural and functional advantages. This technology has been used in dental research to synthesize different materials for a wide range of clinical applications. The core of the review details multifaceted applications of nanowires of different materials. They serve as potent, multifunctional fillers, such as silver nanowires, which can enhance the mechanical strength and impart sustained antibacterial activity to restorative materials. When applied as coatings on titanium implants, metallic nanowires, such as zinc- or magnesium-based nanowires, synergistically promote osseointegration and provide antibacterial defense through controlled ion release or photocatalytic self-cleaning. In regenerative dentistry, nanowire-based scaffolds, most notably hydroxyapatite nanowire scaffolds, guide periodontal bone and soft tissue healing by providing structural support combined with bioactive signaling and immunomodulation. Beyond structural use, silver and silicon nanowires enable highly sensitive diagnostic platforms for detecting oral cancer biomarkers and facilitating on-demand drug delivery. Notably, ultralong hydroxyapatite nanowires with exceptionally high aspect ratios (>10,000) are being engineered into hierarchical, biomimetic materials that replicate the exceptional mechanics and aesthetics of natural enamel. While promising, the transition to clinical practice requires addressing key challenges regarding long-term biosafety, standardized evaluation protocols, and scalable manufacturing.

1. Background

Over the past two decades, nanotechnology has revolutionized the field of dentistry by introducing novel approaches to enhance the performance of restorative, preventive, and regenerative materials [1,2]. By manipulating material properties at the nanometric scale, researchers can optimize mechanical strength, antibacterial activity, aesthetic quality, and biological interactions. This precision addresses many of the inherent limitations associated with conventional dental materials [3,4]. Current nanostructured systems have been utilized to enhance adhesion to dental tissues [5], stimulate mineralization [6,7], and regulate cellular behavior [8,9]. These advancements ultimately lead to more durable and biologically integrated outcomes.

Among the diverse range of nanostructures developed for dental applications, nanowires have emerged as a particularly compelling class of materials, distinguished by their unique one-dimensional (1D) geometry and high aspect ratio [10,11]. Unlike spherical nanoparticles (0D), which often suffer from aggregation and lack structural continuity, nanowires facilitate superior stress transfer and interfacial bridging within dental matrices. Their elongated morphology enables the formation of continuous percolation networks at lower filler loadings than 0D analogues, ensuring functional connectivity, such as enhanced ionic or electrical transport [12,13]. Furthermore, while sharing 1D characteristics with nanotubes, the solid core of nanowires provides greater structural integrity under the heavy compressive loads characteristic of the oral environment. A critical comparison of the nanostructured geometries is summarized in Table 1.

Nanowires can be synthesized from a versatile range of materials, including metallic nanowires (e.g., silver, zinc, magnesium), bioceramic nanowires (e.g., hydroxyapatite), semiconductor nanowires (e.g., silicon), and polymer nanowires (e.g., polylactic acid, polypyrrole), each offering unique structural and functional advantages relevant to dental

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Table 1
Critical comparison of nanowires with other nanostructured geometries in dental applications.

Property	Nanoparticles (0D)	Nanotubes (1D hollow)	Nanowires (1D solid)
Geometry	Spherical	Cylindrical (Hollow)	Cylindrical (Solid)
Reinforcement mechanism	• Point-contact reinforcement • Prone to stress concentration	• Structural bridging • Risk of wall collapse under pressure	• Continuous scaffolding • Superior crack bridging and pull-out effects
Mechanical integrity	Low (acts as fillers only)	Moderate (limited by hollow interior)	High (solid core withstands heavy masticatory loads)
Surface area & connectivity	• High surface area but discrete sites	• Very high • Inner and outer surfaces available	• High and interconnected • Facilitate a continuous percolation network
Biological interaction	• Rapid release • Potential for burst-release toxicity	• Controlled release from the internal lumen	• Sustained, localized release • Enhanced cell attachment via topographical cues
Primary limitation	• Tendency to aggregate • Weakens the matrix at high loading	• High synthesis cost • Potential structural fragility	• Synthesis complexity compared to simple nanoparticles

applications [14,15]. The tunable surface chemistry of nanowires allows for precise, tailored interactions with both restorative systems and surrounding tissues, creating a synergistic effect that integrates mechanical strength with bioactivity [16,17]. Consequently, nanowires serve as a multifunctional bridge between structural reinforcement and biological functionality in next-generation dental materials.

This review aims to provide an overview of the development and application of nanowire technology in dentistry. It focuses on their synthesis methods, structural characteristics, and multifunctional roles in enhancing the performance of dental materials and biological systems. By integrating current evidence across restorative, regenerative, and diagnostic contexts, this review seeks to provide a comprehensive understanding of how nanowire technology contributes to next-generation dental technologies and to outline key challenges that remain for their clinical translation.

2. Methods

The search strategy in this review utilized the search terms related to either "nanowire" or "dentistry". According to the specific requirements in PubMed, MEDLINE, and Embase (updated until October 2025). These databases were selected because they are widely recognized as the primary sources for biomedical and dental research, covering both clinical and experimental studies in biomaterials and dentistry.

The inclusion criteria for the selection of articles in this review were focused on original studies investigating the synthesis, properties, and dental applications of nanowire structures. Review articles, communications, editorials, case reports, and non-relevant research reports were excluded from this review.

3. Synthesis of nanowires

Precise control over the length and diameter of nanowires is critical for their practical applications [18]. The synthesis strategies, while

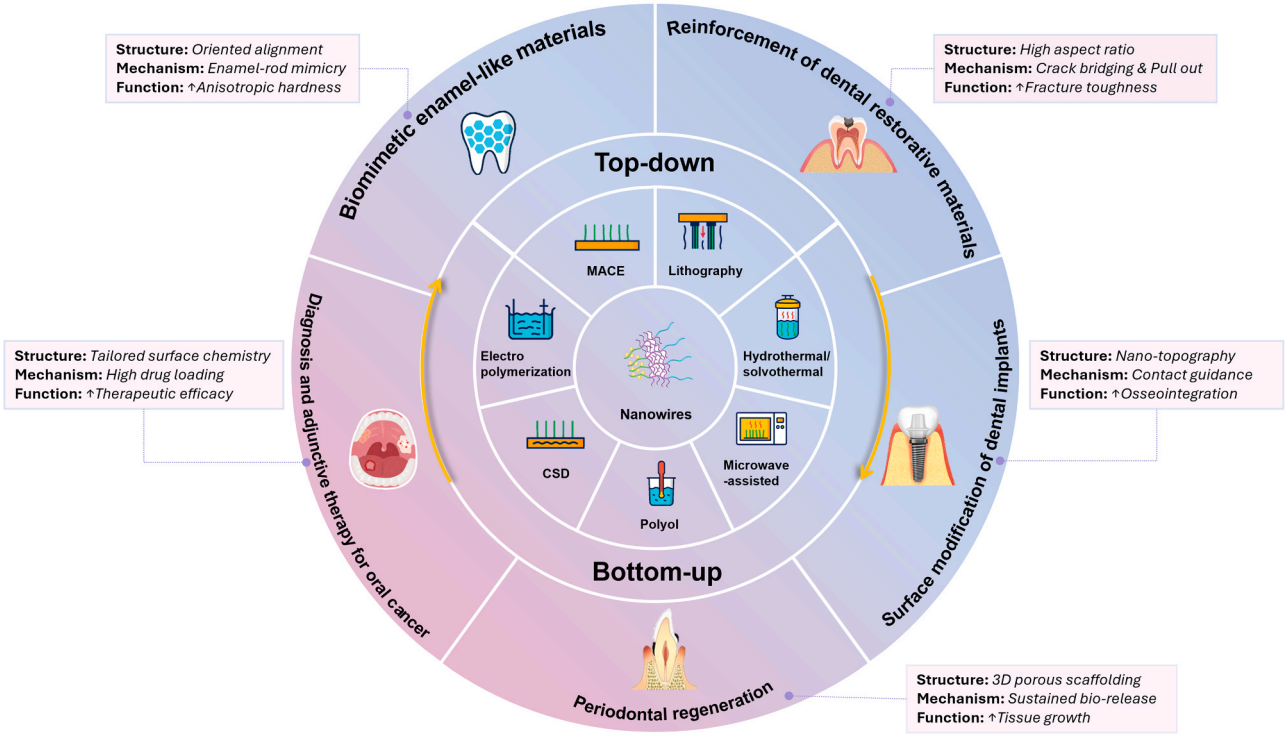

Fig. 1. Schematic showing the application of nanowire technology in dentistry. The central diagram depicts the top-down and bottom-up fabrication routes. Yellow arrows at the periphery of the synthesis ring represent the versatile technological flow, indicating that these methodologies serve as a foundational platform applicable to any of the five major clinical dental domains, rather than having a fixed one-to-one positional correspondence. The callout boxes (linked by dashed lines) summarize the specific structural parameters and mechanisms (e.g., crack bridging, contact guidance) required for each application, providing a thematic index for the detailed structure-property-function discussions throughout the text. *Abbreviations*: CSD, chemical solution deposition; MACE, metal-assisted chemical etching.

diverse, can be conceptually divided into two categories: the bottom-up approach and the top-down approach (Fig. 1). A summary of the advantages and disadvantages of these synthesis methods is provided in Table 2. Each of these synthesis methods presents unique opportunities and challenges for dental applications. The selection of an appropriate synthesis strategy depends on multiple factors, including the desired nanowire composition, the required structural characteristics, and the intended clinical application (such as antibacterial or regenerative). Crucially, the translation from laboratory-scale synthesis to clinical practice is governed by manufacturing constraints, particularly scalability and reproducibility. For instance, maintaining consistent aspect ratios across large-volume batches in bottom-up processes or balancing the cost-to-throughput ratio in precision top-down lithography is essential for meeting the Good Manufacturing Practice standards and rigorous quality control required for standardized dental materials. Recent advances have increasingly focused on hybrid approaches that combine multiple techniques to overcome the limitations of individual techniques while preserving the advantages of each methodology.

3.1. Bottom-up approaches

Bottom-up approaches assemble nanowires atom by atom or molecule by molecule, offering precise control over composition, crystallinity, and aspect ratio compared to the top-down approach [11]. Among bottom-up approaches, hydrothermal and solvothermal synthesis are the most widely used methods for synthesizing nanowires through controlled crystal growth in sealed autoclaves at high temperatures and under autogenous pressure. By modulating parameters such as precursor concentration, pH, temperature, and reaction time, the morphology and crystallinity of the resulting nanowires can be precisely tuned [38,39]. This tunability makes the method particularly suitable for producing highly crystalline metal oxides, including zirconia oxide (ZrO_2) [29], zinc oxide (ZnO) [20], and titanium oxide (TiO_2) [30], as well as bioceramic nanowires, such as hydroxyapatite (HA) [31], with customized aspect ratios for biomedical and coating applications.

Other bottom-up variant approaches offer distinct advantages tailored to addressing specific needs. Microwave-assisted synthesis enables rapid and energy-efficient production by generating uniform volumetric heating, significantly reducing reaction times, and improving product homogeneity [32]. Polyol synthesis enables fine control over reduction of kinetics and surface chemistry, making it suitable for metallic nanowire synthesis, such as silver (Ag), which is widely used in antibacterial coatings [33,40]. Chemical solution deposition is a relatively simple solution-based process and is advantageous for generating large-area thin films fabricated at low processing temperatures [34]. Electropolymerization represents a unique electrochemical route for fabricating conductive polymer nanowires directly on substrates, making them suitable for applications such as drug delivery and oral cancer therapy [35].

Ultimately, bottom-up approaches excel in chemical tunability and crystal quality, making them suitable for bioactive or reinforcing materials. However, their primary limitation remains the difficulty of achieving precise spatial control and structural alignment. This lack of deterministic placement can be a critical drawback for device-based dental applications that require exact geometric configurations.

3.2. Top-down approaches

In contrast, top-down synthesis utilizes bulk materials, shaping them into nanowires through external chemical or physical treatments [11]. This strategy excels in structural precision, alignment control, and structural reproducibility, aspects that bottom-up approaches typically lack.

Metal-assisted chemical etching has become a prominent method that utilizes a noble metal catalyst, typically gold (Au) or Ag, to promote selective dissolution and vertical etching of semiconductors, forming

Table 2
The advantages and disadvantages of the nanowire synthesis methods applied in dentistry.

Synthesis method	Category	Advantages	Disadvantages and manufacturing constraints
Hydrothermal/ solvothermal synthesis [19–31]	Bottom-up	• Simple setup and low cost • Good control over morphology and crystalline • Suitable for high-quality 1D nanostructures	• Long reaction time • Requires high-pressure vessels (autoclave) • Limited scalability due to thermal gradients in large volumes, affecting batch-to-batch reproducibility
Microwave-assisted synthesis [32]	Bottom-up	• Rapid heating and short reaction time • Uniform nucleation and size distribution • Energy-efficient	• Requires specialized equipment • Risk of non-uniform electro-magnetic field distribution in industrial reactors, hindering large-scale clinical production
Polyol synthesis [33]	Bottom-up	• Well-established for Ag nanowires • Relatively low cost • Tunable morphology via reaction conditions • Good yield and reproducibility	• Limited mainly to metals (Ag, Cu) • Requires high-temperature organic solvents • Surfactant removal is a critical quality control bottleneck for biocompatibility
Chemical solution deposition [34]	Bottom-up	• Low-cost and scalable • Simple experimental setup • Suitable for large area coatings	• Poor crystallinity without post-annealing • Long deposition times • Challenges in achieving consistent orientation and thickness across complex 3D dental geometries
Electropolymerization [35]	Bottom-up	• Precise control over the nanowire dimensions • Compatible with polymer-based and hybrid nanowires • Low-temperature process	• Requires conductive substrates • Limited to certain monomers or precursors • Lower crystalline compared with hydrothermal methods • Low throughput for mass-producing restorative fillers
Metal-assisted chemical etching [36]	Top-down	• High aspect ratio nanowires • Uniform vertical alignment • Compatible with silicon and other semiconductors	• Requires noble metal catalysts (costly) • Potential metal contamination • High catalyst cost and chemical waste management limit its economic feasibility for bulk materials

(continued on next page)

Table 2 (*continued*)

Synthesis method	Category	Advantages	Disadvantages and manufacturing constraints
Top-down lithography [37]	Top-down	• Precise control over size, alignment, and architecture • Highly reproducible • CMOS-compatible and scalable for integrated devices	• Requires expensive equipment and cleanroom facilities • Multi-step and time-consuming • Material waste • Limited mainly to semiconductors, not feasible for routine dental clinical translation

Abbreviations: CMOS, complementary metal-oxide-semiconductor

well-aligned nanowire arrays [36]. This method offers a cost-effective and scalable pathway for implant surface texturing and bioactive scaffolds, where vertical structures can enhance cell adhesion and antibacterial performance [41].

Lithography-based techniques, including photolithography, electron-beam lithography, and nanoimprint lithography, enable nanoscale patterning with exceptional reproducibility, making them ideal for biosensing and diagnostic platforms [42,43]. For instance, lithography-assisted silicon nanowire biosensors have demonstrated high sensitivity in detecting oral squamous cell carcinoma, supporting early diagnostic applications [37].

Overall, top-down methods provide superior structural precision, pattern reproducibility, and compatibility with integrated devices. However, top-down approaches are not as frequently adopted as bottom-up approaches, mainly due to their high equipment cost, complex processing, and limited applicability to diverse material systems [44]. Fig. 2 provides representative scanning electron microscopic (SEM)/transparent electron microscopic (TEM) images of the fabricated

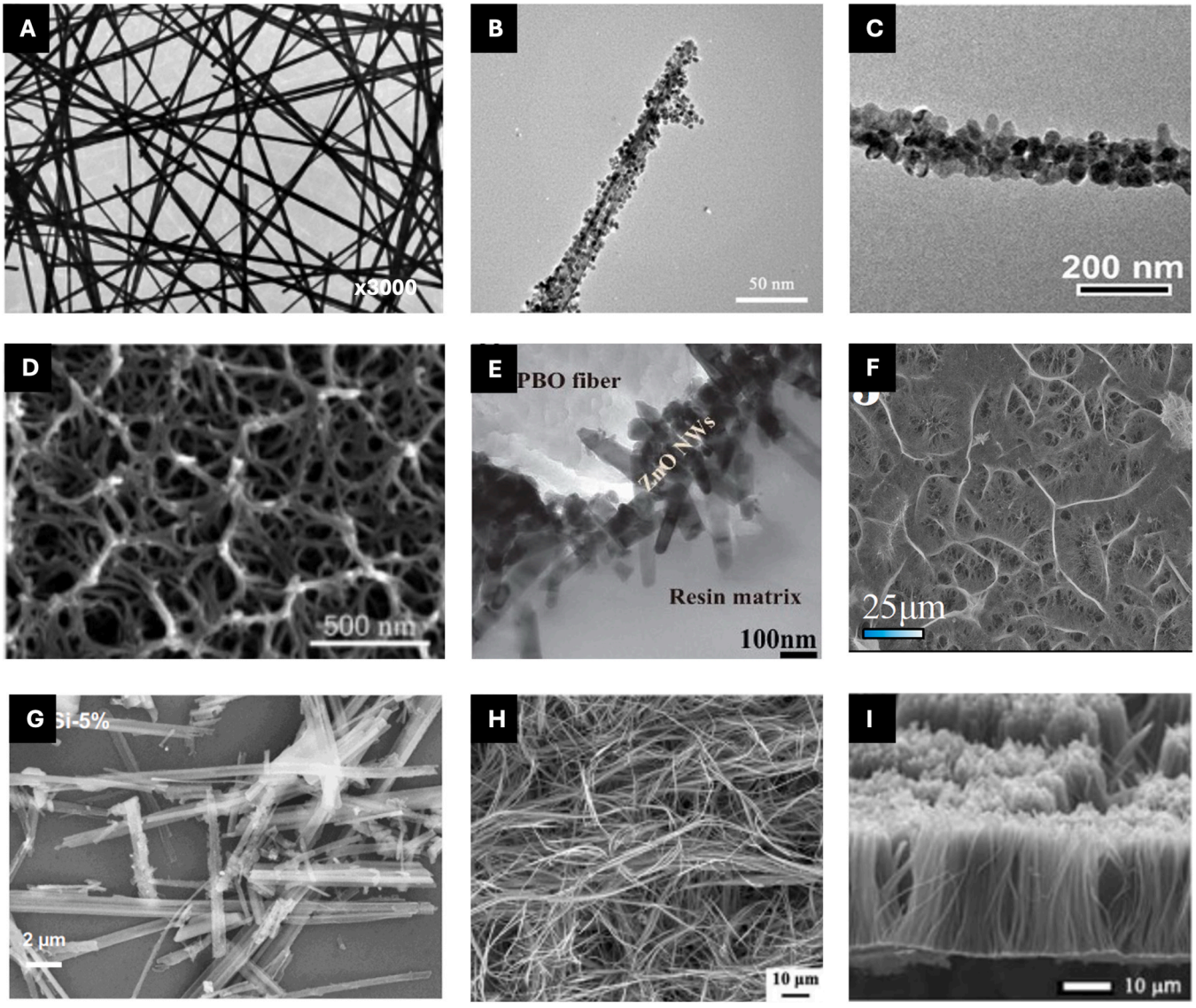

Fig. 2. Representative SEM/TEM images of nanowires used across major dental applications. **A.** Silver nanowires (AgNWs) [24]; **B.** Platinum-palladium core-shell nanowires (Pt@Pd NWs) [21]; **C.** Zinc oxide nanowires (ZnO NWs) [20]; **D.** Magnesium-incorporated titanium nanowires (Mg-NW-Ti) [26]; **E.** Poly (p-phenylene-2, 6-benzobisoxazole) fiber system modified with zinc oxide nanowires (PBO-ZnO NW) [34]; **F.** TiO_2-B@anatase nanowires (TiO_2-B@ANWs) [30]; **G.** Lithiated porous silicon nanowires (LipSiNS) [36]; **H.** Hydroxyapatite nanowire (HANW) [22]; **I.** Polypyrrole nanowire arrays loaded with doxorubicin (DOX/Ppy) [35]. *Images shown at different magnifications to illustrate representative morphologies rather than enable direct dimensional comparison.*

nanowires and nanowire-based composites.

4. Application of nanowires in dentistry

Nanowires have demonstrated significant potential application across various dental specialties. Their diverse clinical roles are fundamentally dictated by their intrinsic material properties, such as bioactivity, mechanical strength, or antimicrobial activity. Table 3 categorizes nanowires by material class and summarizes their multifaceted applications, functional roles, inherent limitations, and potential strategies, as discussed in the following sections.

4.1. Reinforcement of dental restorative materials

The reinforcement of dental restorative materials, such as glass ionomer cements (GICs) and resin composites, is crucial for ensuring the clinical longevity of dental restorations. Conventional restorative materials often suffer from premature fatigue failure due to the limited toughening effects of spherical nanoparticles, which can act as stress concentrators. As outlined in Table 1, the transition to nanowires introduces unique mechanical benefits. Unlike nanoparticle systems, the anisotropic geometry of nanowires enables effective crack bridging and pull-out effects, creating a reinforcing scaffold that arrests micro-crack propagation. Consequently, nanowires can significantly enhance fracture toughness and flexural strength without the handling or aesthetic trade-offs typical of high nanoparticle loading, providing a robust rationale for their application in restorative dentistry. However, the successful integration of these reinforcements depends on precise control over their dispersion stability and interfacial bonding within the matrix. Table 4 details the methodologies reported in the studies, including dispersion and optimized loading concentrations, used to ensure uniform reinforcement and functional synergy in various dental restorative systems.

Nanowire-based reinforcement across different restorative systems shares several functional themes that help clarify their comparative advantages. Silver nanowires (AgNWs) represent one of the most extensively investigated systems for use in glass ionomer cements (GICs), offering dual benefits of mechanical strengthening and sustained antibacterial activity. At optimized low loadings (~0.5 wt%), AgNWs preserve the intrinsic properties of GICs, including compressive

Table 3
Material-based classification of nanowires in dental applications: functions, limitations, and strategies.

Nanowires category	Representative materials	Primary dental applications (Section)	Biological functions	Limitations	Potential strategies
Metallic & metal-decorated nanowires	Silver nanowires (AgNWs)	Reinforcement of GICs (4.1)	• Broad-spectrum antibiosis • Electrocatalytic activity for biosensing • Enhanced surface energy	• Non-linear ion release kinetics • Potential systemic translocation • Tooth discoloration (Ag)	• Developing core-shell architectures (e.g., Ag@SiO2) for sustained and controlled ion release kinetics • Surface passivation with polydopamine to stabilize aesthetics
	HA-PDA-Ag	Reinforcement of composite resin (4.1)			
	AgNWs@ZIF	Diagnostics of oral cancer (4.4)			
	AgNW-modified titanium (AgNW-Ti)	Modification of the dental implant surface (4.2)			
	Pt@Pd NWs-Hemin-PEI-rGo	Diagnostics of periodontitis (4.4)			
Metal oxides & Derivatives	Zinc-coated magnesium oxide nanowires (zMgO NWs)	Reinforcement of composite resin (4.1)	• Antibacterial activity via ROS generation • Ion-mediated bioactivity (Zn/Mg ions) • Mechanical reinforcement	• Potential cytotoxicity at high concentrations • pH-dependent stability in oral biofilm	• Design stimuli-response "smart" coatings that trigger ion release only in response to acidic shifts (infection) in the oral microenvironment
	PBO-ZnO NW-POSS	Reinforcement of fiber-reinforced composite (4.1)			
	Zn/Mg-NW-Ti	Modification of the dental implant surface (4.2)			
	TiO_2-B@ANWs	Modification of the dental implant surface (4.2)			
	IMC/ZnO	Periodontal tissue regeneration (4.3)			
Bioactive ceramics & hydroxyapatite	Ultralong hydroxyapatite nanowires (UHANWs)	Construction of enamel-mimetic materials (4.5)	• Biomimetic mineralization • Osteoconduction • Controlled release of growth factors (Wnt3a)	• Brittle nature of pure ceramic NWs • Difficulty in maintaining hierarchical alignment during large-scale fabrication	• Hybridization with flexible polymers to improve toughness • Utilizing field-assisted 3D bioprinting for precise biomimetic orientation
	UHANW-amorphous zirconia (HA@A-ZrO_2)	Construction of enamel-mimetic materials (4.5)			
	UHANW/polylactic acid (HANW/PLA)	Periodontal tissue regeneration (4.3)			
	Wnt3a-HANW@MpSi	Periodontal tissue regeneration (4.3)			
Semiconductor & Synthetic nanowires	Silicon nanowires (SiNWs)	Diagnostics of oral cancer (4.4)	• High-sensitivity biomarker detection • Targeted drug (DOX) delivery • Photothermal therapy	• Complex integration into clinical diagnostic workflows • Long-term degradation profiles of SiNWs	• Surface modification (e.g., PEGylation) to reduce protein fouling • Developing point-of-care (POC) microfluidic platforms for chairside diagnostics
	Lithiated porous silicon nanowires (LipSiNS)	Periodontal tissue regeneration (4.3)			
	DOX/Ppy NW	Adjunctive therapy for oral cancer (4.4)			

Abbreviation: AgNWs@ZIF, AgNW-zeolitic imidazolate frameworks; DOX/Ppy NW: Polypyrrole nanowire arrays loaded with doxorubicin; GICs: glass ionomer cements; HA-PDA-Ag, Hydroxyapatite nanowires-polydopamine-silver nanoparticles; IMC/ZnO, zinc oxide nanowires incorporated into intrafibrillar mineralized collagen scaffolds; PBO-ZnO NW-POSS, Poly (p-phenylene-2,6-benzobisoxazole) fiber system modified with zinc oxide nanowires and polyhedral oligomeric silsesquioxane; Pt@Pd NWs-Hemin-PEI-rGo, Platinum-palladium core-shell nanowires, combined with hemin-polyethyleneimine-reduced graogene oxide; ROS, reactive oxygen species; TiO_2-B@ANWs, TiO_2-B@anatase nanowires; Wnt3a-HANW@MpSi, Wnt3a-loaded HANW@mesoporous silica; Zn/Mg-NW-Ti, Zinc/magnesium-incorporated titanium nanowires.

Table 4
Performance of nanowires in dental restorative materials.

Nanowire system	Restorative materials	Incorporated amount	Dispersion & interfacial control	Key findings (including optimal amount)
AgNWs [45,46]	Glass ionomer cements (GICs)	0.05, 0.5 wt%	Manual spatulation integration into GIC powder	• Optimal: 0.05 wt% • Maintained compressive strength while providing antibiofilm effect • 0.5 wt% led to potential ion leaching concerns but higher efficacy
HA-PDA-Ag [24]	Resin composites	0, 1, 2, 5, 10 wt%	Ultrasonic dispersion in ethanol + evaporation	• Optimal: 2 wt% • Flexural strength increased by 38.5% • higher loading (>5%) caused aggregation and strength decay.
zMgO [32]	Resin composites	0, 0.3, 0.5, 1, 2 wt%	Standardized manual/light-curing.	• Optimal: 0.3–0.5 wt% • Balanced antimicrobial effect with colour stability ($\Delta E < 3.3$) • 1–2% caused severe discoloration.
PBO-ZnO NWs-POSS [34]	Fiber-reinforced endodontic posts	N/A	*In situ* growth on fibers + POSS silane treatment.	• Significantly improved ILSS and load transfer via chemical/mechanical interlocking

Abbreviations: AgNWs, silver nanowires; HA-PDA-Ag, Polydopamine-coated hydroxyapatite nanowires with silver; ILSS, interlaminar shear strength; PBO-ZnO NWs-POSS, ZnO nanowire-POSS modified PBO fibers; zMgO, Zinc-coated magnesium oxide nanowires.

strength, fluoride release, and biocompatibility, while significantly suppressing cariogenic bacteria viability (e.g., *Streptococcus mutans*, *Streptococcus sobrinus*, *Lactobacillus fermentum*, and *Lactobacillus rhamnosus,* ~5.8%), with less discoloration and aggregation than silver nanoparticles (AgNPs) [45,46]. This potential bioactivity is primarily driven by three synergistic pathways that general antibacterial mechanisms of metallic nanowires discussed throughout this review: (1) physical disruption of bacterial membranes through high-aspect-ratio contact; (2) the localized generation of reactive oxygen species (ROS) leading to fatal oxidative stress; and (3) the sustained release of metallic ions (e.g., Ag^{+}) that penetrate cell walls to impair DNA replication and enzymatic functions. Their high aspect ratio also enables effective stress transfer within the polyacrylate matrix, although excessive loading may cause interfacial disruption and compromise overall performance.

Hierarchical nanowires enhance the performance of resin-based composites by improving both their mechanical properties and bioactivity. Hydroxyapatite nanowires coated with polydopamine and functionalized with silver nanoparticles (HA-PDA-Ag) exhibit a combination of mineral-like rigidity and enhanced interfacial adhesion, along with sustained antibiofilm activity [24]. The polydopamine interface facilitates strong coupling with the polymeric matrix, enhancing nanowire dispersion and yielding notable improvements in flexural properties without compromising biocompatibility [47,48]. Compared with AgNW-modified GICs, these hybrid nanowires offer a broader spectrum of mechanical and biological benefits, making them well-suited for resin matrices.

Specialized nanowire systems can be tailored for targeted performance in esthetic composites. Zinc-coated magnesium oxide nanowires (zMgO NWs) prioritize color stability, thermal durability, and structural integrity, making them particularly suitable for esthetic resin composites where antibacterial potency is desired secondary benefit rather than the primary objective. Their balanced combination of chemical stability and mild Zn^{2+} release offers a moderate antimicrobial effect relative to silver-based systems [32].

Nanowires also reinforce fiber-based endodontic posts by creating hierarchical micro- and nano-scale interfaces. Poly (p-phenylene-2,6-benzobisoxazole) (PBO) fiber system modified with zinc oxide nanowires and polyhedral oligomeric silsesquioxane (PBO-ZnO NWs-POSS), forms a multi-scale interphase that markedly improves interfacial performance, increasing interfacial shear strength by approximately 60% and achieving a flexural strength of by around 900 MPa, exceeding most commercial glass-fiber posts [34]. This hierarchical architecture, which combines mechanical interlocking with chemical bonding, addresses a key limitation of conventional fiber posts by enhancing stress transfer and reducing fiber pullout underload [49,50].

Overall, these systems demonstrate that the success of nanowire reinforcement depends less on the specific type of nanowire material and more on the quality of the nanowire bond with the matrix, their orientation, and the organization of their microstructure within the restoration. Across GICs, resin composites, and fiber-reinforced posts, nanowires have shifted restorative design from passive filler reinforcement toward active modulation of stress distribution, antibacterial functionality, and long-term interfacial stability. However, most current studies are *in vitro*, and the clinical success of these reinforced systems depends on addressing technical challenges related to nanowire dispersibility, interfacial coupling, and loading optimization. Given their high surface energy, techniques such as high-energy ultrasonication or surface functionalization (e.g., silanization) are essential to ensure a homogeneous distribution and prevent stress-concentrating clusters. Effective stress transfer is further dictated by the quality of the interfacial bond with the matrix rather than the material type alone. Typically, an optimized loading range is required to maximize mechanical and antibacterial benefits without compromising material viscosity or handling properties, although the exact optimum is system-dependent and may occur at lower levels (e.g., ~0.5 wt% AgNW-modified GICs). Continued progress in precisely controlling nanowire orientation and matrix integration is expected to further translate these nanoscale advantages into clinically durable restorative solutions.

4.2. Surface modification of dental implants

Peri-implant complications remain a persistent challenge for dental implants, as conventional surface treatments are often unable to simultaneously support osseointegration, modulate local biological responses, and prevent bacterial colonization [51]. Most commercially available implant systems rely on microscale roughening strategies, such as sandblasted, large-grit, acid-etched (SLA) surfaces, anodized titanium (e.g., TiUnite-type oxide layers), or plasma-sprayed hydroxyapatite coating stable. These approaches primarily enhance mechanical interlocking and surface energy to facilitate early bone deposition. However, their biological activity is largely passive and does not actively regulate the peri-implant microenvironment. Nanowire-based surface modification introduces a hierarchical micro-nano architecture that extends beyond roughness enhancement toward multifunctional bioactivity. Unlike isolated nanoparticle coatings, interconnected nanowire arrays provide continuous topographical guidance for protein adsorption and cell attachment, while simultaneously enabling controlled ion release. The specific therapeutic outcomes of these nanowire-modified surfaces, including critical metrics such as Bone-to-Implant Contact (BIC), antibacterial rates, and corrosion resistance across various animal models,

are systematically summarized in Table 5. This transition from passive micro-roughness to active biological regulation is further evidenced by the precise experimental parameters and quantitative findings detailed below

Zinc-incorporated titanium nanowires (Zn-NW-Ti) effectively stimulate osteogenesis and inhibit pathogens without exerting cytotoxicity. The dense, interwoven nanowire structure increases surface roughness and hydrophilicity, creating a favorable environment for osteoblast adhesion. Sustained Zn^{2+} release further stimulates cell proliferation and tissue regeneration, while directly inhibiting pathogens such as *Porphyromonas gingivalis*, *Actinobacillus actinomycetemcomitans*, and *Staphylococcus aureus* without significant local tissue cytotoxicity [25,27]. *In vivo*, Zn-NW-Ti implants increased bone-implant contact and bone volume fraction in zebrafish and rabbit mandibular models [27,52]. These two parameters reflect the degree of direct bone adhesion and the proportion of new bone formation around implants, respectively [53–55]. These data support the material enhancing bone formation and implant integration.

Magnesium-incorporated titanium nanowires (Mg-NW-Ti) provide prolonged osteogenic stimulation for guided bone regeneration. Compared with Zn^{2+}, Mg^{2+} is released more moderately, promoting prolonged osteogenic stimulation without cytotoxic effects. Mg^{2+} enhances osteoblast differentiation, matrix mineralization, and vascular formation [49,56,57]. In rabbit mandibular defects, Mg-NW-Ti meshes enhanced bone regeneration and osseointegration, particularly in poorly vascularized regions, indicating stable osteogenesis under challenging physiological conditions [26].

Silver nanowire-modified titanium (AgNW-Ti) enhances antibacterial properties while maintaining biocompatibility. The high aspect ratio and interconnected structure of AgNWs provide a large active surface for Ag^{+} release [58], resulting in stronger inhibition of peri-implant pathogens, such as *Porphyromonas periodontium*, compared with AgNPs. This antibacterial performance follows the general mechanisms of metallic nanowires described previously, primarily involving membrane disruption and Ag^{+} release. Meanwhile, the nanowire architecture maintains favorable compatibility with osteoblasts, highlighting the importance of nanowire morphology in antibacterial efficacy [33].

Self-regenerating oxide nanowires offer smart surfaces that combine photocatalytic activity with osteoconduction. TiO_2-B@anatase nanowires (TiO_2-B@ANWs) with oxygen vacancies generate hydrophilic, chemically active interfaces under ultraviolet light, which promote protein adsorption, cell attachment, and early osteogenic differentiation [59,60]. *In vivo* evaluation using rat femoral models demonstrates that TiO_2-B@ANWs significantly increased bone-implant contact and bone area compared with conventional sandblasted, large-grit, acid-etched controls, even outperforming ultraviolet irradiation on its own [30]. These findings highlight a sophisticated dual functionality that far exceeds the performance of conventional passive antibacterial coatings.

Overall, compared with commercially established roughened or coated surfaces, nanowire-based modifications shift implant design from passive topographical enhancement toward multifunctional surface engineering. By integrating nanoscale architecture with controlled ion release and, in some systems, photocatalytic self-regeneration, nanowire-modified implants offer a more active strategy for promoting durable osseointegration while reducing the risk of peri-implant disease.

4.3. Periodontal tissue regeneration

Successful periodontal bone and soft tissue regeneration benefits from biomaterials that can simultaneously provide osteoconductivity, antibacterial activity, and immunomodulatory activity within the complex oral microenvironment [61]. Unlike non-directional nanoparticles, the elongated morphology of nanowires provides continuous topographical guidance for cells. This structure mimics the natural orientation of periodontal fibers, promoting organized tissue growth that discontinuous nanoparticles cannot facilitate. The biological efficacy of various nanowire systems is further detailed in Table 6, which highlights critical quantitative findings from both *in vitro* evaluations and *in vivo* animal models, including specific defect specifications and repair durations.

Hydroxyapatite nanowires (HANWs) show strong osteoconductive potential, supported by their chemical similarity to native apatite and high Ca–P availability. Their large surface area enhances Ca^{2+}/PO_4^{3-} release and protein adsorption, promoting cell adhesion and matrix deposition [62]. When incorporated into polylactic acid (PLA) membranes, HANWs create bilayered structures in which the nanowire surface supports osteogenesis, while PLA prevents epithelial down-growth. *In vitro*, HANWs enhance protein adsorption and osteoblast adhesion. *In vivo*, HANW/PLA membranes have been shown to increase new bone formation and upregulate osteogenic markers in rat mandibular defects [28].

HANWs can also function as controlled-release therapeutic

Table 5
Quantitative analysis of nanowire-mediated systems in implant surfaces.

Nanowire system	Key findings *in vitro*	Animal model	Defect site & size	Repair time	Key findings *in vivo*
Zn-NW-Ti [25,52]	• Decreased corrosion current density • Increased antioxidant enzymes by around 2-fold • Promoted HUVEC tubulogenic	Zebrafish	Systemic development & caudal fin/cranium	3–7 days	• Significantly increased in mineralized area • Observed clear vascular sprouting and upregulation of osteogenic factors
Zn-NW-Ti [27]	• Antibacterial rate: > 90% against *P. gingivalis*	Rabbit	Mandible (extraction socket) Φ 3.5 mm × 8 mm	4 & 12 weeks	• BIC: 64.55 ± 4.31% at 12 weeks • Successful osseointegration even under bacterial challenge
Mg-NW-Ti [26]	• Significantly increased cell adhesion numbers compared to pure Ti	Rabbit	Mandible Φ 8 mm × 5 mm vertical bone defect	4 & 8 weeks	• Bone volume (BV) is significantly higher than pure Ti mesh • BIC: increased to around 55% • Maintained space stability for GBR
AgNW-Ti [33]	• MIC: 12.5 μg/ml against *P. gingivalis* • Cell viability maintained > 85% • Identified that longer/thinner nanowires possess stronger membrane penetration and higher killing efficiency	N/A	N/A	N/A	N/A
TiO_2-B@ANWs [30]	• Protein absorption increased by 1.8-fold • Photocatalytic cleaning restored super-hydrophilicity by removing organic contaminants.	Beagle Dog	Alveolar ridge	2 & 4 weeks	• BIC: 58.4 ± 5.2% at 4 weeks • Bone formation area (BA) increased by 1.2-fold compared to the control group

Abbreviations: AgNW-Ti, Silver nanowire-modified Titanium; BIC, bone-to-implant contact; GBR, guided bone regeneration; HUVEC, human umbilical vein endothelial cell; Mg-NW-Ti, Magnesium-incorporated titanium nanowires; MIC, minimum inhibitory concentration; TiO_2-B@ANWs, TiO_2-B@anatase nanowires; Zn-NW-Ti, Zinc-incorporated titanium nanowires.

Table 6
Quantitative analysis of nanowire-mediated system in periodontal tissue regeneration.

Nanowire system	Key findings *in vitro*	Animal model	Defect site & size	Repair time	Key findings *in vivo*
HANW/PLA membrane [28]	• Significantly enhanced protein adsorption and BMSC proliferation	SD Rat	Calvaria defect (Φ 5 mm)	8 weeks	• BV/TV: 36.21 ± 3.25% • Significantly enhanced bone mineral density compared to pure polylactic acid
Wnt3a-HANW@MpSi [31]	• Promoted DPSC migration and enhanced oxidative stress resistance	SD rat	Pulp chamber (Φ 1 mm × 2 mm	4 weeks	• New dentine area: ~0.6 mm^2 • Formation of a continuous mineralized bridge and dense microvessels
IMC/ZnO scaffold [20]	• Antibacterial rate: >99% against *S. mutans* • Induced high expression of M2 macrophage markers	Infected SD rat	Cranium defect (Φ 5 mm + *S. aureus*)	8 weeks	• BV/TV: 29.74 ± 2.82% • Achieved near-complete bone healing under active *S. aureus* infection
LipSiNWs [36]	• Achieved stable and sustained release of Li^+ ions • Significantly induced the differentiation of PDLCs	Beagle Dog	Periodontal defect (5 × 3 × 3 mm^3)	12 weeks	• New cementum: 2.31 ± 0.45 mm • Integrated regeneration of alveolar bone, periodontal ligament, and cementum

Abbreviations: BV/TV, bone volume/total volume; BMSC, bone marrow stromal cells; DPSC, dental pulp stem cells; HANW, hydroxyapatite nanowire; IMC, intrafibrillar mineralized collagen; PDLCs, periodontal ligament cells.

platforms. A representative example is the Wnt3a-loaded HANW@mesoporous silica (Wnt3a-HANW@MpSi) system for dentine-pulp regeneration [31]. The silica shell enables sustained Wnt3a release, which supports odontogenic differentiation and promotes reparative dentine formation, while the HA core dissolves, releasing Si^{4+} ions that enhance antioxidant capacity and odontogenic differentiation *in vitro*. These synergistic effects alleviate oxidative stress, stimulate the formation of dentine-producing cells, and help maintain pulp vitality during tissue repair [63–65].

Zinc oxide (ZnO) nanowires incorporated into intrafibrillar mineralized collagen scaffolds (IMC/ZnO) was able to provide a pH-responsive antibacterial and osteogenic platform [20]. Under acidic inflammatory conditions, Zn^{2+} release contributes to antibacterial activity against *P. gingivalis* [66], and has also been shown to support osteogenic differentiation *in vitro* [67,68]. Evidence from both *in vitro* and *in vivo* shows that local released Zn^{2+} also help shift the local immune response toward a more pro-healing state and reduces inflammatory cytokines, enhancing regenerative conditions [69].

Lithiated porous silicon nanowires (LipSiNWs) combine the osteogenic effects of silicic acid with the regenerative activity of lithium [36]. Controlled Li^+/Si^{4+} release has been shown to enhance stem cell proliferation and osteogenic differentiation *in vitro*, while *in vivo* application in a murine periodontal defect model demonstrated increased vascularized bone and periodontal ligament regeneration [70,71].

Overall, nanowire-based scaffolds offer a multifunctional approach to periodontal tissue regeneration, combining positive effects on osteogenesis, angiogenesis, and immune regulation. Their adaptability positions them as next-generation candidates for dental and periodontal tissue regeneration, bridging structural reinforcement with bioactive signaling.

4.4. Diagnosis and adjunctive therapy for oral diseases

Nanowires are now emerging as versatile platforms for use in oral diseases (mainly periodontitis and oral cancer) diagnostics and therapy. Their large surface area, electrical conductivity, and tunable surface chemistry allow highly sensitive biomarker detection and localized, stimulus-responsive treatment. In diagnostic applications, nanowires can be integrated into electrochemical, optical, and fluorescence systems to enable rapid and low-cost monitoring of oral disease-related molecules.

One notable example of this diagnostic potential is the use of platinum-palladium core-shell (Pt@Pd) nanowires. When combined with hemin-functionalized, polyethyleneimine-modified reduced graphene oxide (Hemin-PEI-rGO), these bimetallic nanowires significantly accelerate electron transfer. In this system, the hemin provides enzyme-like catalytic activity while the PEI enhances analyte capture [21], enabling the ultrasensitive detection of chlorogenic acid, a compound associated with periodontal inflammation [72,73]. Such advancements support the creation of simple and non-invasive tools for monitoring the oral environment.

Nanowire-based breath analysis also provides an additional non-invasive route for early oral cancer detection. AgNWs coated with zeolitic imidazolate frameworks (AgNWs@ZIF) form surface-enhanced Raman scattering active nanochains that enrich volatile sulfur compounds. This allows for highly sensitive detection of methanethiol, a key oral cancer biomarker [74]. When paired with an artificial intelligence (AI) system, particularly artificial neural networks [75], this platform has simulated oral-cancer breath profiles with 99% accuracy, demonstrating the potential for nanowire substrates and AI analytics to be used to support rapid chairside screening.

Silicon nanowire field-effect transistors (SiNW-FET) offer a clinically relevant approach for multiplex saliva testing. Antibody-functionalized SiNWs detect cytokines at levels far below those of conventional immunoassays, utilizing label-free modulation of surface charge to generate an electrical signal [37]. Their ability to measure multiple biomarkers in real-time supports the potential integration of this technology into routine screening workflows for oral squamous cell carcinoma.

Nanowires can also function as localized therapeutic platforms for oral cancer. Polypyrrole nanowire arrays loaded with doxorubicin (DOX/Ppy) allow on-demand drug release under electrical stimulation while simultaneously generating near-infrared photothermal heating [35]. This dual-trigger approach enhances local drug delivery and induces thermal damage to tumor cells, resulting in a reduction in the viability of oral cancer cells *in vitro* [76,77]. The combined electro-responsive release and photothermal effect disrupts cancer-cell survival mechanisms, highlighting the potential for minimally invasive, site-specific therapy.

Overall, nanowires can bridge the gap between early diagnosis and targeted therapy, offering rapid detection, real-time monitoring, and localized treatment options that align with the growing emphasis on personalized and minimally invasive oral cancer care.

4.5. Biomimetic enamel-like materials

Nanowires provide versatile structural units for constructing enamel-mimetic materials that reproduce key architectural and mechanical features of natural enamel. Ultralong hydroxyapatite nanowires (UHANWs), with diameters of approximately 50–200 nm and lengths ranging from 10 to 200 μm (aspect ratios >10,000), have garnered attention as effective building blocks for enamel-like tissue. Their

length, alignment potential, and chemical similarity to enamel make them a promising candidate for next-generation restorative materials.

Ordering UHANWs into enamel-like bundles enables the development of composites with mechanical behavior approaching a natural enamel structure. Wang et al. functionalized UHANWs with silane coupling agents (e.g., KH-570) and aligned the UHANWs into enamel rod-like bundles under shear forces. This process, combined with pressure-assisted densification, yielded composites with a hardness of between that of enamel and dentine, and demonstrated an enamel-like wear behavior, highlighting the importance of an ordered microstructure for mechanical performance [22].

UHANW assemblies can also reproduce enamel's anisotropic structure and esthetic properties. Anisotropic structure refers to the way enamel rods are aligned in different directions in natural teeth, resulting in enamel with varying mechanical and optical properties along different axes. Self-aligned UHANW networks have demonstrated enamel-level mechanical properties by mimicking prism orientation. When embedded in a polymer matrix with a matching refractive index, the composites also achieve enamel-like translucency and fluorescence [23]. This emphasizes that both structural anisotropy and optical matching are critical for clinical esthetics.

Core-shell nanowires can further strengthen enamel analogs by replicating enamel's amorphous-crystalline interface. Coating UHANWs with an amorphous zirconia (HA@A-ZrO_2) layer can recreate the amorphous intergranular phase of natural enamel, increasing fracture strength and strain at the single-nanowire level compared with uncoated UHANWs [29]. This nanoscale interface design provides a mechanism for damage tolerance that exceeds the capabilities of monolithic UHANWs.

When these core-shell nanowires are assembled into ordered arrays, they generate artificial enamel with superior integrated mechanical performance. Techniques such as bidirectional freezing, where nanowires are aligned along the growth direction of ice crystals formed from two temperature gradients, create aligned HA@A-ZrO_2 arrays that bonded effectively with polymer matrices, enabling efficient stress transfer and energy dissipation. The resulting composites exhibited stiffness and hardness exceeding natural enamel while retaining high toughness and viscoelasticity, demonstrating the value of hierarchy from atomic coating to bulk alignment [29].

Advanced techniques, such as magnetic assembly, allow for the introduction of gradient alignment for these enamel-like materials to achieve increased strength and crack resistance. Magnetically functionalized nanowires (HA@A-ZrO_2-F) can be oriented layer-by-layer orientation into decussating (criss-crossing) structures that resemble inner enamel [19]. This gradient arrangement promotes crack deflection and interfacial toughening under load, significantly enhancing fatigue resistance without compromising the material's high stiffness and hardness [78,79].

While UHANWs have demonstrated promising biomimetic outcomes in *in vitro* studies, their successful clinical translation will benefit from further advances in scalability and seamless integration into modern restorative workflows [80]. Recent developments in centrifugal casting and large-scale hydrothermal synthesis provide feasible pathways for industrial-scale fabrication [81,82]. In parallel, incorporating these biomimetic structures into pre-fabricated CAD/CAM blocks presents a practical route for clinical adoption. Such an approach would enable manufacturers to produce materials that replicate the mechanical anisotropy and aesthetics of natural enamel while remaining fully compatible with chairside milling technologies. These "biomimetic blocks" could, in turn, allow clinicians to leverage existing digital workflows to deliver restorations with enhanced wear resistance and improved biological integration compared to conventional isotropic materials.

5. Future perspectives

Most current studies are limited to *in vitro* experiments or short-term animal models, underscoring the need for comprehensive evaluation of long-term biosafety and systemic toxicity. In particular, the long-term safety of metallic nanowires warrants systematic investigation, including their ion release kinetics, potential systemic translocation, biodistribution, and accumulation in distant organs. Such insights are essential for defining safe dosage ranges and minimizing unintended biological effects. Table 3 summarizes different classes of nanowires exhibit material-specific limitations associated with their intended dental applications.

At the same time, successful clinical translation depends on the development of scalable synthesis methods capable of producing nanowires with consistent dimensions and surface properties under Good Manufacturing Practice standards. Establishing standardized evaluation frameworks for antibacterial performance, osteogenic potential, and long-term mechanical stability will further enable meaningful comparisons across studies and support regulatory approval.

With continued interdisciplinary collaboration among materials scientists, biologists, and clinicians, nanowire-based technologies are well positioned to progress from laboratory proof-of-concept toward reliable and predictable clinical applications in dentistry.

6. Conclusion

This narrative review highlights the transformative potential of nanowires as a foundational technological platform in modern dentistry. Owing to their high aspect ratio and structural tunability, nanowires provide a unique strategy to bridge nanotechnology with clinical needs, enabling the replication of key structural, mechanical, and optical features of natural dental tissues. From a translational perspective, nanowire applications in dentistry are at different stages of development. Nanowire-reinforced restorative materials and antibacterial nanowire composites are among the most advanced, as they can be more readily integrated into existing dental material systems. Approaches such as nanowire-based regenerative scaffolds, smart drug delivery systems, and biosensing platforms remain largely exploratory, with current evidence primarily derived from *in vitro* and early-stage *in vivo* studies. Overall, the integration of nanowire-based technologies represents a shift from conventional material replacement toward biomimetic restoration of dental form and function.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Melo MA, Guedes SF, Xu HH, Rodrigues LK. Nanotechnology-based restorative materials for dental caries management. Trends Biotechnol 2013;31:459–67.
[2] Jandt KD, Watts DC. Nanotechnology in dentistry: present and future perspectives on dental nanomaterials. Dent Mater 2020;36:1365–78.
[3] Deshpande AS, Daddanala A, Kaur M, Chahen NA, Patel M, Tummeti N. Nanotechnology in dentistry: bridging science and practice. Bioinformation 2025; 21:522.
[4] Padovani GC, Feitosa VP, Sauro S, Tay FR, Durán G, Paula AJ, et al. Advances in dental materials through nanotechnology: facts, perspectives and toxicological aspects. Trends Biotechnol 2015;33:621–36.

[5] Gulati K, Chopra D, Kocak-Oztug NA, Verron E. Fit and forget: the future of dental implant therapy via nanotechnology. Adv Drug Deliv Rev 2023;199:114900.
[6] Sowmya S, Bumgardener JD, Chennazhi KP, Nair SV, Jayakumar R. Role of nanostructured biopolymers and bioceramics in enamel, dentin and periodontal tissue regeneration. Prog Polym Sci 2013;38:1748–72.
[7] Dai D, Li D, Zhang C. Unraveling nanomaterials in biomimetic mineralization of dental hard tissue: focusing on advantages, mechanisms, and prospects. Adv Sci 2024;11:2405763.
[8] Kunrath MF, Diz FM, Magini R, Galárraga-Vinueza ME. Nanointeraction: the profound influence of nanostructured and nano-drug delivery biomedical implant surfaces on cell behavior. Adv Colloid Interface Sci 2020;284:102265.
[9] Tang X, Liu Y, Li L, Song Y, Dai Y, Yang Y, et al. Ferro-catalysis bioelectronics: progress and prospects. Nano Energy 2024;120:109059.
[10] Yang M, Kowsari K, Myrie NO, Espinosa-Hoyos D, Jagielska A, Kim S, et al. Additive manufacturing of high aspect-ratio structures with self-focusing photopolymerization. Light Adv Manuf 2022;3:542–71.
[11] Tian S, Chen X, Ding B. Manipulation of single nanowire and its applications. Small Methods 2025;9:e2402053.
[12] Wang Q, Huang Y, Qian Z. Nanostructured surface modification to bone implants for bone regeneration. J Biomed Nanotechnol 2018;14:628–48.
[13] Chavan K, Mane V, Raskar N, Dake D, Sonpir R, Dole B. Nanostructured MnO2-based Zn-doped Bi2O3 nanocomposite for improved antimicrobial and photocatalytic applications. Chem. Select 2024;9:e202403806.
[14] Mane V, Dake D, Raskar N, Sonpir R, Stathatos E, Dole B. A review on Bi2O3 nanomaterial for photocatalytic and antibacterial applications. Chem Phys Impact 2024;8:100517.
[15] Dake D, Raskar N, Mane V, Sonpir R, Stathatos E, Vasundhara M, et al. Intriguing physicochemical properties and impact of co-dopants on N-doped graphene oxide based ZnS nanowires for photocatalytic application. Sci 2023;13:7595.
[16] Mane VA, Dake DV, Raskar ND, Sonpir RB, Dole BN. Synergistic enhancement of photocatalytic and antifungal activities in microwave-assisted ZnO/Fe-doped Bi2O3 nanocomposites. Phys Status Solidi (a 2024;221:2300954.
[17] Mane V, Dake D, Raskar N, Sonpir R, Stathatos E, Dole B. Magneto-optical properties of Fe-doped bismuth oxide nanorods for photocatalytic and antimicrobial applications. Results Chem 2023;6:101083.
[18] Hu W, Jhulki S, Fu W, Chen L, Wang F, Turcheniuk K, et al. Strain-induced transformation of bulk alloys to zinc nanowires. Chem Mater 2021;33:5368–76.
[19] Li Y, Yue H, Lu J, Zhao Q, Liu S, Yin W, et al. A gradient enamel-mimetic composite via crisscross assembly of aligned hybrid nanowires for excellent mechanical performance. Adv Mater 2025:e2503537.
[20] Zhang Y, Li Z, Guo B, Wang Q, Chen L, Zhu L, et al. A zinc oxide nanowire-modified mineralized collagen scaffold promotes infectious bone regeneration. Small 2024; 20:e2309230.
[21] Li W, Deng X, Wu Z, Zhang L, Jiao J. An electrochemical sensor for quantitation of the oral health care agent chlorogenic acid based on bimetallic nanowires with functionalized reduced graphene oxide nanohybrids. ACS Omega 2022;7:4614–23.
[22] Wang QQ, Wu LP, Zhang S, Tao Y, Li YZ, Zhou QL, et al. Assembly of ultralong hydroxyapatite nanowires into enamel-like materials. J Dent Res 2022;101: 1181–9.
[23] Zhang S, Xu W, Wu L, Li X, Liu X, Wu X, et al. Bottom-up assembling hierarchical enamel-like bulk materials with excellent optical and mechanical properties for tooth restoration. Adv Healthc Mater 2024;13:e2401095.
[24] Ai M, Du Z, Zhu S, Geng H, Zhang X, Cai Q, et al. Composite resin reinforced with silver nanoparticles-laden hydroxyapatite nanowires for dental application. Dent Mater 2017;33:12–22.
[25] Zhu WQ, Shao SY, Xu LN, Chen WQ, Yu XY, Tang KM, et al. Enhanced corrosion resistance of zinc-containing nanowires-modified titanium surface under exposure to oxidizing microenvironment. J Nanobiotechnol 2019;17:55.
[26] Shen Z, Zhu YW, Wei YW, Zhou Y, Xu Y, Chen W, et al. Enhanced osteogenic activity of a titanium mesh modified with magnesium-doped nanowires for peri-implant guided bone regeneration: In vitro and in vivo. ACS Biomater Sci Eng 2025;11:2664–76.
[27] Shen Z, Xu Y, Qian XN, Zhou YH, Zhou Y, Zhou JY, et al. Enhanced osteogenic and antibacterial properties of titanium implant surface modified with Zn-incorporated nanowires: preclinical in vitro and in vivo investigations. Clin Oral Implants Res 2024;35:427–42.
[28] Han J, Ma B, Liu H, Wang T, Wang F, Xie C, et al. Hydroxyapatite nanowires modified polylactic acid membrane plays barrier/osteoinduction dual roles and promotes bone regeneration in a rat mandible defect model. J Biomed Mater Res Part A 2018;106:3099–110.
[29] Zhao H, Liu S, Wei Y, Yue Y, Gao M, Li Y, et al. Multiscale engineered artificial tooth enamel. Science 2022;375:551–6.
[30] Liu Y, Yang J, Guo Y, Liu Q, Chen J, Gao Y. Photocatalytic cleaning effect of TiO2-B@anatase nanowires increase the osteoconductivity of the titanium surface. SSRN 2025;04.
[31] Luo N, Deng YW, Wen J, Xu XC, Jiang RX, Zhan JY, et al. Wnt3a-loaded hydroxyapatite nanowire@mesoporous silica core-shell nanocomposite promotes the regeneration of dentin-pulp complex via angiogenesis, oxidative stress resistance, and odontogenic induction of stem cells. Adv Healthc Mater 2023;12: e2300229.
[32] Naguib G, Mously H, Magdy W, Binmahfooz A, Qutub O, Hajjaj M, et al. Color behavior of composite resin enhanced with different shapes of new antimicrobial polymer coated nanoparticles. BMC Oral Health 2023;23:771.
[33] Shan XF, Zhang ST, Qi ZW, Guan QH, Xu WW, Yi HN. Preventive effect of silver nanowires (Ag NWs) on oral implant repair infection. Micro Nano Lett 2022;17 (10):252–7.
[34] Hu C, Lin YQ, Yang YJ, Wang LL, Liang HM, Wu JR, et al. High-performance dental composites based on hierarchical reinforcements. J Dent Res 2022;101:912–20.
[35] Lee H, Hong W, Jeon S, Choi Y, Cho Y. Electroactive polypyrrole nanowire arrays: synergistic effect of cancer treatment by on-demand drug release and photothermal therapy. Langmuir 2015;31:4264–9.
[36] Kaasalainen M, Zhang R, Vashisth P, Birjandi AA, S'Ari M, Martella DA, et al. Lithiated porous silicon nanowires stimulate periodontal regeneration. Nat Commun 2024;15(1) (no pagination).
[37] Zhang Y, Chen R, Xu L, Ning Y, Xie S, Zhang GJ. Silicon nanowire biosensor for highly sensitive and multiplexed detection of oral squamous cell carcinoma biomarkers in saliva. Anal Sci 2015;31:73–8.
[38] Feng S-H, Li G-H. Hydrothermal and solvothermal syntheses. Modern inorganic synthetic chemistry. Elsevier; 2017. p. 73–104.
[39] Li J, Wu Q, Wu J. Synthesis of nanoparticles via solvothermal and hydrothermal methods. Handbook of nanoparticles. Springer; 2016. p. 295–328.
[40] Zhang Y, Wang J, Yang P. Convenient synthesis of Ag nanowires with tunable length and morphology. Mater Res Bull 2013;48:461–8.
[41] Leonardi AA, Faro MJL, Irrera A. Silicon nanowires synthesis by metal-assisted chemical etching: a review. Nanomaterials 2021;11:383.
[42] Biswas A, Bayer IS, Biris AS, Wang T, Dervishi E, Faupel F. Advances in top–down and bottom–up surface nanofabrication: techniques, applications & future prospects. Adv Colloid Interface Sci 2012;170:2–27.
[43] Mijatovic D, Eijkel JC, Van den Berg A. Technologies for nanofluidic systems: top-down vs. bottom-up—A review. Lab a Chip 2005;5:492–500.
[44] Kumar N, Salehiyan R, Chauke V, Botlhoko OJ, Setshedi K, Scriba M, et al. Top-down synthesis of graphene: A comprehensive review. FlatChem 2021;27:100224.
[45] Guo T, Wang D, Gao SS. The antibiofilm effect and mechanism of silver nanowire-modified glass ionomer cement against multi-species oral biofilm. BMC Oral Health 2025;25:160.
[46] Guo T, Yang M, Wang D, Zheng J, Gao SS. Antibiofilm and mechanical properties of silver nanowire-modified glass ionomer cement. J Dent 2023;135:104569.
[47] Lee H, Dellatore SM, Miller WM, Messersmith PB. Mussel-inspired surface chemistry for multifunctional coatings. science 2007;318:426–30.
[48] Yang L, Phua SL, Teo JKH, Toh CL, Lau SK, Ma J, et al. A biomimetic approach to enhancing interfacial interactions: polydopamine-coated clay as reinforcement for epoxy resin. ACS Appl Mater Interfaces 2011;3:3026–32.
[49] Gu Y, Zhang J, Zhang X, Liang G, Xu T, Niu W. Three-dimensional printed Mg-doped β-TCP bone tissue engineering scaffolds: effects of magnesium ion concentration on osteogenesis and angiogenesis in vitro. Tissue Eng Regen Med 2019;16:415–29.
[50] Utsel S, Bruce C, Pettersson Tr, Fogelström L, Carlmark A, Malmström E, et al. Physical tuning of cellulose-polymer interactions utilizing cationic block copolymers based on PCL and quaternized PDMAEMA. ACS Appl Mater Interfaces 2012;4:6796–807.
[51] Kunrath MF, Garaicoa-Pazmino C, Giraldo-Osorno PM, Haj Mustafa A, Dahlin C, Larsson L, et al. Implant surface modifications and their impact on osseointegration and peri-implant diseases through epigenetic changes: a scoping review. J Periodo Res 2024;59:1095–114.
[52] Zhu WQ, Li K, Su S, Chen W, Liu Y, Qiu J. Effects of zinc ions released from Ti-NW-Zn surface on osteogenesis and angiogenesis in vitro and in an in vivo zebrafish model. Front Bioeng Biotechnol 2022;10:848769.
[53] de Oliveira PGFP, de Melo Soares MS, Silveira e Souza AMM, Taba Jr M, Palioto DB, Messora MR, et al. Influence of nano-hydroxyapatite coating implants on gene expression of osteogenic markers and micro-CT parameters. An in vivo study in diabetic rats. J Biomed Mater Res A 2021;109:682–94.
[54] Wang W, Chen H, Xiao J, Luo D, Hou Y, Zhan J, et al. Microenvironment-responsive injectable hydrogel for neuro-vascularized bone regeneration. Mater Today Bio 2024;29:101369.
[55] Qi D, Wang N, Wang S, Liu L, Zhu S, She P, et al. High-strength porous polyetheretherketone/hydroxyapatite composite for the treatment of bone defect. Compos Commun 2023;38:101473.
[56] Zhao Q, Tang H, Ren L, Wei J. vitro apatite mineralization, degradability, cytocompatibility and in vivo new bone formation and vascularization of bioactive scaffold of polybutylene succinate/magnesium phosphate/wheat protein ternary composite. Int J Nanomed 2020:7279–95.
[57] Tsai K-Y, Lin H-Y, Chen Y-W, Lin C-Y, Hsu T-T, Kao C-T. Laser sintered magnesium-calcium silicate/poly-ε-caprolactone scaffold for bone tissue engineering. Materials 2017;10:65.
[58] Rycenga M, Kim MH, Camargo PH, Cobley C, Li Z-Y, Xia Y. Surface-enhanced Raman scattering: comparison of three different molecules on single-crystal nanocubes and nanospheres of silver. J Phys Chem A 2009;113:3932–9.
[59] Yang D, Zhao J, Liu H, Zheng Z, Adebajo MO, Wang H, et al. Enhancing photoactivity of TiO2 (B)/anatase core–shell nanofibers by selectively doping cerium ions into the TiO2 (B) core. Chem Eur J 2013;19:5113–9.
[60] Liu B, Khare A, Aydil ES. TiO2–B/anatase core–shell heterojunction nanowires for photocatalysis. ACS Appl Mater Interfaces 2011;3:4444–50.
[61] Wu H, Li Y, Shi L, Liu Y, Shen J. New advances in periodontal functional materials based on antibacterial, anti-inflammatory, and tissue regeneration strategies. Adv Healthc Mater 2025;14:2403206.
[62] Kim H-W, Kim H-E, Salih V. Stimulation of osteoblast responses to biomimetic nanocomposites of gelatin–hydroxyapatite for tissue engineering scaffolds. Biomaterials 2005;26:5221–30.
[63] Florimond M, Minic S, Sharpe P, Chaussain C, Renard E, Boukpessi T. Modulators of Wnt signaling pathway implied in dentin pulp complex engineering: a literature review. Int J Mol Sci 2022;23.

[64] Rathinam E, Rajasekharan S, Chitturi RT, Martens L, De Coster P. Gene expression profiling and molecular signaling of dental pulp cells in response to Tricalcium silicate cements: a systematic review. J Endod 2015;41:1805–17.
[65] He L, Zhou J, Chen M, Lin CS, Kim SG, Zhou Y, et al. Parenchymal and stromal tissue regeneration of tooth organ by pivotal signals reinstated in decellularized matrix. Nat Mater 2019;18:627–37.
[66] Neal AL, Kabengi N, Grider A, Bertsch PM. Can the soil bacterium Cupriavidus necator sense ZnO nanomaterials and aqueous Zn^{2+} differentially? Nanotoxicology 2012;6:371–80.
[67] Park KH, Choi Y, Yoon DS, Lee KM, Kim D, Lee JW. Zinc Promotes Osteoblast differentiation in human mesenchymal stem cells via activation of the cAMP-PKA-CREB signaling pathway. Stem Cells Dev 2018;27:1125–35.
[68] Song Y, Wu H, Gao Y, Li J, Lin K, Liu B, et al. Zinc silicate/nano-hydroxyapatite/collagen scaffolds promote angiogenesis and bone regeneration via the p38 MAPK pathway in activated monocytes. ACS Appl Mater Interfaces 2020;12:16058–75.
[69] Huang X, Huang D, Zhu T, Yu X, Xu K, Li H, et al. Sustained zinc release in cooperation with CaP scaffold promoted bone regeneration via directing stem cell fate and triggering a pro-healing immune stimuli. J Nanobiotechnol 2021;19:207.
[70] Alaohali A, Brauer DS, Gentleman E, Sharpe PT. A modified glass ionomer cement to mediate dentine repair. Dent Mater 2021;37:1307–15.
[71] da Silva JG, Babb R, Salzlechner C, Sharpe PT, Brauer DS, Gentleman E. Optimisation of lithium-substituted bioactive glasses to tailor cell response for hard tissue repair. J Mater Sci 2017;52:8832–44.
[72] Hu X, Wang L, He Y, Wei M, Yan H, Zhu H. Chlorogenic acid promotes osteogenic differentiation of human dental pulp stem cells through Wnt signaling. Stem Cells Dev 2021;30:641–50.
[73] Tsou S-H, Hu S-W, Yang J-J, Yan M, Lin Y-Y. Potential oral health care agent from coffee against virulence factor of periodontitis. Nutrients 2019;11:2235.
[74] Xie X, Yu W, Chen Z, Wang L, Yang J, Liu S, et al. Early-stage oral cancer diagnosis by artificial intelligence-based SERS using Ag NWs@ZIF core-shell nanochains. Nanoscale 2023;15:13466–72.
[75] Shin H, Choi BH, Shim O, Kim J, Park Y, Cho SK, et al. Single test-based diagnosis of multiple cancer types using Exosome-SERS-AI for early stage cancers. Nat Commun 2023;14:1644.
[76] Chen M, Fang X, Tang S, Zheng N. Polypyrrole nanoparticles for high-performance in vivo near-infrared photothermal cancer therapy. Chem Commun 2012;48:8934–6.
[77] Yang K, Xu H, Cheng L, Sun C, Wang J, Liu Z. vitro and in vivo near-infrared photothermal therapy of cancer using polypyrrole organic nanoparticles. Adv Mater 2012;24:5586–92.
[78] Liu X, Lin K, Wu C, Wang Y, Zou Z, Chang J. Multilevel hierarchically ordered artificial biomineral. Small 2014;10:152–9.
[79] Angker L, Swain M. Nanoindentation: application to dental hard tissue investigations. J Mater Res 2006;21:1893–905.
[80] Li B, Ai R, Chen X, Wang Y, Pan C, Song S, et al. Multiscale design of dental restorative materials: mechanistic foundations, technological innovations, and clinical translation. Adv Mater 2025;12:e11258.
[81] Liu L, Jiang G, Wang S, Zhao J, Yang J, Li Y. Response surface study on continuous supercritical hydrothermal synthesis of nano-zirconia: scale-up from laboratory to industrialization. Chem Eng J 2024;493:152393.
[82] Chakraborty D, Yurdusen A, Mouchaham G, Nouar F, Serre C. Large-scale production of metal–organic frameworks. Adv Funct Mater 2024;34:2309089.