# Bio-based Nanomaterials in Dentistry

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**Abstract**

This chapter will look at the big picture of bio-based nanomaterials in dentistry, discussing their types, applications, advantages, challenges, and potential solutions. Bio-based nanomaterials have generated considerable interest in dentistry due to their superior physical qualities, increased biocompatibility, and potential for targeted drug delivery. Various bio-based nanomaterials, including nanoparticles, nanofibers, and nanocomposites, are explored in restorative dentistry, preventive dentistry, endodontics, and dental implants. These materials offer promising alternatives to traditional dental materials, with applications ranging from antibacterial agents and remineralizing agents to biocompatible dental implants and endodontic sealers.

Despite their potential advantages, several challenges need to be addressed, such as potential cytotoxicity, regulatory hurdles, and the cost and scalability of production. The chapter highlights future research directions, including the development of novel bio-based nanomaterials, exploration of new applications

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in dentistry, advancements in nanofabrication techniques, and integration with digital dentistry. Furthermore, addressing safety concerns and improving biocompatibility will be crucial to successfully implementing bio-based nanomaterials in dental practice. The continued development and research in this field have the potential to revolutionize dentistry, offering improved treatment options and overall patient care.

**Keywords**

Nanotechnology · Dentistry · Dental materials · Bio-based nanomaterials · Nano dentistry

## 9.1 Introduction

### 9.1.1 Overview of Bio-based Nanomaterials

The concepts of nanotechnology have completely upended methods used in conventional dentistry (Freitas Jr 2000). Since the beginning of the millennium, numerous proposals have surfaced in the healthcare industry that holds great promise as innovative methods of dispensing pharmaceuticals, antimicrobials, and biomolecules. Different types of goods could be developed using nano-dentistry's many different methods. These include nano-composites, nano-impressions, antibacterial mouthwashes, and the widely used nano-fillers. Nanomaterials are special because of their unusual nanoscale surface activity and nanomechanical, nanoelectrical, nanomagnetic, nanooptical, and nanothermal behavior, as well as their ability to boost nanobiological activity, nanodrug delivery capacity, and their transbarrier transport ability, are to blame. Enhanced cell adhesion, proliferation, and differentiation can be achieved by tailoring sophisticated nano-biomaterials' surface characteristics and chemical composition to promote optimal protein activity (Chen et al. 1997; Bianchi et al. 2017).

### 9.1.2 Importance of Bio-based Nanomaterials in Dentistry

Nanodentistry products have limitless potential. New therapeutic ideas, especially those more conservative or regenerative, have helped dentistry progress in this direction. In addition to using nonliving substances, current ideas call for creating materials that can communicate with living species like bacteria, fungi, viruses, immune cells, and stem cells. As a result, nanotechnology has the potential to facilitate the creation of smart drugs with lower toxicity in a way that helps targeted activities in places where standard pharmaceuticals are ineffective. Despite the lack of human trials, these biomaterials show promise for routine usage in clinical practice and could make important contributions to many dental techniques in the near future.

### 9.1.3 Objectives of the Chapter

Our goal in this chapter is to present a synopsis of the numerous nanomaterials used in dentistry and to emphasize their advantages over traditional dental materials by discussing their application in preventative and restorative dentistry, endodontics, and implantology. Furthermore, we will discuss the difficulties and potential of using nanoparticles in dentistry.

## 9.2 Types of Bio-based Nanomaterials Used in Dentistry

### 9.2.1 Nanoparticles

Nanoparticles, nanocrystals, nanorods, and nanofibers are all examples of tailored nanomaterials, consisting of atomic clusters with dimensions between 1 and 100 nm (Masciangioli and Zhang 2003). Despite this, nanoparticles (NPs) are mostly used in nanocomposites for dental applications (Fig. 9.1) (Jandt and Watts 2020). Prosthodontics, endodontics, tooth restoration, orthodontics, periodontology, bone regeneration, and preventive dentistry are among the areas where NPs have been put to use (Sreenivasalu et al. 2022a, b). Dental infection treatment, prevention, and tissue engineering could benefit from using NPs (Magalhães et al. 2016; Yazdanian et al. 2021). Their specific surface area and extremely small scale make them particularly effective against bacteria by allowing them to bind to the anionic surface of bacterial cells (Cao et al. 2018). It was discovered that NPs exhibited antibacterial characteristics within the mouth when coupled and deposited onto biomaterial surfaces or fabricated using polymers (Saafan et al. 2018). In addition, innovative strategies based on the utilization of nanoparticles in dentin remineralization have been implemented in recent investigations (Liang et al. 2017, 2018; Weir et al. 2017; Sereda et al. 2019). Carbonaceous nanoparticles include buckyballs, graphene, and carbon nanotubes; nanostructured organic materials consist of dendrimers, micelles, liposomes, and polymers; nanostructured inorganic materials include nanometal and nanometal oxide particles; and so on (Ealia and Saravanakumar 2017).

#### 9.2.1.1 Nanometallic Particles

The wide-ranging bactericidal activity of nanometallic and nanoorganic particles has made them useful in many dental uses as antibacterial agents (Magalhães et al. 2016). Restoration margin biofilm development has been combated using composite resins and adhesives containing silver, silica, and zinc nanoparticles (Zhang et al. 2013; Rezvani et al. 2016; Teymoornezhad et al. 2016). Resins and composites containing calcium phosphate nanoparticles that can be recharged in carries

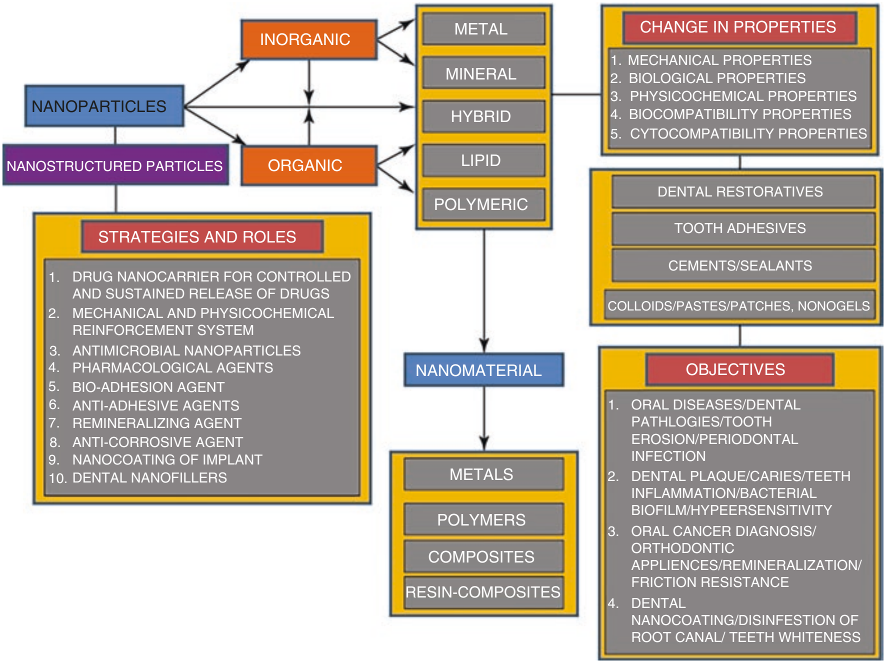

**Fig. 9.1** Application of nanoparticles in dentistry (Priyadarsini et al. 2020)

therapeutic application (Zhang et al. 2016a). Iron oxide- and copper oxide-covered dental implants are more antimicrobial and promote more effective bone regeneration (Xu et al. 2022). The prospective application of nanometallic particles in dental practice has been the subject of a number of investigations. Nanometallic particles have been shown to be cytotoxic to *Candida* and other microorganisms in dental plaque, including those on PAMA denture coating; however, they must be used at extremely low concentrations to avoid disrupting the mechanical qualities of the prosthesis (Ahmad et al. 2020). The most promising candidates to simultaneously combat viruses and bacteria are nanometallic particles. Molecular expression profile can be regulated, leading to antiviral effects. In addition to ROS production, cation efflux, degradation of biomolecules, ATP exhaustion, and membrane interaction, there is also membrane contact (Fig. 9.2) (Slavin et al. 2017).

### Nano-silver Particles

Antimicrobial characteristics and biological processes of nano-silver particles (AgNP) against bacteria, fungi, and enveloped viruses have received the greatest attention among nanometallic particles (Lara et al. 2011; Gupta et al. 2016; Banakar et al. 2022a, b, c). Nanosilver particles have killed several strains of bacteria that have developed resistance to multiple antibiotics (Lara and Ayala-Núñez 2010; Panáček et al. 2018). Bactericidal activity and resistance against it are modest

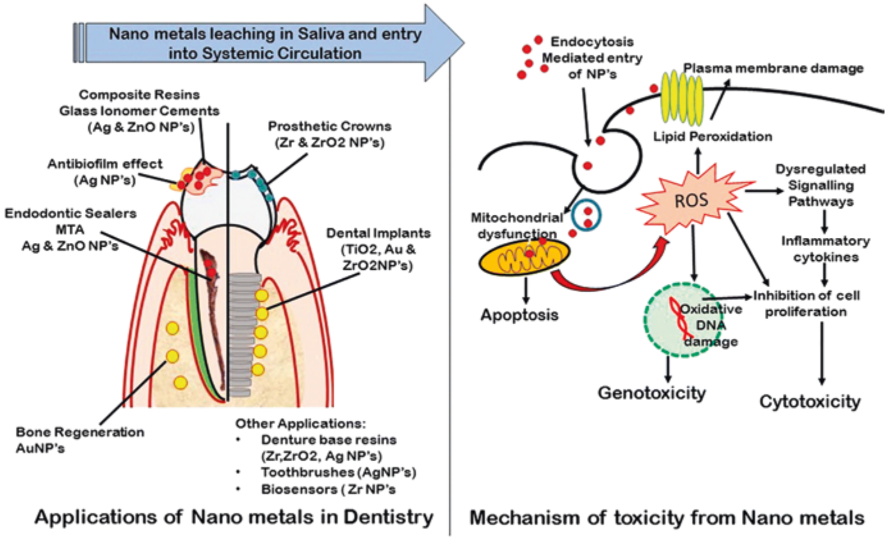

**Fig. 9.2** Possible toxicity mechanisms and dental applications of nanometals (Agnihotri et al. 2020)

(Percival et al. 2005; Corrêa et al. 2015). AgNPs mode of action is mostly attributable to the oxidative potential and silver cation discharge (Porenczuk et al. 2019). The typical size of an AgNP is less than 100 nm, and in addition to their low concentration antibacterial action (Oves et al. 2018), they are inexpensive, show little cytotoxicity, and provoke little immune response (Samuel et al. 2020). AgNPs are commonly used in dental prosthetics and microbiology (Fernandez et al. 2021).

AgNPs have shown great promise as an antiviral agent since they can block virus replication in several ways (Basak and Packirisamy 2020). They have increased compressive strength and bacterial growth inhibition due to silver nanoparticles mixed with glass ionomer cement (Paiva et al. 2018). Various methods of synthesis of nanoparticles are shown in Fig. 9.3.

## Nano-gold Particles

While nano-silver particles (AgNPs) have a low MIC (minimum inhibitory concentration), nano-gold particles (AuNPs) have a high MIC (Fu et al. 2014). However, because of their bactericidal activities on *S. mutans* (Park et al. 2014a, b), AuNPs are being explored as potential anticaries agents and added to oral disinfectants (Elgamily et al. 2018). As osteogenic agents for dental implants, AuNPs can be used cheaply thanks to their biocompatibility and surface specificity (Yi et al. 2010). In periodontal regeneration, AuNPs have demonstrated positive outcomes by boosting the quantity of stem cells in the human periodontal ligament (hPDLC) (Lu et al. 2010; Li and Li 2016). Dental bonding material (Dadkan et al. 2014) that contain nano-gold particles (AuNPs) have been used even though they cannot compare to

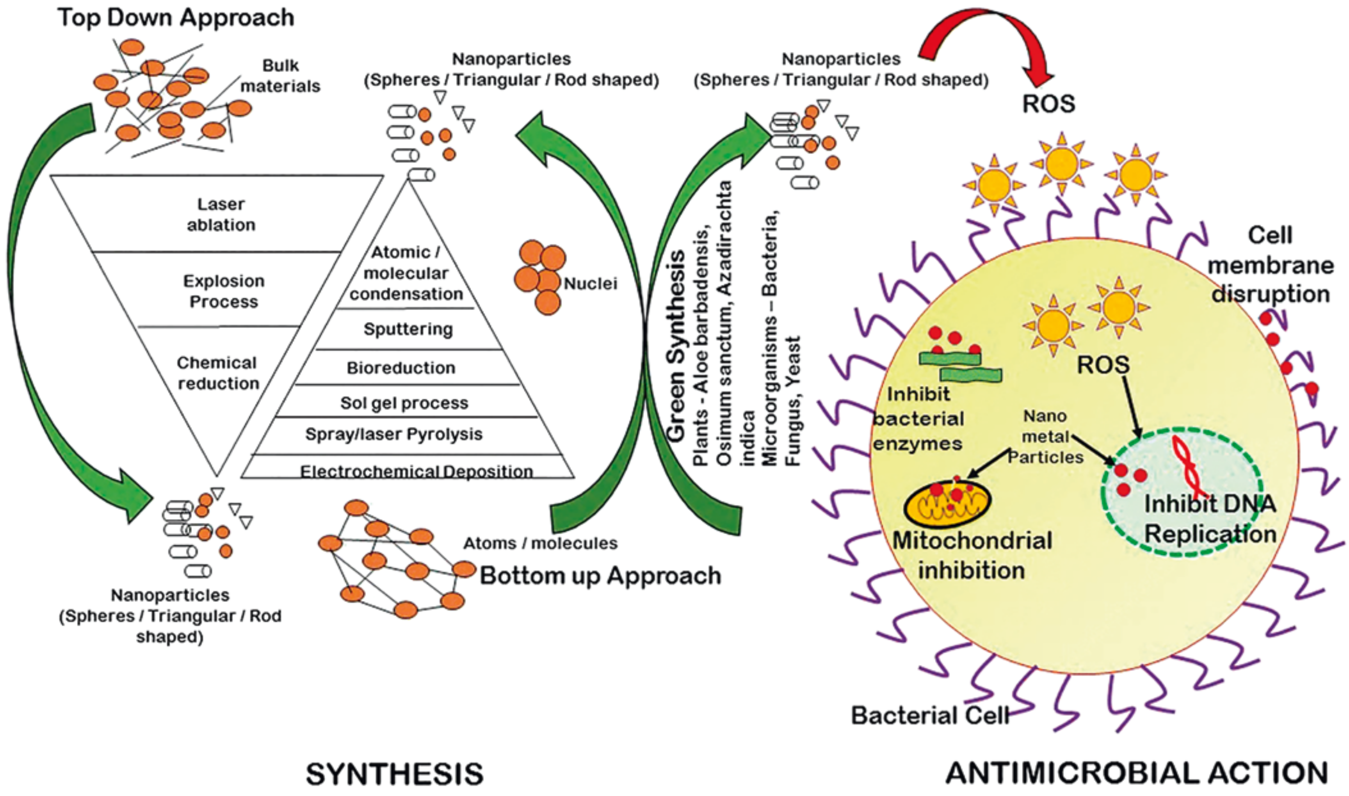

**Fig. 9.3** Synthesis and bactericidal activity of nanometallic particles utilized in dental materials (Agnihotri et al. 2020)

nano-platinum particles in terms of cytotoxicity (PtNPs) (Hashimoto et al. 2016). Synthesis challenges and high costs have prevented comprehensive research into using AuO NPs in dentistry (Moradpoor et al. 2021). Porous nanocrystalline hydroxyapatite has been modified with copper, gold, and silver nanoparticles to boost their ability to inhibit the growth of *S. aureus* and *E. coli*. However, among these NPs, AuO nanoparticles have the highest biocompatibility (Banerjee et al. 2018).

### Nano-copper Particles

The bactericidal effects of several dental supplies are enhanced by nano-copper(Cu) particles (CuNP), and the physio-mechanical properties of these products may also be enhanced (Xu et al. 2022). Oxidized cupric ions generated from copper nanoparticles (100 nm) have "contact killing" antibacterial activities and are both cost-effective and nontoxic (Ingle et al. 2014). Natural or chemical synthesis methods exist for creating these nanoparticles (Wei et al. 2010; Ermini and Voliani 2021). The application of CuNPs as an amalgam modifier and bactericidal agent has been investigated in dentistry. A variety of dental uses: cements, restorative supplies, resins, adhesives, irrigation solutions, obturations, orthodontic backets and arch-wires, implant coatings, and tissue engineering, have shown recent promise due to the use of CuNPs (Yoon et al. 2007; Argueta-Figueroa et al. 2015; Gosau et al. 2016; Alghanem et al. 2017; Renné et al. 2017; Zhang et al. 2022b).

### Nano-zinc Particles

Because of its advantageous biocompatibility, low toxicity, low cost, and excellent stability, ZnO NPs have remarkable biomedical potential (Xiong 2013). These NPs can be applied to various dental fields, including restorative, endodontic, regenerative, prosthetic, orthodontic, preventative, implantological, and periodontal care (Moradpoor et al. 2021). Since ZnO NPs have many useful features, technologies that use electricity, light, piezoelectricity, electromagnetic shielding, heat, motion, touch, sight, and smell are produced and employed to boost bacterial activity connected to caries (Mitwalli et al. 2020). Antimicrobial activity in both aerobic and anaerobic bacteria via oxidative stress has been demonstrated by Zn-NPs in adhesive resins, leading to enhanced material penetration and remineralization capabilities (Angel Villegas et al. 2019).

New endodontic sealers have been developed using ZnONPs, and existing sealers have been modified to optimize ZnO nanoparticles for enhanced physical, chemical, and antimicrobial performance (Kishen et al. 2008; Javidi et al. 2014b). Results from this and other preliminary research highlighting the prospective applications of nanotechnology in endodontics showed that nano-zinc oxide particles, with or without nano-chitosan particles, can be effectively integrated into zinc oxide eugenol-based sealer. The antibacterial effects were heightened (Kishen et al. 2008). Root canals treated with gutta-percha and nano-zinc oxide eugenol obturation were shown to have reduced apical fluid penetration compared to those filled with AH 26TM and micro-sized zinc oxide eugenol sealer (Javidi et al. 2014b). Similar negative effects were seen with nano-zinc oxide eugenol sealer as with other commercially available AH 26TM and PulpdentTM sealers (Javidi et al. 2015). Eugenol-based nano-zinc oxide sealant produced the same tissue responses to Pulp Canal SealerTM and AH 26TM implanted on rats in polyethylene tubing (Omidi et al. 2017). Zinc oxide eugenol sealer was modified by Versiani et al. by adding different amounts of ZnONPs. Improvements in stability in size, pliability, radiopacity, and dissolvability were observed when ZnONPs were substituted for 25% of the zinc oxide powder (Versiani et al. 2016). According to a recent study, more effective antibacterial activity was achieved at lower concentrations when nano zinc oxide and nano-silver particles were combined with a novel composite sealer made of urethane and acrylate (Chang et al. 2020).

#### Nano-iron Particles

These NPs have become widely used in biomedicine because of their superparamagnetism and their ability to adhere to biocompatible coatings (Arias et al. 2018). The iron oxides magnetite and maghemite are the most frequently utilized forms that exhibit magnetic properties variations (Can et al. 2012). Iron base NPs are important in eradicating antibiotic-resistant endodontic and dental implant biofilms (Sathyanarayanan et al. 2013). However, iron oxide must be used with the use of a stabilizer like dextran (Naha et al. 2019).

### 9.2.1.2 Nano-ceramic Particles

#### Nano-hydroxyapatite Particles

Nanoscale hydroxyapatite (nHAP) is a promising bioactive nanomaterial for dentistry. Metal substitutions in nHAP provide antibacterial properties, allowing it to be employed in treating dental caries (by increasing mineralization in early caries lesions) (Imran et al. 2023). nHAP-infused mouthwashes outperform commercially available mouthwashes in terms of tooth whitening. Adipose-derived mesenchymal stem cells show enhanced odontogenic potential when treated with nHAP. Furthermore, nHAP can improve the tooth-forming capacity of dental pulp stem cells isolated from adipose tissue (Shang and Kunzelmann 2021; Elgamal and Fahmi 2022).

#### Nano-zirconia Nanoparticles

Due to its crystalline structure, zirconium dioxide ($ZrO_2$) has a white, tooth-like appearance and a melting point of 2.715 C (Piconi and Maccauro 1999). Zirconia is a very desirable electro-ceramic because of its excellent conductivity to electricity. It benefits from high temperatures because oxygen ions may move freely throughout its structure (Heydari et al. 2021). Zirconia's insolubility in water makes it less appealing to microorganisms (Lughi and Sergo 2010; Zarone et al. 2011). Fixed partial dentures (FDP) made with three-unit zirconia ceramics using CAD/CAM technology have shown encouraging results (Vigolo and Fonzi 2008). Because of their bactericidal effects on some microbes like *E. faecalis* (Guerreiro-Tanomaru et al. 2014), $ZrO_2$ NPs are commonly utilized as an antimicrobial agent in endodontics. Incorporating zirconia NPs into Portland cement as a radio pacifier does not compromise the cement's biocompatibility (Hu et al. 2019). Zr nanoparticles added to PAMMA resins improve the material's bending strength, bending modulus, fracture resistance, and surface hardness (Alhenaki et al. 2021). Zirconium's potential in the biomedical field has been demonstrated by its widespread use in recent years (Chellan and Sadler 2015).

### Nano-silica Nanoparticles

Because of its ability to reduce a polished substrate's roughness, nano-silica particles are extensively employed as dental filler in restorative materials (Priyadarsini et al. 2018b). By incorporating silica NPs into silicon colloidal nanoparticle clusters, the compressive strength of SCNCs used in dental resin composites can be increased (Yang et al. 2020). The introduction of Si nanoparticles into a polymeric bonding solution has been shown to boost bond strength in dental adhesives compared to unmodified adhesive resins (Alhenaki et al. 2021).

### Nano-titanium Particles

Dental implants often consist of titanium (Ti) or titanium dioxide ($TiO_2$) due to these materials' high biocompatibility. The optical characteristics of teeth have been mimicked by using $TiO_2$ NPs in dental adhesives and resin. Agglomeration of $TiO_2$ NPs is not constant enough to make these materials useful for improving dental materials' mechanical properties (Sun et al. 2011). Due to their photocatalytic and lipid peroxidation capabilities, titanium dioxide ($TiO_2$) nanoparticles are effective antibacterial agents. When it comes to the fluidity of membranes and disruption of cell membranes, $TiO_2$ is unrivaled. $TiO_2$ NPs may also be effective against fluconazole-resistant fungi (Allahverdiyev et al. 2011; Haghighi et al. 2012; Ahmed et al. 2020). The growth of germs on normal hydroxyapatite (HA) as a scaffold is a major issue in implant surgery in dentistry. Microbes, particularly *S. mutans*, can be prevented from growing on HA by using CuO or $TiO_2$ NPs (Imani et al. 2021). Unlike other tooth replacement options, titanium implants may now be custom-made to match the biomechanical properties of real bone, thanks to advancements in additive manufacturing technology (Sidambe 2014). Coatings made of $TiO_2$ NPs are applied to dental titanium implants to boost their adhesive qualities and durability (Azzawi et al. 2018). Since $TiO_2$ NPs and cellulose nanocrystals (CNCs) were found to have enhanced antifungal effects on *C. albicans*, Sun et al. (2019) looked into their integration.

### Nano Magnesium Oxide and Calcium Oxide Particles

The particles perturb the membrane, which results in the escape of intracellular content and, ultimately, apoptosis, making them capable of killing bacteria of diverse Gram staining (Yamamoto et al. 2010; Jin and He 2011). Microleakage was reduced, and root dentin was strengthened through induction of remineralization after endodontic therapy when Ca nanoparticles were applied to the dentin (Toledano et al. 2020). In addition to exhibiting antibacterial characteristics against *C. albicans* and *S. aureus*, zein-coated MgO nanoparticles have demonstrated capacities to construct bacterial suppression zones when used as dental cement (Naguib et al.

2022). Coating metallic dental implants with calcium phosphate (CaP) compounds improves biocompatibility and has been shown to stimulate the growth of dental tissue and osteogenesis (Quaranta et al. 2010; Hamlet and Ivanovski 2011). For instance, compared to uncoated titanium (Ti) implants, those coated with CaP nanoparticles show improved osseo-integrative behavior (Bucci-Sabattini et al. 2010). Hydroxyapatite (HA) is the most frequently employed member of the CaP family because of its ability to improve biocompatibility and porosity similar to hard tissue, promote fusion of tissues and bone formation, reduce recovery time, and smooth the rough surface of metallic implants (Yang et al. 2009).

### 9.2.1.3 Nano-polymeric Nanoparticles (Natural)

#### Nano-chitosan Particles

Because of its inherent qualities (Rao and Sharma 1997; Xia et al. 2008) as a polymer and the benefits of its small particle size, chitosan is often employed in dentistry in the form of nano-chitosan particles (CNP) (Fakhri et al. 2020). Nano-chitosan particles (CNP) have antibacterial and antifungal actions at the same time, meaning they can be used in conjunction with tissue conditioners in whole dentin (Mousavi et al. 2018). Incorporating CNPs into GICs improves their mechanical characteristics in several ways (Mulder and Anderson-Small 2019). CNPs can erase dentin's smear layer and prevent germs from recolonizing the area. Making them a viable alternative to EDDTA or the final irrigant in pulpal therapy (del Carpio-Perochena et al. 2015). The oral bacteria *S. aureus, P. aeruginosa*, *E. faecalis*, and *C. albicans* were inhibited in vitro by 5% of CNPs for up to 48 incubation hours, as found by Mousavi et al. (2018). CS polymer's biggest drawback is its sensitivity to moisture (Zhang et al. 2017). However, several methods propose using it in conjunction with other polymers (Koosha and Mirzadeh 2015).

### 9.2.1.4 Poly (Lactic-co-Glycolic Acid) (Synthetic)

Dental medicine makes extensive use of PLGA nanoparticles as carriers for a wide range of purposes, consisting of the delivery of antibiotics to periodontal tissues, the reduction of dental plaque bacteria in chronic periodontitis, and the treatment of endodontic infections. In addition, dental implants with Positive outcomes have been observed using PLGA nanoparticles containing growth factors. PLGA showed superior and maintained antibacterial activity over 2 weeks when compared to nanoparticulate chitosan as a potential intracanal antibiotic delivery agent (Makkar and Patri 2017).

### 9.2.1.5 Nanofibers

Ceramic materials, metal compounds, and natural and man-made polymers are all potential sources for nanofibers. The ability of nanofiber to resist or remain stable can be further enhanced by combining these polymers (Grafe and Graham 2003; Nandi et al. 2019). Commonly reported polymers for fabricating nanofibers in dentistry include PCL, PDS, and CS (Sousa et al. 2020). New scaffolds for bone regeneration was the first branch of research into applying nanofibers in dentistry, with the second branch focusing on improving the mechanical qualities of dental materials. Nanofibers of hydroxyapatite and fluorohydroxyapatite, with dimensions from 250 nm to 1550 nm, were initially utilized in dentistry by Kim and Kim (2006).

The electrospinning method (Fig. 9.4) (Kim and Kim 2006) was employed to develop these materials; it is now the most popular method of nanofiber manufacturing because of its low cost, great repeatability, and ease of usage (Ranjbar et al. 2019). This method can provide nanofibers with dimensions as tiny as 3 nm and as large as 6 m and features including high porosity, nanoporous, specific surface area, and adaptability (Lopez and Trejo 2017; Mohammadian and Eatemadi 2017). In addition, there are now in-progress nanofibers that have been joined with metals, proteins, or inorganic substances (Ranjbar et al. 2019). The properties of these hybrid nanofibers, such as resistance to a range of temperatures, were encouraging (Ranjbar et al. 2019).

Hybrid nanofibers of polyacrylonitriles with cellulose nanocrystals have enhanced mechanical resistance when utilized in dental composites, as demonstrated by Peres et al. (2019). There has been much research into the mechanical qualities and biological attributes of hybrid nanofibers, including their ability to promote cell development and mineralization (Boda et al. 2019; Elsayed et al. 2019; Hosseini et al. 2019) helping cells stick together, multiply, and differentiate into bone (Kim and Kim 2006). After 16 days of treatment with PCL and PDS

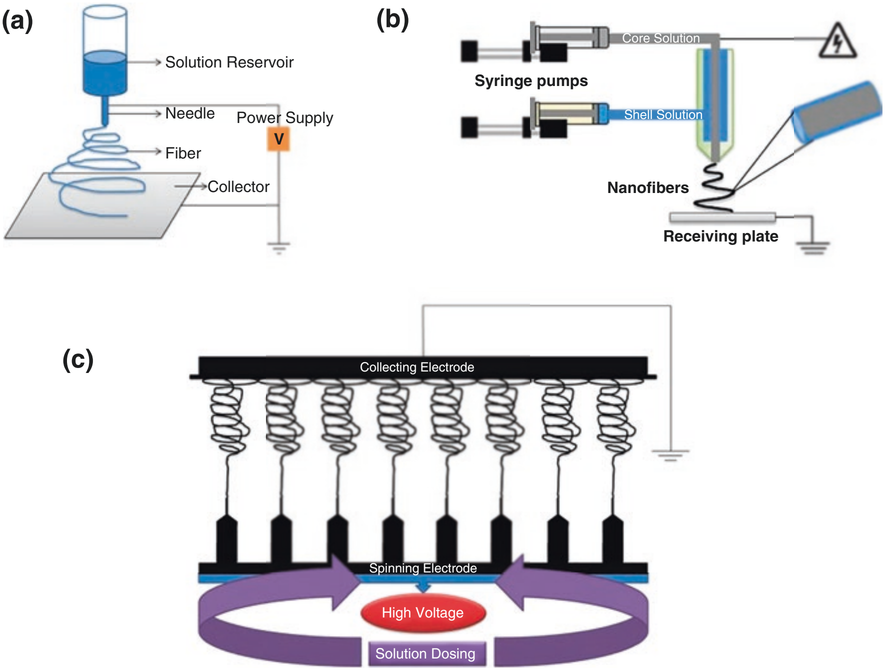

**Fig. 9.4** (**a**) Single nozzle electrospinning, (**b**) co-axial electrospinning, (**c**) multinozzle electrospinning (Muthukrishnan 2022)

nanofibers and *Elaeagnus angustifolia* extract, human dental pulp stem cells displayed enhanced bonding and growth, as well as overexpression of a few genes (Kim and Kim 2006). The potential for nanofibers to aid in the transport of various compounds in the form of drugs is another area of investigation. Dental biofilms may benefit from compounds with antibacterial and anti-cariogenic properties (Kaushik et al. 2016). As a medication delivery technique in dentistry, anti-infective nanofibers typically undergo electrofabrication, spontaneous arrangement, and component partitioning after the molecules have been blended together (Mohammadian and Eatemadi 2017). The adduction of different molecules and polymers can result in materials with varying stabilities and release times (Balagangadharan et al. 2017). The large-scale manufacture of nanofibers with mechanical qualities related to clinical dental demands also presents a number of promising prospects. To create smart and usable materials, dentistry must collaborate with other, more foundational fields, such as electrical and material engineering (García-López et al. 2017).

### Natural Nanofibers

Biopolymer cellulose, found abundantly in nature, is increasingly being used in the medical area by using nanoparticles like nano-cellulose fibers (CNFs) and nanocellulose crystals (CNCs) (Halib et al. 2017; Banakar et al. 2022a, b, c). As most dental restorative materials suffer from a degradation of their physical qualities when exposed to water, a high concentration of CNFs (plus water) in GIC has no useful applications. However, the mechanical features of typical GICs have progressed with the addition of cellulose nanocrystals and microfibers, which are easily accessible and researchable (Garoushi et al. 2020).

### Synthetic Nanofibers

In the form of a linear aliphatic polyester, caprolactone is biodegradable and has good temperature constancy but can undergo changes to its surface, including hydrophobicity and degradation, due to its receptivity to these modifications (Pulapura and Kohn 1992; Zhou et al. 2018). Due to its biocompatibility, PCL can be utilized to make nanotubes, nano-capsules, and nanofibers (Bharadwaz and Jayasuriya 2020). Several dental specialties use PCLs, including odontogenesis 3D-printed mandibular, and bone tissue reconstruction (Tao et al. 2019; Banakar et al. 2022). Studies have revealed that stem cells produced from gingival mesenchyme may proliferate more and differentiate into the mineralized matrix after exposure to PCL nanofibers (Jauregui et al. 2018). However, similar to the biomaterial poly(p-dioxanone), its higher price may be a drawback. Hydrophilic crystalline biomaterial PDS is made up of numerous nodes of 1,4-dioxan-2-one (DX) monomers, as opposed to the hydrophobic amorphous biomaterial PCL (Goonoo et al. 2015). Antimicrobial nanofibers made from this biomaterial are used in endodontics (Albuquerque et al. 2014; Banakar et al. 2022a, b, c). Chitosan is a cationic polymer made up of glucosamine and *N*-acetylglucosamine found in the cell walls of insects, bacteria, and fungi (Balagangadharan et al. 2017). Crustacean, insect, bacterial, and fungal cell walls all include chitosan, a cationic polymer made up of glucosamine and *N*-acetylglucosamine (Vasconcelos et al. 2013; Miller et al. 2018). Since CS's instability in damp conditions is a major drawback, numerous methods have been proposed using it in conjunction with other polymers (Koosha and Mirzadeh 2015; Zhang et al. 2017). Several reports have documented the application of these biomaterials in the oral cavity, where they have been linked to both conventional dentistry practices and novel applications like bone replacement and medication delivery (Bapat et al. 2019; Zafar et al. 2019).

#### 9.2.1.6 Nanocomposites

Nanoparticles have multiple uses in dentistry, but one of the most important is as fillers in nanocomposites. Improved mechanical features, superior ductility without sacrificing strength, antiscratch coating, optical settings (particle size determines the degree of light transmission), and thermal properties are touted as the main differences between nanocomposites and other composite materials (Omanović-Mikličanin et al. 2020).

When comparing nano-fill and submicron composites to conventional microhybrids, a systematic evaluation of ex vivo investigation fails to uncover any supporting proof to justify former use due to superior gloss stability and polishability (Kaizer et al. 2014). Nanocomposites may have drawbacks such as lower toughness and impact performance mixture composition, structural property connection, and particle dispersion, all of which present unique challenges (Omanović-Mikličanin et al. 2020).

Two microfilled composites, three nanofilled composites, and four universal hybrid composites were analyzed by Buen et al. for their inorganic percentage and mechanical characteristics (Beun et al. 2007). Researchers found that the stiffness properties of the nanofilled resin composites compared to the composites were much greater. However, additional investigations have not confirmed the enhanced mechanical capabilities of nanocomposites (Junior et al. 2008a, b).

The mean particle dimension of the nanosilica particles used in the dental resin composites examined by Karabela et al. (2011) ranged from 7 nm to 40 nm. Their findings revealed that composites exhibiting an identical ratio of silanized silica to organic matrix had very similar bending strength and bending modulus. However, smaller filler particle size was discovered to decrease the flexural modulus of composites, which may indicate a size threshold below which particle size no longer affects mechanical properties.

##### Organic–Inorganic Hybrids (Silicate-based Materials)

For these reasons, silica nanoparticles are widely employed in dental fillings as well as their great wear resistance and potent antimicrobial and antibacterial capabilities (De Cesero et al. 2017). Escherichia coli levels in test subjects' mouths dropped significantly. Near silica nanoparticles, bacterial species of both Gram-negative and Gram-positive classes, such as *E. coli* and *S. aureus* are killed (Song et al. 2009). Researchers mixed dental resins with nanosilica particles (OX-50) and permeable diatomaceous particles at various mass ratios (60–75%). It was found that the Resin improved mechanical characteristics by increasing the mass content of silica-diatomite. The composite has the maximum microhardness at 75% silica-porous diatomite particles (Wang et al. 2011).

## 9.3 Applications of Biobased Nanomaterial in Dentistry

### 9.3.1 Biobased Nanomaterials for Restorative Dentistry

#### 9.3.1.1 Overview of Restorative Dentistry and Common Materials Used

Restorative dentistry aims to replace missing teeth and other oral (gum and bone) tissue with artificial restorations so that the mouth may function normally again (Cox et al. 2000; Seo et al. 2014). Fillings, crowns, bridges, and implants are all viable options for tooth replacement. Nanotechnology's most well-known applications are in fillers and implants (Sreenivasalu et al. 2022a, b). Reviewing the literature, we find that since 1981, resin-based dental composites have been used for 44.0% of dental restorations, amalgams for 40.9%, dental polymeric restoratives for 13.4%, and other restorations (such as indirect and temporary restorations) for 1.7% (Eltahlah et al. 2018). Dental composites made of resin material have replaced amalgams in widespread use. Additionally, prior to the year 2000, restorations accounted for 56% of the total placement, whereas afterward, that number rose to 58% (Eltahlah et al. 2018). Poor dental repair life service and the high cost of dental care after the data uncover further clinical intervention. Dental composites based on the resin are utilized to create direct restorations that look and feel much like natural teeth (Yingchao et al. 2015). Composite systems come in three primary varieties: those that cure with light, those that cure on their own, and those that do both (Yan et al. 2021). Composite systems come in three primary varieties: those that cure with light, those that cure on their own, and those that do both (Zhang et al. 2018a; Cho et al. 2020). Polymer-based composites have three major drawbacks. Three major drawbacks of resin-based dental composites are their; recurrent cavities, susceptibility to marginal/bulk fracture, and their potential for health complications; studies have focused on addressing these issues (Aminoroaya et al. 2021). The best way to achieve a long-lasting composite material while keeping the process manageable and economical has not been determined as of yet (Raszewski et al. 2022). For almost a century, dentists have relied on dental amalgams, a mixture of elemental mercury (42–50%), Ag (22–32%), Sn (14%), and Cu (8%), for restorative dental work (Rathore et al. 2012; Kern et al. 2014). Modern amalgams have been demonstrated to be less stable and emit ten times as much mercury vapor, according to current studies on amalgam toxicity (Bengtsson and Hylander 2017). Restorative dentistry makes use of a variety of materials, including (1) dental cements, (2) alloyed gold, (3) ceramics(porcelain), and (4) denture PMMA base 5 bonding structures (Sahu et al. 2022). Because of this, digital precision restorations are also being used by dentists (Neme et al. 2002).

#### 9.3.1.2 Introduction to Biobased Nanomaterials As An Alternative to Traditional Materials

Many different nanomaterial-based dental products with dental uses have been developed by applying nanotechnology-based approaches. Resin-based nanocomposites and glass-ionomer nanocomposite cement are two examples (Siang Soh et al. 2006; Khurshid et al. 2015a, b). Demand for novel dental nanomaterials will drive innovation in the field, leading to enhanced biocompatibility and mechanical qualities in both stand-alone and integrated solutions Gurtu and Mehrotra 2012). Replacing missing tooth structure or oral (gingivae and bone) tissue with dental materials is what restorative dentistry is all about. Dentition (baby or adult), size, location, restoration function, and dental material composition can all shorten the lifespan of a dental restoration (Chadwick et al. 2001). Reducing the likelihood of secondary caries, which can cause tooth tissue deterioration, is a major focus of modern dentistry (Xie et al. 2011). Biofilm buildup is a major cause of unsuccessful repair efforts (Poole et al. 2020). Secondary caries can form around dental restorations at reported rates of 50–60% due to factors like microleakage and microbial activity, as well as a lack of resilience and inadequate bonding to tooth tissue (Fan et al. 2011). To combat tissue failure, dental restoratives must adhere to tooth tissue, have acceptable mechanical qualities like dentin and enamel, and come in various shades (Rekow et al. 2013).

Using nanoparticles in restorative dentistry began with the creation of nanocomposites (Mitra et al. 2003). These nanomaterials need to be able to withstand the harsh conditions of the mouth, which include constant moisture, masticatory forces, temperature and pH variations, microbial and enzymatic attacks, and protecting against the alteration of food color by exogenous materials (such as carotenoids, synthetic colors, and anthocyanins). Moreover, bite forces range from 100 to 500 Newtons, depending on the pressure area and the individual (Raadsheer et al. 1999; Castro-Rojas et al. 2021). Nano-sized particles and fibers are emerging as promising tools for preventing dental plaque and reducing the formation of biofilm (Cheng et al. 2015). Nanofibers are becoming an increasingly popular alternative to nanoparticles in dental applications (Samprasit et al. 2015). Glass ionomer cements with carbon nanotube reinforcement have superior color stability profiles compared to those with silver nanoparticle reinforcement (Sun et al. 2018). This means these resources are well-suited for posterior restorations, especially in baby teeth, where concerns about esthetics and color stability are less paramount (Pani et al. 2020). Although PMMA is a frequently used and clinically approved restorative material, creating nanoparticles presents unique challenges (Matsuo et al. 2015; Wen et al. 2016). The fact that this nanomaterial still lacks adequate antibacterial characteristics despite its extensive use is a major barrier.

#### 9.3.1.3 Properties and Advantages of Biobased Nanomaterials for Restorative Dentistry, Including Their Mechanical Strength, Durability, and Esthetic Qualities

Nanomaterials are distinguished not only due to specific surface area but also by the high surface energy resulting from the fact that they have a lot of atoms up top

(Nagpal et al. 2011). Despite their heterogeneous nanomaterial makeup, these materials have also proven to be biocompatible in patients' mouths (Eisenstat et al. 2021). High reactivity with inorganic dental filling materials is advantageous, while problematic oral tissue sensitivity includes gums, tongue, and enamel (Eisenstat et al. 2021). A particle's reactivity is proportional to its surface area, which is calculated by dividing its volume by itself. A particle's reactivity grows steadily as its radius decreases. Nanomaterials' small size, so that they can overcome specific biological barriers, also contributes to their toxicity (Adabi et al. 2017). Polymeric hybrid materials and glass-based dental cements are two examples of materials that take advantage of these characteristics and have found a home in restorative dentistry (Siang Soh et al. 2006; Khurshid et al. 2015a, b).

Composite resins, which look like natural tooth enamel, are widely utilized for dental fillings (Salim 2019). It was found through experimentation that a nanoparticle support system consisting of a 5% volume fraction of 40% titanium oxide ($TiO_2$) and 60% calcium aluminate ($CaAl_2O_4$) had specific surface contacts (frictional properties), and optimal nano-configuration (Salim 2019). Nanocomposite resin filling polymethyl methacrylate (PAMMA) has shown acceptable cytotoxicity metrics, with minimum erythrocyte damage and even promoting cellular activity (Chen et al. 2019). With its tougher enamel surface replacement and greater wear resistance compared to other artificial materials, PAMMA has been used for a long time with positive results for dentures (Kamonwanon et al. 2015).

#### 9.3.1.4 Examples of Biobased Nanomaterials Used in Restorative Dentistry

##### Bio-active Glass Nanoparticles

There have been numerous attempts to create novel nanocomposites that can match the tooth's physiological elements composition. The tooth's primary inorganic mineral is HA. Mixing HA NPs with other nanoparticles like chitosan (Chung et al. 2016), CuO/$TiO_2$ (Imani et al. 2021), silver (Melo et al. 2013; Fatemeh et al. 2017), titanium dioxide (Behnaz et al. 2018; Kotta et al. 2020), TiF4 (Abbatepaulo et al. 2019), Zinc oxide (Jowkar et al. 2018), Ag NPs, graphene oxide (GO), multiwalled carbon nanotubes (MWCNTs), and graphene oxide nano-ribbons (GONRs) results in novel HA nanocomposites (Balu et al. 2021). Because of their large surface area concerning their size, nanoparticles can provide strong mechanical interlocking with the polymer matrix (Arcís et al. 2002). Additionally, this quality results in nanoparticles with a thixotropic thickening effect and reduced viscosity, enhanced handling capabilities, and increased hardness (Sharan et al. 2017). Nanoparticle-filled materials' resistance to micro-fracture via cyclic fatigue loading is the primary field of use (Turssi et al. 2005). An in vitro study infused nanoparticles of silica and hydroxyapatite in dentin blocks for the goal of collagen remineralization. Then, the infiltrated blocks were compared to their noninfiltrated counterparts in terms of calcium and phosphorus levels, mineral volumetric content, and mineral segregation. Phosphorus and calcium levels were restored by 55% in the HA group, while 20% were restored in healthy dentin after silica NPs penetration (Besinis et al. 2014). Researchers in another study looked at how well nano-HA remineralized the tooth's cementum and enamel at its edges after placing a CAD/CAM ceramic restoration. After the area has been demineralized, a treatment of nano-HA or clinpro (CP) can be applied. Both enamel and cementum surfaces treated with nano-HA were more resistant to micro-abrasion than their untreated counterparts (Juntavee et al. 2018).

### Bioactive Glass-Modified Composite Resins and Natural/Synthetic Polymers (Such as PVA, Chitosan, PEG, Gelatin) Modified Composite Resin

GICs are versatile dental materials because their characteristics may be adjusted by modifying the powder/liquid ratio or the formulation (Nicholson 1998). Some research attempted to fuse silver-based amalgams with traditional GICs to create a ceramic/metallic composite cement; however, insufficient bonding was found between the ceramic and metallic components (Kilpatrick et al. 1995; Sarkar 1999). The mechanical properties of ordinary GICs have been studied, and it has been found that adding components such as Al2$O_3$, C, $Ca_3(PO_4)$2, glass, SiC, and $ZrO_2$ can enhance fracture resistance and strength. For instance, compared to classic glass ionomer cement, the addition of glass fibers increased fractural hardness by 140% (Lohbauer et al. 2004). In addition, some studies have looked at slow-release bioactive compounds as a way to boost biomimetic reactivity and bioharmony (Moshaverinia et al. 2008; De Paula et al. 2011). Many GICs have recently been created to stimulate cell and tissue proliferation, increase osteoconductivity, and induce osteoinductivity (Webster 2003). Although the addition of these materials improves the GICs' bioactivity and physiochemical properties (Khoroushi et al. 2013; Chen et al. 2016; De Caluwé et al. 2017), other research has shown that high bioactive glass concentration level and supplementary bioactive component in GICs include mechanical properties (Yli-Urpo et al. 2005).

Nano-fillers, materials on the nanoscale scale, have been used in the matrix of GICs in response to the need for new incorporating fillers, allowing for larger filler loads and less curing shrinkage, as well as enhanced strength and hardness over traditional GICs (Terry 2004; Raj and Mumjitha 2014). Nanoparticles of zirconia oxide ($ZrO_2$) can boost strength by 20% (Wang et al. 2006). Carbone nanotubes were included, and the material's mechanical qualities and other features were enhanced by 30% (Peigney et al. 2000; An et al. 2003). Alumina, hydroxyapatite, silica, titania, and zirconia are some of the most widely used nanofillers (Moy et al. 2005; Sadat-Shojai et al. 2010; Besinis et al. 2012; Safi 2014; Yu et al. 2014). Incorporating nano-HA and silica into GICs improved their mechanical characteristics and maintained their fluoride release (Moheet et al. 2018). Increased compressive and bending strength, better aqueous dispersibility, and less microleakage were all the results of silica adduction (Vanajassun et al. 2014; Calvo et al. 2015; Sadeghi Aqbash and Rahimnejad 2017), resin-modified glass ionomers were also effective against microorganisms (Elsaka et al. 2011; Esmi et al. 2014). Antibacterial activity and biocompatibility were improved by including alumina/zirconia and hydroxyapatite in the GICs (Anusha Thampi et al. 2014). Graphene (GFN) is notable for its increased wear resistance of dental composites and its ability to stimulate biofilm development (Hirsch 2010). GFNs are investigated for their capability to strengthen the structural settings of glass ionomers (Ge et al. 2018). Glass ionomer cements' poor resistance to wear (Xu and Burgess 2003) is due to the void inclusion during cement mixing, which might eventually degrade the set cement (Kent 1973; Liu et al. 2014). Several studies have found evidence that the incorporation of nanosized particles into GICs as the mechanism by which vacancies are filled (Elsaka et al. 2011; Gjorgievska et al. 2015). Various nanoparticles were added to GICs at varying concentrations and kinds in order to increase their mechanical qualities (surface hardness, nano-indentation adhesion strength to dentin, flexural, and compressive strength) (Paiva et al. 2018; Jowkar et al. 2019). Improved chemical, thermal, and physical features were demonstrated by the addition of multilayered carbon nanotubes to glass ionomer cements, guaranteeing their placement at the back of a tooth for restoration, as demonstrated by Goyal and Sharma (2021).

### Chitosan Nanomaterial

Chitin, found in crustacean shells like shrimp and crab, is the source of the organic, natural biopolymer known as chitosan. The positive charge of chitosan enables it to interact with the bacterial membrane's negative charge, resulting in a wide-ranging bactericidal activity. The increased permeability and subsequent leakage of intracellular components from this interaction ultimately lead to cell death (Kong et al. 2010). Chitosan is antibacterial, biodegradable, and biocompatible. It can also serve as a chelating agent (Dutta et al. 2004; Banakar and Sijanivandi 2022).

The use of chitosan as a nanomaterial has been shown to have several applications in dental care. Ectopic bone formation was reported in mice when chitosan nanoparticles were applied to titanium implants and used with BPM-2 (bone growth protein) (Stewart et al. 2018). Nair et al. showed that regarding antibiofilm efficacy, CS- and ZnO-NPs exhibited antibacterial effects against two strains of *E. faecalis* (Nair et al. 2018). Regarding cytotoxicity, Elgendy and Fayyad (2017) compared CS-NPs to non-nanosized chitosan particles and propolis terms cytotoxicity. Propolis, a resinous material with antibacterial action, has shown promise for use in restorative dentistry. Propolis, a resinous material with antibacterial action, has shown promise for use in restorative dentistry (Abbasi et al. 2018). When stem cells from the tooth pulp were exposed to various materials, it was shown that CS-NPs induced the fewest alterations in cell phenotype (Elgendy and Fayyad 2017). CS-NPs show weak processing and mechanical properties, and they are insoluble in many common organic solvents, despite their promising biocompatibility, antibacterial activities, and low toxicity levels (Eisenstat et al. 2021).

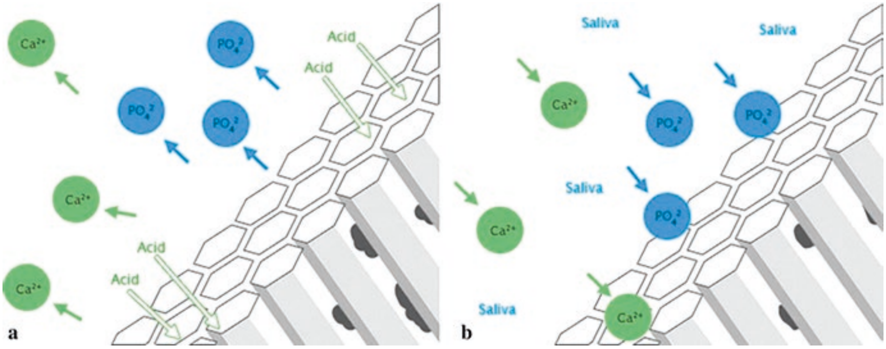

**Fig. 9.5** Schematic drawings of (**a**) demineralization and (**b**) remineralization processes of dental enamel (Dorozhkin 2016)

## 9.3.2 Biobased Nanomaterials for Preventive Dentistry

### 9.3.2.1 Overview of Preventive Dentistry and Common Materials Used

Bacterial infection of the tooth's hard enamel causes dental caries. Over time, acid- and fermentable-carbohydrate-producing microbes contribute to this process, creating a cavity (Fig. 9.5) (Selwitz et al. 2007). Problems associated with dental caries have a negative effect on people of all ages, including difficulties eating, tooth loss, pain, slowed language development in youngsters, and increased absence from work or school (Peres and Heilmann 2015; Ramos-Jorge et al. 2015). Preventing dental caries helps keep teeth strong, stops enamel from wearing away, and promotes the body's natural healing process (Ismail et al. 2013). In the case of early-stage lesions, fluoride can speed up and improve the remineralization process. Home-based topical treatments that can be used as a paste, gel, or mouthwash (Newbrun 2001). In the last several decades, there has been a rise in the use of gums without sugar, whitening pastes, and tooth varnishes that contain calcium and fluoride that dissolves in water and is readily absorbed. These ingredients can be found in products like calcium phosphoryl oligosaccharides with casein-modulated amorphous calcium phosphate phosphopeptide (Reynolds et al. 2003; Hamba et al. 2011; Kitasako et al. 2012). The ability to replenish fluoride ions should also allow glass-ionomer fillers that have already reacted on a resin-based product's surface to gradually release fluoride over time (Tay et al. 2001). These binders release extra ions stimulating mineral growth (Tay et al. 2001).

### 9.3.2.2 Introduction of Biobased Nanomaterials for Preventive Dentistry, Such as Antibacterial and Remineralizing Agents

Because of how much we now know about dental issues, preventive dentistry has become crucial (Acharya et al. 2018). Preventive dentistry uses nanomaterials for purposes such as biofilm management on tooth surfaces and demineralizing microscopically small enamel defects (Visscher et al. 2018). Silver nanoparticle (AgNP) formulation for caries removal is provided by Schwass et al. (2018). Here, monodispersed stabilized Ag NPs with 6.7–9.2 nm diameter were produced via reducing silver nitrate chemically ($AgNO_3$) by sodium borohydride ($NaBH_4$) while being surrounded by sodium dodecyl sulfate, constituting constituents of a micelle aggregation. Biofilm coated with AgNP significantly changed as measured by microplate absorption of crystal violet light at 590 nm. This formulation inhibited the development of biofilms in vitro for *Streptococcus* spp. and *Enterococcus faecalis* strains, suggesting a therapeutic effect. Also, the dental bacteria *Lactobacilli* sp. and *Streptococcus mutans* were inhibited by a formulation including silver oxide nanoparticles ($Ag_2O$ NP) and Ficus benghalensis prop root extract (FBPRE). Therefore, after conducting several animal testings, they reasoned that synthesized FBPRE and $Ag_2O$ NPs might be an effective germicidal component in toothpaste (Manikandan et al. 2017).

#### 9.3.2.3 Properties and Advantages of Biobased Nanomaterials for Preventive Dentistry, Including Their Ability to Inhibit Bacterial Growth and Promote Remineralization

Preventive dentistry exists to prevent tooth decay and gum disease by eliminating plaque early on through mechanical and behavioral management to limit or minimize rates of dental disease. Several nanomaterials have entered the dentistry market in recent years, such as toothpaste, mouthwash, and liquid (Sahoo et al. 2007). Carious lesions and periodontal disease can be avoided with regular use of mouthwashes and toothpaste (Ferrari 2005). Nano-hydroxyapatite (n-HA) found in toothpaste and mouthwashes has increased remineralization and strengthened tooth enamel and dentine. Acidic erosions (white spots) on teeth can be repaired by interacting with these nanoparticles at the nanometer scale (Li et al. 2008). Remineralization and restoration of enamel surfaces occur when calcium and phosphate ions released by n-HA enter enamel rods and crystallize to produce apatite (Roveri et al. 2009; Pepla et al. 2014). In clinical trials, toothpastes infused with nanomaterials significantly reduced cavities by 56% compared to those without nanomaterials (AlKahtani 2018).

The application of n-HA in dental products has been found to minimize dentine hypersensitivity and prevent bacterial colonization of tooth surfaces (Freitas Jr 2005; Gupta 2011; Najibfard et al. 2011). Results showed that tooth hardness and remineralization benefited from adding 3% nano-sized sodium tri-phosphate to toothpaste. There was a 20% improvement in enamel hardness and a 66% improvement in enamel remineralization (Danelon et al. 2015). Colloidal gold or silver (gold or silver nanoparticles submerged in a solvent) placed between the bristles of a toothbrush reported to decrease dental cavities and promote dental wellness (Raval et al. 2016). In order to destroy biofilm and/or plaque, silver and gold's positive charges attract the negatively charged phosphate molecules (Raval et al. 2016). X-ray imaging is widely used for caries detection nowadays, although only in the advanced stages of caries (Eisenstat et al. 2021). Recently discovered starch nanoparticles are sensitive enough to identify the tiniest flaws in tooth enamel that form at the start of caries development. These nanoparticles are small enough to enter microscopic pores and bind to a cavity in its early stages of development. In this way, they can emit a luminescent blue hue when exposed to bright curing light. In addition, restorative gels containing starch nanoparticles bound with calcium and phosphate are currently under development with the potential to enhance the remineralization of decaying teeth (Eisenstat et al. 2021).

#### 9.3.2.4 Examples of Biobased Nanomaterials Used in Preventive Dentistry

##### Phosphopeptide-Calcium Amorphous Complex (CPP-ACP)

Because of this, it is hypothesized that acidic conditioners and adhesive monomers will diffuse more easily through caries-affected dentin (Haj-Ali et al. 2006). The physical and topographical differences between CAD and normal dentin improve the binding strength of composite resin to CAD (Zaki et al. 2016). A paste containing a phosphopeptide-calcium amorphous complex can supersaturate the readily accessible calcium and phosphate ions in dental substrates (Poggio et al. 2013). This allows for the remineralization of the intratubular dentin that has been partially demineralized due to the diffusion and subsequent deposition of Ca and P ions into the porous lesions (Poggio et al. 2013). The beneficial effect of restoration of mineral content within dentine in CAD may be nullified by the unfavorable effects of CCP-ACP on dentin's calcium precipitates (Jowkar et al. 2021). Antioxidant polyphenolic substance proanthocyanidin (PA) is also employed as a dentin pretreatment for CAD (Shafiei et al. 2020). In addition to boosting collagen production, PA also slows down the degradation of collagen matrices (Ku et al. 2007). The utilization of a 6.5% PA solution on dentin considerably increased the initial adhesive strength between the composite material and dentin, as shown by Macedo et al. (2009). The use of PA in conjunction with fluoride has been proposed as a means of preventing caries by Pavan et al. (2011). However, PA in dental adhesives can prevent the adhesive resins from curing when exposed to light (Liu and Wang 2013).

##### Carbonate Hydroxyapatite (HA) and Zinc Carbonate HA

The most efficient dentifrice for occluding dentinal tubules has been discovered to include 20% nano-sized carbonate apatite (n-CAP) (Lee et al. 2008). In order to remineralize the damaged enamel surfaces, carbonate-hydroxyapatite nanocrystals (CHA) have been used. New apatite mineral is deposited over the degraded enamel surface during remineralization (Roveri et al. 2008; Al Asmari and Khan 2019). Dentin hypersensitivity can be alleviated by regular use of CHA dentifrice for 4–8 weeks, as shown by research by Orsini et al. (2010). Another study compared three desensitizing dentifrices, and Zn-CHA dentifrice was found to be the most effective at reducing dentine hypersensitivity quickly (Orsini et al. 2013). Zinc-modified hydroxyapatite toothpaste has been found to prevent enamel demineralization in vitro (Alessandri Bonetti et al. 2014).

### Metal and Metal Oxide Nanoparticles

Silver nanoparticles for caries prevention show promise due to their wide range and nonresistant antibacterial capabilities (Espinosa-Cristóbal et al. 2019). Nano-silver particles have been proven in lab investigations to suppress both mature biofilms and planktonic strains of *S. mutans* isolated from a clinical setting (Pérez-Díaz et al. 2015). not only do they have beneficial effects against germs, but they can also increase the microhardness of tooth tissue (Scarpelli et al. 2017). Collaborative applications involving silver NPs and other nanoparticles are possible. Nanosilver particles combined with sodium fluoride have shown promise in reducing tooth decay and boosting remineralization (Zhao et al. 2020; Aldhaian et al. 2021). Clinical research found that the combination of a sodium fluoride oral rinse with nanosilver particles effectively prevented dentin caries without discoloring the teeth (dos Santos Jr et al. 2014). The use of nanosilver particles into fluoride varnish was reported to be an adequate method of encouraging dental remineralization in an in vivo investigation (Butrón-Téllez Girón et al. 2017).

Compared to nano-scale silver and zinc, nano zinc-oxide particles are more bio-harmonious (Jiang et al. 2009). Nano-zinc oxide and copper oxide particles containing fluoride have been found to show bactericidal characteristics, inhibit enzymes, and promote bio-mineralization in dental decay-inducing environments (Matsuda et al. 2019). Zinc oxide's effectiveness in preventing caries when combined with organic chemicals has been demonstrated in laboratory experiments. For instance, no cell death was seen when human gingival fibroblast cells were exposed to a chitosan hydrogel combined with a zinc oxide-zeolite nanocomposite. The composite material was also proven to inhibit dental plaque formation by *S. mutans* (Afrasiabi et al. 2021). In addition, it was shown that *S. mutans* was inhibited by a nanocomposite material made of zinc oxide and decorated graphene (Kulshrestha et al. 2014; Zanni et al. 2016).

Finally, magnesium NPs have been claimed to be effective in preventing tooth decay, according to a small-scale investigation. Different studies have found either a significant or nonsignificant (MacKeown et al. 2003) link between magnesium and tooth decay (Jawed et al. 2011).

### Carbon Nanotubules

Carbon nanotubes (CNTs) are hollow, cylinder-shaped structures made of a triangular lattice of carbon atoms from nanometer to micrometer in length (Journet and Bernier 1998). CNTs have been applied in dentistry for the last couple of decades, mostly as scaffolds and drug delivery systems for specific areas of the mouth (Kleverlaan et al. 2004). The loading of CNTs as padding or reinforcement to polymers or other supplies is constrained by agglomeration. Increased CNT dispersion of CNTs results in less clumping, which is often addressed through chemical functionalization. This results in a higher loading capacity of the matrix, which improves the final composite's mechanical properties (Bonilla-Represa et al. 2020).

### 9.3.3 Biobased Nanomaterials for Endodontics

#### 9.3.3.1 Overview of Endodontics and Common Materials Used

Current research shows that microbial mats have a critical role in initiating and developing apical gum disease, a form of endodontic infection (Nair 1987; Vickers 2017). With the aim of successfully eradicating root canal infection, an effective chemo-mechanical debridement process is required. Bacterial mats, however, take advantage of several factors that ensure their continued existence. For instance, a self-synthesize EPS matrix protects the bacteria in a dental plaque. The efficiency of root canal disinfectants is diminished due to the matrix's resistance to penetration (Wilson 1996; Skrdlantova et al. 2005). Furthermore, infection can persist in the root canal system if microscopic anatomical sections are not adequately cleaned during debridement (Vickers 2017). The failure of post-treatment results is often associated with the survival of bacteria(Wong and Cheung 2014), notably *E. faecalis,* because irritants often fail to reach the deep regions of dentinal tubules (Love 2001; Stuart et al. 2006). The most common irrigant used in endodontics is sodium hypochlorite (NaOCl), with concentrations typically falling between 0.5% and 5.25% (Zehnder 2006; Dutner et al. 2012). Previous studies have widely acknowledged its antibacterial and tissue-dissolving properties (Byström and Sundqvist 1983; Hasselgren et al. 1988). However, there are potential drawbacks to using NaOCl, such as the degradation and weakening of the organic dentin matrix (Marending et al. 2007), damage to the periapical tissue (Hülsmann and Hahn 2000), and the development of persistent bacteria (Evans et al. 2002). It has been suggested that using a 2% chlorhexidine solution as an endodontic disinfection would be less harsh on the teeth (Zehnder 2006). Its fundamental drawback, however, is that it cannot decompose necrotic tissue (Naenni et al. 2004) and the fact that it is not as efficient against Gram-negative bacteria (Ringel et al. 1982). 2.5% NaOCl was reported to be more effective against *E. faecalis* biofilm when used in conjunction with 17% EDTA (Ozdemir et al. 2010). Dentin demineralization and erosion can occur with excessive EDTA use, especially when paired with NaOCl (Niu et al. 2002). Hydrophilic and biocompatible mineral trioxide aggregate (MTA) endodontic cement that promotes bone growth. Tricalcium oxide, silicon oxide, and bismuth oxide are the fine trioxides that make up this aggregate, along with additional hydrophilic elements (Lopes et al. 2019; Serin Kalay 2019; Tu et al. 2019; Lin and Lin 2020; Liu et al. 2020). When mixed with water, the result is a pH 12.5 colloidal gel that sets in 3–4 h (Lo Giudice et al. 2015; Cervino et al. 2017; Lapinska et al. 2018; Zarra et al. 2018). MTA has been widely used in endodontics and conservative dentistry for the past decade. MTA's strong compatibility with a mechanism comparable to calcium hydroxide makes it a viable candidate for use as cement. Because of its high consistency, it can be used for any repair (Serin Kalay 2019). These advantageous characteristics suggest its potential application in partial pulpotomies for dental trauma (Cervino et al. 2017). When in touch with human tissue, MTA releases calcium ions, which stimulate cell growth. In addition, the alkaline pH of this environment inhibits the growth of germs and controls the release of cytokines. MTA has many of the same advantageous attributes as other materials used in surgical endodontic procedures, including biocompatibility, antibacterial capabilities, marginal adaptability, and sealing capacity (Giudice et al. 2012; Colombo et al. 2018; Fiorillo et al. 2018).

#### 9.3.3.2 Introduction of Biobased Nanomaterials for Endodontics, Such as Engineered Endodontic Strategies

Endodontic treatment often entails root canal cleaning, contouring, and filling. However, since Banchs and Trope's seminal work, many scientists have focused on regenerative therapeutics (Banchs and Trope 2004). By eradicating infection, encouraging growth and sealing of immature root apices, and restoring dental pulp vitality, these treatments help restore a tooth's structure and function (Banchs and Trope 2004; Galler et al. 2016). Stem cells, bioactive compounds, and scaffolds are used in regenerative endodontics, which stems from tissue engineering and biological methods (Banchs and Trope 2004). Some have proposed using nanoparticle-based delivery methods to ensure the controlled release of bioactive substances (Shrestha and Kishen 2017; Kishen and Hussein 2020). Their regulation of cellular activities like proliferation, migration, and differentiation makes them crucial in regenerative endodontics (Lee et al. 2011). Nanoparticle-enable drug release has the capability to induce the dissolution and absorption of bioactive composition and pharmaceuticals because of their higher solubility, specific surface area, and minute size (Kishen and Hussein 2020). Numerous polymeric nanocarriers have been explored for both conventional root canal therapy and regenerative treatments. Some of the nanocarriers discussed earlier, such as chitosan, PLGA, and PolymP-n Active nanoparticles (Makkar and Patri 2017; Abdel Raheem et al. 2019; Arias Moliz et al. 2020) are only a few of the nanocarriers that have been studied for this purpose (Shrestha et al. 2014, 2015, 2016; Kharaziha et al. 2015; Kukreti et al. 2020). Apical papilla-derived stem cells had their vitality boosted by chitosan nanoparticles loaded with bovine serum albumin (Shrestha et al. 2014). Stem cells' odontogenic specialization was improved via chitosan nanoparticles loaded with dexamethasone (Shrestha et al. 2015). The odontogenic differentiation of these stem cells was improved by using chitosan nanoparticles loaded with dexamethasone. Stem cell attachment, viability, and differentiation were all improved by using chitosan nanoparticles or chitosan nanoparticles (dexamethasone-modified) in teeth polishing, and the application of these nanoparticles was found to be protective against the deleterious effects of NaOCl and LPS (Shrestha et al. 2016; Kukreti et al. 2020). Stem cells derived from the exfoliation of human deciduous teeth can be stimulated to proliferate and develop into osteogenic lineages by exposing them to dexamethasone for a prolonged period within poly (−caprolactone)-forsterite nanocomposite fibrous membranes (Kharaziha et al. 2015). C Scaffolds are a crucial feature of regenerative endodontic therapies, and customized nanoparticles have been used to construct a variety of scaffolds. Scaffolds are transient constructs designed to emulate the characteristics of the extracellular matrix, which are used to help stem cell proliferation and specialization as well as regulate the release of therapeutics and bioactive chemicals (Bae et al. 2012). Multiple bioactive compounds can be released from nanoparticles in a variety of ways (Martinho et al.

2016). Because of its malleability and ability to grow into a variety of shapes, as well as its receptivity to conjugation with other molecules (Bernkop-Schnürch 2000). Bellamy et al. found that SCAP viability, differentiation, and migration could all be enhanced by using a carboxymethyl chitosan scaffold that included nanochitosan particles loaded with transforming growth factor-1 (Bellamy et al. 2016). Odontoblast progenitor cells have the capacity to undergo differentiation into many cell lines, for instance to odontogenic tissue by combining a nanofiber scaffold with dexamethasone and bioactive glass nanoparticles (Lim et al. 2016). Scaffolds that have been infused with nanostructured bioactive glass have been reported to enhance physical properties, In addition, the release and deposition of calcium can effectively enhance bioactivity and mineralization (Rad et al. 2019). Hydrogel scaffolds were improved in another study by adding cellulose nanocrystals, which increased their rigidity. The thrombocyte-derived bioactive solution, which has a high concentration of angiogenesis-inducing and migratory agents, was pumped into the reinforced hydrogel to promote pulpal tissue regeneration and revascularization (Silva et al. 2018).

Finally, nanoparticles have been applied to evaluate regeneration outcomes in unique ways. Biz et al. created compounds that stem cells could easily take in by complexing Au nanoparticles with a sustainable biopolymer, L-lysine. The study demonstrated that microtomography might be used to detect cellular viability post-regenerative procedures without any adverse cytotoxic effects due to the resulting rise in cell radiopacity (Biz et al. 2020).

#### 9.3.3.3 Properties and Advantages of Biobased Nanomaterials for Endodontics, Including Their Ability to Improve Sealing and Disinfection

Owing to their nanoscale size and specific surface area, nanomaterials share unique physiochemical features that set them apart from their bulkier counterparts (Vickers 2017; Jeevanandam et al. 2018). Because of their similarity to biological structures, responsiveness, dissolvability, and the possibility of modification with other substances like medications, biologically active molecules, and substances that enable photosynthesis, nanomaterials have a lot of exciting prospective applications (Rai et al. 2012; Brück and Kebede 2013; Vickers 2017). In addition, bactericidal nanoparticles can penetrate biofilms better, are effective even at lower doses, and may lessen the overuse and misuse of antibacterial treatments (Beyth et al. 2015). The processes by which several different nanoparticle antimicrobials work are very similar. They can penetrate biofilms and attract microorganisms through electrostatic interactions, causing leaky membranes, increased cellular permeability, ROS generation, pathway disruption, protein and DNA damage, and ultimately apoptosis (Rabea et al. 2003; Robert and Freitas 2010; Beyth et al. 2015; Vickers 2017).

#### 9.3.3.4 Examples of Biobased Nanomaterials Used in Endodontics

**Nano-chitosan Particles**

It was found that solutions containing nanoparticles of chitosan were bactericidal against *E. faecalis* and successfully inhibited biofilm formation (del Carpio-Perochena et al. 2015; Ionescu et al. 2020). However, additional research demonstrated that the efficacy of its bactericidal capabilities may depend on the stability of the bacteria cells. Biofilm cells survived up to 72 h after planktonic bacteria were killed (Shrestha et al. 2010). Chitosan nanoparticles maintained their antibacterial properties even after 90 days of storage (Shrestha et al. 2010). Furthermore, chitosan's bactericidal efficacy is dose-, time-, and distance dependent (Shrestha et al. 2010; Upadya et al. 2011). Pulpal residues and bovine serum albumin are two examples of inhibitors that may be present that may reduce its antibacterial characteristics' efficacy. Chitosan's effectiveness, however, was found to be unaffected by dentin, the dentin matrix, or lipopolysaccharides (LPS) (Shrestha and Kishen 2012).

Another study found that nanoparticle formulations of chitosan for use in surface treatment did not improve antibiofilm effects directly but that it might provide additional benefits by improving the structural integrity of collagen via cross-linking (DaSilva et al. 2013). Various approaches have been created to widen the availability and efficiency of chitosan NPs through the root canal. The latter includes manually pumping the cleaned and shaped root canal with a gutta-percha cone to create microbubbles that improve fluid dynamics (Li et al. 2019). Researchers have found that chitosan has chelating capabilities and has the potential to improve dentin's wetting properties, thus it is worth exploring further (Pedullà et al. 2012; del Carpio-Perochena et al. 2015; Hashmi et al. 2019). Concurrently, chitosan nanoparticles showed promise in protecting dentin collagen by defending it from the degradative impacts of bacterial collagenase (Kishen et al. 2016). In spite of recent advances, traditional chelating agents have been theorized that be the most efficient means of easing sealer penetration. Moreover, new research shows that sealing dentin with tricalcium silicate after treating it with a nanocomplex of chitosan and hydroxyapatite precursors first significantly boosts the typical sealer penetration depth into the tubules (Hashmi et al. 2019). In addition to its antibacterial properties, chitosan nanoparticle-containing solutions show promise as cutting-edge irrigants (del Carpio-Perochena et al. 2015; Ratih et al. 2020). Some have pointed to the lengthy treatment time and the need for direct contact with the solution as drawbacks that more study is needed to resolve (Shrestha et al. 2010). Since time and proximity play a role in how effective nano-chitosan particles are as antibacterial agents, these nano-biopolymers may be useful in developing novel antimicrobial endodontic sealers (Shrestha et al. 2010; Nagas et al. 2012; DaSilva et al. 2013). Increasing the effectiveness of zinc oxide eugenol sealers against bacteria and biofilms has been the focus of multiple studies investigating the possibility of altering these products using chitosan nanoparticles (Chen et al. 2009; DaSilva et al. 2013). When compared to calcium hydroxide, the usage of a medication based on chitosan nanoparticles showed significant antibacterial characteristics and had less of an impact on dentine strength. Chitosan's neutralizing action on matrix metalloproteinases and its ability to increase collagen cross-linking are likely responsible for this effect (Sireesha et al. 2017). Chitosan's tendency to agglomerate was also found to potentially limit sealer access to the dentinal tubules in the same investigation (Sireesha et al. 2017).

### Nano-metal and -Metal Oxide Particles

The use of metal oxide NPs as an endodontic irrigant has also been investigated. Similarly to silver nanoparticles (AgNPs), zinc oxide nanoparticles (ZnONPs) have a reputation for being able to kill microorganisms (Beyth et al. 2015). It was found that a ZnONP-based irrigant could kill planktonic *E. faecalis* and break the biofilm matrix and that it retained its antibacterial efficacy even after 90 days of storage (Shrestha et al. 2010). Biofilm bacteria were less at risk to bactericidal effects than their planktonic counterparts (Shrestha et al. 2010). The bactericidal effects of AgNPs and ZnONPs against *E. faecalis* were enhanced when they were used together in a polymeric solution, as opposed to when they were used separately. Colony-forming units (CFU) were reduced to a greater extent with 2.5% NaOCl (Samiei et al. 2015). A solution containing ZnONPs was shown to be less effective at killing *E. faecalis* than solutions containing 2% chlorhexidine and 5% NaOCl, according to the results of a study. However, there was no discernible change in efficacy (De Almeida et al. 2018). The average fracture resistance of teeth treated with chitosan as a final irrigant was around 400 N higher than that of teeth treated with NaOCl (Jowkar et al. 2020), but when irrigated with a polymeric slurry including AgNPs and ZnONPs, a different study indicated that the push-out bond strength of endodontic sealers reduced. One possible explanation is that deposited nanoparticles on the dentine area reduced the sealer's ability to adhere to the tooth (Yavari et al. 2017). Furthermore, the oxides of magnesium, titanium, and iron all have antibacterial properties (Beyth et al. 2015; Monzavi et al. 2015), but there has been relatively little study on these chemicals as possible irrigants for endodontic operations. Monzavi et al. report that under laboratory and tissue-like conditions, a solution containing nano-magnesium oxide demonstrated prolonged antibacterial efficacy against *E. faecalis* (Monzavi et al. 2015). Endodontically treated teeth with a final rinse containing titanium dioxide nanoparticles had a fracture resistance that was twice as high as that achieved with NaOCl (Jowkar et al. 2020). The peroxidase-like properties of iron oxide nanoparticles in an irrigating solution against *E. faecalis* were responsible for its antibiofilm and bactericidal actions (Bukhari et al. 2018).

Nano-metal and -metal oxide particles might also have cytotoxicity, just like AgNPs. Before moving further with in vivo research, conducting risk assessment and biocompatibility tests is crucial (Beyth et al. 2015). Finally, nano-gold particles are widely recognized as a promising nanomaterial with numerous potential biomedical applications (Hu et al. 2020). There has been less investigation into their possible applications in endodontics, presumably due to questions about their antibacterial efficacy (Beyth et al. 2015; Samiei et al. 2015; Kushwaha et al. 2018). Kushwaha et al. investigated the effect of irrigants containing nano-silver particles (AgNPs) and nano-gold particles (AuNPs), under the condition of both inclusion and exclusion of Nd-YAG laser augmentation, in killing microorganisms in teeth infected with *E. faecalis*. Using a Nd-YAG laser to activate gold nanoparticles increases their efficacy against bacteria, but the mean value of viable colonies is still significantly lower when using AgNPs (Kushwaha et al. 2018). However, in other areas, such as the treatment of burn wound infections, Au nanoparticles have shown to have antibacterial effects. This is because the microbial profile contrasts with that of root canal infections, and the bacteria present are more susceptible to treatment (Arafa et al. 2018). In the endodontic field as a whole, research into irrigants based on nanoparticles could lead to novel and highly efficient disinfection strategies. More study is needed to understand the potential of different nanomaterials as endodontic irrigants completely. Nanoparticles have been shown to have antimicrobial effects and to be beneficial in vivo, thus research should also look into how to integrate them into irrigation solutions while limiting any negative side effects (Vickers 2017). Intracanal dressings must have specific physical and chemical qualities to ensure they stay within the root canal system and keep their antibacterial activity at an optimal level. The used vehicle may modify these characteristics (Fava and Saunders 1999). Although all three created stable formulations, hydroxyethyl cellulose stood out due to its superior homogeneity, fluidity, and antibacterial efficacy when compared to polyethylene glycol and carbomer, which were also examined as possible carriers for AgNPs (Bruniera et al. 2014). However, compared to a calcium hydroxide and 2% chlorhexidine gel, an AgNPs and methylcellulose gel showed significantly less antifungal efficacy. The authors blamed possible interactions between the carrier and AgNPs (Mozayeni et al. 2015). In order to improve their disinfecting powers and avoid any interferences between the materials, the study highlighted the necessity for more research to investigate nanoparticle-based intracanal medicaments with different formulations (Samiei et al. 2018).

### Nano-calcium Hydroxide Particles

Deeper submersion, the increased contact area with pathogens, higher solubility, and enhanced antibacterial capabilities are only some of the potential advantages of calcium hydroxide nanoparticles over their conventional counterparts (Dianat et al. 2015b; Louwakul et al. 2017; Sireesha et al. 2017). Multiple research has shown that nano-sized calcium hydroxide is more potent than regular calcium hydroxide at killing *E. faecalis* and penetrating deep into dentinal tubules (Dianat et al. 2015b; Louwakul et al. 2017; Sireesha et al. 2017; Zand et al. 2017). Traditional calcium hydroxide treatment significantly reduced fracture resistance compared to nano-calcium hydroxide (Sireesha et al. 2017). Although there was not any statistically significant difference between nano- and regular-sized calcium hydroxide in terms of cytotoxicity, the latter was shown to be somewhat more harmful (Dianat et al. 2015a).

Although there was no statistically significant difference between nano- and regular-sized calcium hydroxide in terms of cytotoxicity, the latter was shown to be somewhat more harmful (Akbari et al. 2017). Calcium hydroxide, with or without chlorhexidine, and AgNPs on their own all had weaker antibacterial effects than when combined (Javidi et al. 2014a; Afkhami et al. 2015; Zhang et al. 2016b). However, there was no discernible improvement in efficacy from the triple antibiotic paste when using this combination (Balto et al. 2020). According to Balto et al., the potential of these new intracanal medications to eradicate biofilms depends on the length of time that they are in touch with the canal (Balto et al. 2020). In addition, numerous studies have indicated that there was no appreciable shift in dentine hue (Mozayeni et al. 2015; Makkar and Patri 2017; Samiei et al. 2018; Balto et al. 2020). Furthermore, the antibacterial effect of calcium hydroxide and ZnONPs was enhanced when compared to that of ZnONPs alone (Guerreiro-Tanomaru et al. 2013). According to another study, adding chlorhexidine boosted the combination's antibacterial effects even further (Aguiar et al. 2015).

### Porous Calcium Silicate and Bioactive Glass Nanoparticles

Bioactive, biocompatible, and bone-forming characteristics and their potential as drug transporters explain the fame of nano calcium silicate particle compounds with interior permeable frameworks (Fan et al. 2012). Calcium silicate nanospheres penetrated dentinal tubules and stimulated mineralization, paving the way for the development of new intracanal dressings (Fan et al. 2012).

Nano calcium silicate particles with AgNPs added consistently released Ag ions, preventing colonization by *E. faecalis* (Fan et al. 2014, 2016). More research showed that when AgNPs and nano-zinc were added to nano calcium silicate particles with mesoporous characteristics, the particles showed effective antibiofilm properties, minimal cytotoxicity (Leng et al. 2020), steady discharge of ions, infiltration of dentinal tubules, and minimal alterations to the physical properties of dentin (Zhu et al. 2017). The mesoporous structure of chemical substances is responsible for their sustained activity; it carries antibacterial nanoparticles and ensures their steady release (Fan et al. 2015; Leng et al. 2020). Bioactive glasses exhibit antibacterial effects by modifying the ambient alkalinity (Waltimo et al. 2009). In contrast to their bigger micron-sized counterparts, nanoparticulate bioactive glasses produced a greater amount of alkaline chemicals upon release, giving them stronger antibacterial characteristics, as reported by Waltimo et al. (2009). However, alkalinity-promoting nanoparticle bioactive glasses may alter dentin's structural properties. One study indicated that compared to a control group given saline, the group wearing these glasses experienced a 20% decrease in flexural strength. However, there was not a statistically significant difference (Marending et al. 2009). Since radiopacity is essential in endodontic sealers, bismuth oxide was added to nanosized bioactive glasses to increase radiopacity while maintaining their bioactive qualities (Mohn et al. 2010). In addition to their potential use as intracanal disinfectants, calcium silicate nanoparticles have been suggested as an ingredient in development of novel root canal sealers (Mohn et al. 2010; Fan et al. 2015; Leng et al. 2020).

### Quaternary Ammonium Compounds

Root canal sealers and dental fillings containing quaternary ammonium compounds have both been studied for their potential as bactericidal agents (Beyth et al. 2006, 2013). In particular, the positively charged disinfectant polyethyleneimine-based quaternary ammonium compound has exhibited significant bactericidal plus biofilm-suppressing efficacy via electrostatic contact with the membranes of bacterial cells. As a result of this interaction, cells are damaged, and internal components are released (Lan et al. 2019). The unique capacity of nano-QPEI particle to activate intracellular cascade that lead to cell apoptosis which sets them apart from other nanoparticles. Their insolubility also ensures that their antibacterial actions last for quite some time (Beyth et al. 2006). It was discovered that adding nano-QPEI particle to epoxy resin-based sealers increased the sealer's antibacterial performance (Beyth et al. 2013; Kesler Shvero et al. 2013; Abramovitz et al. 2015; Zaltsman et al. 2016). Some researchers believe that QPEI nanoparticles can enhance the antibacterial activities of sealers by acting on both the membrane and the far-flung biofilm components. However, the exact mechanism of action is yet unknown (Kesler Shvero et al. 2013, 2016). In addition, studies have shown that QPEI nanoparticles can be successfully combined with commercially available sealers without changing the sealer's cytotoxicity or its physicochemical properties, including solubility, flow, compressive strength, or dimensional stability (Beyth et al. 2013; Silva et al. 2013; Barros et al. 2014a). However, it has been reported that the inclusion of QPEI nanoparticles did not appreciably improve the antibacterial efficacy of AH PlusTM (Silva et al. 2013). It was found in a separate study that the strain may affect the antibiofilm characteristics of QPEI nanoparticle-modified AH PlusTM when used against *E. faecalis* (Barros et al. 2014b).

Adding nano-QPEI particles to pulp canal sealer enhanced its efficacy as a bactericidal and antibiofilm agent against *E. faecalis* (Silva et al. 2013; Barros et al. 2014b). Variations in experimental design or interactions between the basic sealer components may account for inconsistent results throughout research (Silva et al. 2013; Barros et al. 2014b). It is also worth noting that this nanomaterial's potential disadvantages, such as polymerization contraction, solvent absorption, changes in physical characteristics, and its cytotoxic properties, when considering whether or not to incorporate QPEI nanoparticles into prior root canal sealers (Makvandi et al. 2018). Many studies have been done to develop novel quaternary ammonium methacrylate-based endodontic sealers. Free radical polymerization can be used to permanently embed long-chain chemicals like dimethylaminohexadecyl methacrylate (DMAHDM) within a resin matrix. This method penetrates and damages bacterial membranes on contact, resulting in a prolonged antibacterial action (Li et al. 2013). Synergistic effects between multiple antimicrobial nanoparticles may boost the efficacy of novel root canal sealers against germs and their ability to remineralize tooth enamel. The antibiofilm capabilities of the novel endodontic sealer, including AgNPs and DMAHDM, were promising in a study against *E. faecalis*. This new sealer was six times more effective than AH PlusTM at reducing biofilm CFU (Baras et al. 2019a).

Antibiofilm capabilities and a notable calcium and phosphate ion release from a trial sealer combining amorphous calcium phosphate nanoparticles and DMAHDM were reported, suggesting the possibility of aiding remineralization and rebuilding damaged root systems (Vickers 2017; Baras et al. 2019b, c). Dental materials can be made antibacterial without sacrificing their structure or properties by using quaternary ammonium nanoparticles. Nano-quaternary ammonium polyethylenimine (QPEI) was included into orthodontic brackets to acquire antibacterial capabilities against *S. mutans* and *Lactobacillus casei* (L. casei), two common bacteria detected on orthodontic brackets (Sharon et al. 2018).

**Nanostructured Silver Vanadate with AgNPs**
Although AgNPs have potent bactericidal action, their propensity to aggregate has raised some red flags. Therefore, it has been suggested that stabilizing AgNPs with nanostructured silver vanadate allows for their use to be maximized as endodontic sealers (Holtz et al. 2012; Corrêa et al. 2015). Nanostructured silver vanadate and AgNPs added to endodontic sealers did not significantly alter the sealers' physical and chemical properties (Teixeira et al. 2017a, b). Combining nanostructured silver vanadate and AgNPs into endodontic sealers did not substantially change the sealers' physicochemical qualities (Teixeira et al. 2019). Furthermore, the level of benefit achieved by integrating silver vanadate nanowires coated with AgNPs may differ depending on the particular commercially available sealer and the concentration used (Teixeira et al. 2017a, b). It has been hypothesized that these chemicals can solely boost the sealers' antibacterial activities at very high concentrations; more clinical research is needed to weigh the potential advantages against the risks, such as tooth discoloration and their cytotoxic effects (Brezhnev et al. 2019).

## 9.3.4 Biobased Nanomaterials for Dental Implants

### 9.3.4.1 Overview of Dental Implants and Common Materials Used

The field of oral implantology is predicated on osseointegration, which occurs when an implant bonds with bone (Branemark 1977). Pure titanium (Ti) is the starting point for many dental implant experiments, but other materials, such as aluminum oxide ceramic implants (Schulte et al. 1978), nontreated implants with a Ti-plasma-sprayed surface (Kirsch and Ackermann 1989), and titanium (Ti)-aluminum (V) implants (Niznick 1983), have also been used. Studies conducted in the 1990s showed that a much higher bone response and increased bone-to-implant contact occurred when implant surfaces were moderately or micro-rough (Buser et al. 1991). Subsequently, microporous textured surfaces made through anodic oxidation and others developed through processes like sandblasting and acid etching entered the market (Buser et al. 1998, 1999).

Over the last decade, zirconium dioxide implants have demonstrated similar preclinical and clinical results to moderately rough titanium implants. Implant surfaces with micro-roughness are considered the standard of excellence in implant dentistry (Cionca et al. 2017). Several factors related to the implant can impact the process of integrating dental implants into bone, including the implant's shape (whether it has a root shape, a conical profile, or parallel walls), the design of the threading, the type of implant-abutment connection (example(s): tri-channel, hexagonal, and conical internal hexagon), and the surface of the implant (Rompen et al. 2006; Albrektsson and Wennerberg 2019). The surface properties of dental implants are a crucial factor in determining their clinical effectiveness over both the short and long term (Wennerberg and Albrektsson 2009; Chrcanovic et al. 2017; Milleret et al. 2019). A meta-analysis that was published recently compared the clinical results of various dental implant surface areas (including micro-textured, sintered porous, anodized, Ti plasma-sprayed, and machined finishes) over a period of 10 years. The study revealed that anodized implants showed the lowest failure rate (1.3%, with a range of 0.2–2.4%) and a minor rate of peri-implantitis (1–2%) (Wennerberg et al. 2018). Therefore, both SLA (sandblasted, large-grit, acid-etched) and anodized (via anodic oxidation technique) implants offer adequate surface shape for clinical purposes. Nevertheless, SLA surfaces are still the more popular choice in the clinical field, with many companies favoring SLA over anodized implants (Zhang et al. 2021a).

#### 9.3.4.2 Introduction of Biobased Nanomaterials for Dental Implants

Incorporating biopolymers like chitosan, cellulose, and silk fibroin-based nanomaterials into synthetic implant coatings can significantly enhance their bioactivity and antibacterial properties. Combined with implant surface treatments and polymer-based delivery systems for antibiotics, drugs, or biomolecules, this approach has shown greater potential for improving outcomes than using polymers or drugs alone (Zhang et al. 2021a). Making nano-scale modifications to the surface of titanium-based supplies can also enhance their ability to bond with the bone in laboratory settings (Dey et al. 2011).

With the potential to be used as a biomaterial, silk protein fibroins derived from various sources are employed as a framework to improve cellular attachment, proliferation, and specialization (Altman et al. 2003; Kundu et al. 2012). The fixation of naturally occurring silk proteins like sericin and RGD-enriched fibroin leads to enhanced adhesion of osteoblasts and increased calcium deposition (Nayak et al. 2013; Naskar et al. 2014). Nanoparticles made from silk protein have demonstrated promising outcomes for the gradual release of embedded molecules like drugs and genes. This suggests the idea of using silk protein nanoparticles to simultaneously regulate drug release and surface shape (Gubernator et al. 2006; Das et al. 2014).

#### 9.3.4.3 Properties and Advantages of Biobased Nanomaterials for Dental Implants, Including Their Bioharmony, Physical Strength, and Ability to Promote Tissue Regeneration

Nanoparticles (NPs) can facilitate several therapeutic approaches on the surface area of dental implants, including, but not limited to, immunomodulation, Osseo- and soft-tissue integration, and antibiofouling (Priyadarsini et al. 2018b; Jandt and Watts 2020). In the study of Sharma et al. (2016), nanoparticle deposited Ti (Ti- silk NP) has shown enhanced surface roughness index and hydrophobicity compared to bare titanium (Ti) implants. Enhancing the hydrophilicity and adjusting the surface microhardness of an implant surface are considered to be two of the most crucial factors that promote cell adhesion and impact subsequent differentiation (Rupp et al. 2004; Arima and Iwata 2007). They also reported increased gentamicin release overtime in titanium coated with gentamicin-loaded nanoparticle (Ti-GenNP) compared to Ti-Gen implants.

It is important to note that saliva proteins rapidly attach to dental implants shortly after being implanted, creating a pellicle film. Within 48 h, early colonizers such as

**Fig. 9.6** Strategies for controlling biofilm on dental implants in the modern era (Sivaswamy and Neelakantan 2022)

*Streptococci* bind to these pellicles (Guo et al. 2021a, b). After the initial attachment of early colonizers like *Streptococci*, secondary colonizers like *Fusobacterium nucleatum*, *Aggregatibacter actinomycetemcomitans*, and *Porphyromonas gingivalis* may follow suit (Hao et al. 2018). These bacteria can contribute to the development of peri-implantitis (Shibli et al. 2008). When a biofilm has formed, the standard administration of antibiotics is inadequate. As a result, local treatment using dental implants has been suggested. There was an initial increase in adhesion with no detectable damage to eukaryotic cells when fibroin nanoparticles and gentamicin-loaded nanoparticles were coated on titanium surfaces and tested with osteoblast-like cells (Sharma et al. 2016). Strategies for controlling biofilm on dental implants in the modern era have been shown in Fig. 9.6.

### 9.3.4.4 Examples of Biobased Nanomaterials Used in Dental Implants

**Titania Nanotubes**

Titania nanotubes (TNTs) made from titanium dioxide ($TiO_2$) can be created on pure titanium or titanium alloys through an electrochemical anodization process (Gulati et al. 2015). TNTs have shown potential as a surface modification technique for promoting osteogenesis, based on several in vivo studies, due to their enhanced bioactivity and the capacity to load and discharge proteins and growth factors (Gulati et al. 2016; Gulati and Ivanovski 2017). The enhancement of osseointegration is also facilitated by the mechanical stimulation of osteoblasts and the inclusion of fluoride ions into TNTs during anodization (Zhang et al. 2015). Moreover, upregulated osteogenic outcomes have been demonstrated through the use of different nanoparticles, ions, or coatings of Sr (Zhao et al. 2013), Ta (Frandsen et al. 2014), La (Zhang et al. 2020), and Zn (Huo et al. 2013) on or inside TNTs. In terms of soft-tissue integration, Gulati et al. have recently reported an increase in the proliferation, osteogenesis, and adhesion of human gingival fibroblasts (HGFs) on dual-micro-nano anisotropic $TiO_2$ nanopores. This was achieved through the inclusion of fluoride ions into TNTs during anodization and the mechanical stimulation of osteoblasts, as confirmed by various in vivo investigations (Gulati et al. 2018b). There has been extensive research on utilizing TNTs for the local release of therapeutics, with the aim of localized antimicrobial agent loading and elution optimization (Chopra et al. 2021a, b). Several antibiotics that are typically prescribed, such as gentamicin (Pawlik et al. 2017), vancomycin (Ionita et al. 2017), minocycline, amoxicillin, cephalothin (Park et al. 2014a, b), cefuroxime (Chennell et al. 2013), and cecropin B (Shen et al. 2016), have been combined with titanium implants modified with TNTs, to provide localized antibacterial effects.

Obtaining immunomodulatory effects from modified TNTs is important for the timely establishment of osseointegration by regulating the host's immuno-inflammatory response. Therefore, efforts have been made to achieve this goal (Gulati et al. 2018a). The impact of Ti Nano topography on immune cells, such as macrophages, monocytes, and neutrophils, has shown that it can reduce inflammatory responses (Hamlet and Ivanovski 2011; Alfarsi et al. 2014). Smith et al. observed that immune cell functions, such as viability, adhesion, proliferation, and spreading, were decreased on TNTs compared to bare Ti (Neacsu et al. 2014).

**Nanoparticles**

Various nanoparticles have been applied in dental implants because of their exceptional bactericidal properties, silver nanoparticles (Ag NPs) are a popular choice for dental restorations and as a doping option for dental implants (Bapat et al. 2018). Titanium implants coated Ag NPs using anodic spark deposition have been modified by incorporating ions of silicon, calcium, phosphorus, and sodium to enhance their bactericidal characteristics against microorganisms for instance, *S. epidermidis, S. mutans,* and *E. coli*, as well as promote bone growth in osteoblast-like human cells (SAOS-2) (Della Valle et al. 2012).

Similar to Ag NPs, Zn/ZnO NPs possess bactericidal and osteogenic properties, which is why they are utilized in altering dental implants (Priyadarsini et al. 2018b). Hu et al. integrated zinc into $TiO_2$ coatings on titanium implants through plasma electrolytic oxidation, resulting in exceptional antibacterial and bone-generating effects (Hu et al. 2012). Compared to Ag NPs, copper oxide NPs are remarkable. They are cost effective, chemically stable, and simple to combine with polymers, making them a promising candidate for use in the creation of biomaterials (Ren et al. 2009). In a recent study, Van Hengel et al. (2020) utilized plasma electrolytic oxidation to incorporate different quantities of Ag and Cu nanoparticles into $TiO_2$ coatings on Ti–6Al–4 V porous implants produced by additive manufacturing. Furthermore, Xia et al. described the utilization of plasma immersion ion implantation and deposition (PIIID) technology to alter Ti implants with co-implanted C/Cu nanoparticles (Xia et al. 2020). $TiO_2$ coatings doped with copper nanoparticles (Cu NPs) exhibited remarkable antibacterial properties and enhanced osteoblast and endothelial cells' in vitro proliferation and adhesion (Zhang et al. 2018b). Alternatively, because of its high mechanical strength, resistance to corrosion, and biocompatibility, zirconium (Zr) and zirconia ($ZrO_2$) are becoming other popular alternative options for dental implant materials (Chopra et al. 2021a, b).

In addition, the formation of nanotubes has been expanded to include titanium-zirconium (TiZr) alloys. Grigorescu et al. utilized a two-step electrochemical anodization process to produce nanotubes with varying diameters. They observed that a reduction in diameter resulted in higher hydrophilicity, and the smallest nanotube diameters showed the strongest bactericidal effects against *E. coli*. Although $ZrO_2$/Zr is commonly utilized as a dental implant material due to its biocompatibility and physical characteristics, the release of Zr nanoparticles may initiate cytotoxicity (Grigorescu et al. 2013).

### Carbon Composites

Due to certain toxicity of pure graphene, several derivatives of graphene have been created such as graphene oxide (GO) with oxidative potency and reduced graphene (rGO), which is manufactured through thermal reduction of GO (Zhou and Gao 2014). It is worthy to say whether GO is toxic for cell remains controversial (Chang et al. 2011; Liao et al. 2011; Li et al. 2014). However, experimental studies have revealed high levels of toxicity with micro (and not nano-sized) GO (Kiew et al. 2016). Gu et al. made an effort to enhance the adhesion strength of graphene on Ti substrate by performing a thermal treatment. As a result, they noticed improved antibacterial effects against *E. coli* and *S. aureus*, as well as enhanced cell binding, proliferation, and osteogenesis in both in vitro (utilizing both mesenchymal stem cells from human bone marrow and adipose tissue-derived stem cells) and in vivo experiments (performed on the subcutaneous fat of nude male BALB/c mice at 8 weeks of age). All these effects were observed on Ti implant surfaced with graphene after undergoing dry heating (Gu et al. 2018).

More recently, using the spark plasma sintering technique, Wei et al. (2021) created a novel Ti biomaterial that included graphene (referred to as Ti-0.125G). Results from bioactivity experiments conducted on human gingival fibroblasts and

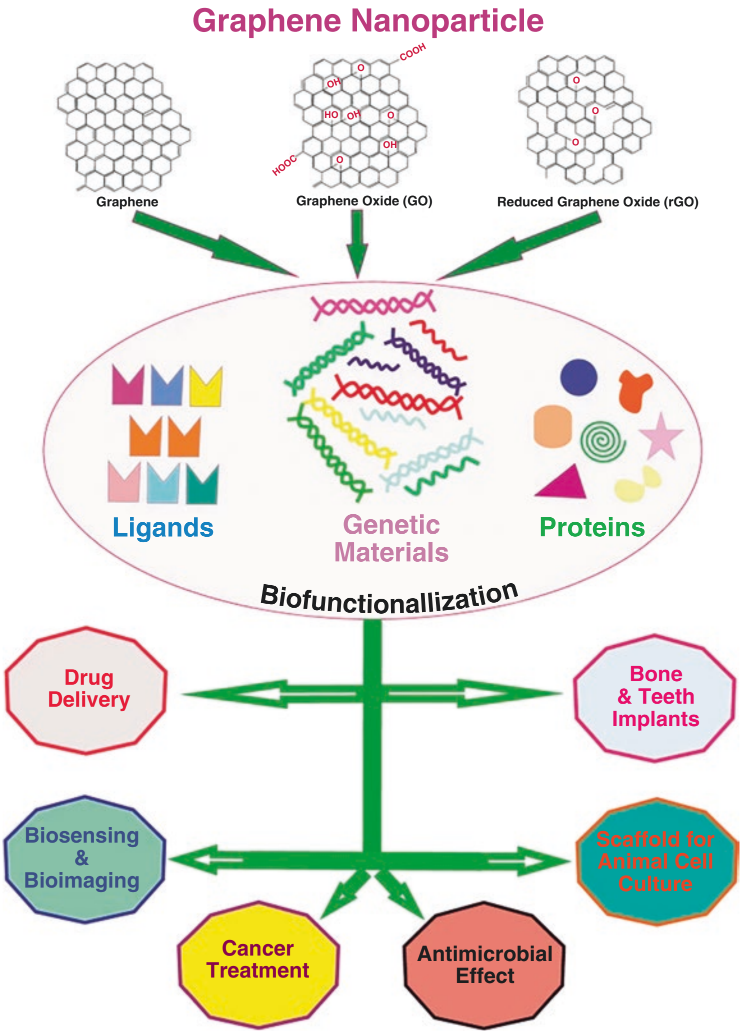

**Fig. 9.7** Nanomaterials with medical and biological applications: graphene and graphene oxide (Priyadarsini et al. 2018a)

bactericidal experiments conducted on *Streptococci mutans*, *Fusobacterium nucleatum*, and *Porphyromonas gingivalis* showed the inclusion of graphene-enhanced both properties. Another carbon-based nanomaterial is graphdiyne (GDY), and it has been forecasted that this particular form of carbon derivative will ultimately be the most stable (Zuo and Li 2019). Compared to graphene, GDY has been shown to have better electrical conductivity and catalytic effects compared to other materials. Additionally, it demonstrated improved biocompatibility and stability in certain in vivo experiments (Hu et al. 2017; Liu et al. 2019). Various applications of graphene and graphene oxide have been shown in Fig. 9.7.

## 9.4 Advantages and Challenges of Bio-based Nanomaterials in Dentistry

### 9.4.1 Advantages

Conventional antibacterial materials or fillers have numerous drawbacks, for instance, poor drug delivery system, inadequate physical strength, and unsatisfactory bactericidal effectiveness, They fall short of meeting the needs of individuals with complicated oral environments (Najeeb et al. 2016; Sharon et al. 2018; Makvandi et al. 2021). Furthermore, because of their susceptibility to rapid breakdown or release, these compounds are unable to deliver long-lasting antibacterial actions. This may result in the onset or recurrence of various dental ailments, including peri-implantitis, secondary caries, and pulpitis (Guo et al. 2021a, b; Qi et al. 2022).

In recent times, different nano-antibacterial agents have been utilized to enhance the resin matrix or fillers, leading to enhanced mechanical and physical properties. For instance, nanomaterials that consist of calcium and phosphorus can also promote remineralization since demineralization typically starts at the nano-level (Abou Neel et al. 2016; Bordea et al. 2020; Kyrylenko et al. 2021). Zhang et al. created nanoparticles of calcium-doped amorphous silica that were combined with ciprofloxacin hydrochloride and integrated them into resin to get a threefold effect of bactericidal properties, remineralization, and improved physical strength. Additionally, the nano-silicon's mesoporous nature allowed for the medicine's slow and steady release (Zhang et al. 2018a). Zhou et al. developed an optimal implant surface by adjusting the depth to 3.6 μm and incorporating 55 nm nanotubes, which provided distinctive structural benefits. These nanotubes could carry medications, including gentamicin and naproxen sodium, presenting a fresh approach to utilizing nanocarriers (Zhou et al. 2020). Nanocarriers offer an added advantage because they can be released intelligently in response to changes in their surroundings, such as shifts in acidity, magnetic field strength, and atmospheric pressure. With their pH-responsive core–shell nano micelle, Zhang et al. developed an innovative way to cure dental caries by releasing bedaquiline only in acidic environments (Zhang et al. 2021b).

### 9.4.2 Challenges

#### 9.4.2.1 Potential Cytotoxicity

Compared to conventional dental materials, nanomaterials exhibit distinct reactions because of their distinct physiochemical makeup, factors such as proportion, reactivity with various biological macromolecules and cell membranes, and differing pharmacokinetic parameters. Therefore, Constructing a nano dental product for different nanomaterials is a difficult procedure that needs a detailed understanding of material science and synthesis approaches, as mentioned earlier. Furthermore, To increase the likelihood of success of commercializing nanomaterials, particularly in dentistry, it is crucial to comprehend these interactions, conduct toxicity evaluations (in particular immunotoxicity and chemical profiling), develop in vitro-in vivo models, and adhere to regulatory standards (Bansal et al. 2021). In terms of potential cytotoxicity, various nanomaterials have demonstrated toxic effects. For example, carbon nanotubes used in dental coatings have been shown to induce inflammatory responses in biological membranes (Kou et al. 2013).

#### 9.4.2.2 Long-term Safety Concerns

To ensure long-term safety, it is important to consider that certain nanomaterials may cause cytotoxicity over time. An example of this is the release of Zr ions from $ZrO_2$ nanoparticles used in implant coatings (Bannunah 2023). It is noteworthy to mention that the production of nanomaterials and subsequent inhalation exposure can also result in toxic respiratory symptoms. A potential risk of lung cancer and impaired cognitive performance is associated with titanium dioxide ($TiO_2$) nanoparticle exposure (Naima et al. 2021). The safety of using certain nanomaterials, such as silver nanoparticles, has shown promising results in some application areas. However, there are certain areas, such as the systemic reactions of silver nanoparticles released into the human body or the environment, whose full implications we do not yet know (Yin et al. 2020). The utilization of HA NPs in a dental filling causes them to attach to blood proteins, creating a compound that gets eradicated by macrophages. This compound is then carried to significant vascular organs, including the spleen and lungs, causing toxic reactions (Wang et al. 2016).

#### 9.4.2.3 Regulatory Hurdles and Standardization

Furthermore, the current production methods for manufactured nanomaterials often demand significant amounts of energy, water, and chemically problematic substances such as solvents, which could potentially counteract any benefits. Moreover, conducting thorough life cycle assessments is crucial with the aim of accurately assessing the environmental risks and benefits related to MNMs. However, such assessments are not readily available for most cases (Cerrillo et al. 2017). Despite advances in nanotechnology, producing uniform nanostructures quickly and in large quantities still poses a challenge, and there is potential for the field of additive manufacturing, often known as 3D printing to be utilized in creating customized implants tailored to individual patient requirements (Lopez-Heredia et al. 2008).

#### 9.4.2.4 Cost and Scalability of Production

Currently, most nano-products require complicated synthetic processes and are expensive to produce, which impedes their ability to be utilized on an industrial scale. Therefore, numerous challenges must be addressed regarding the toxic effects and manufacturing expenses of nanomaterial as they transition from lab testing to clinical use (Chen et al. 2023). In recent years, defective engineered nanoparticles have gained significant attention in biomedical research because of their unique physicochemical qualities, which include optical characteristics and redox reaction capability. Notably, these nanomaterials do not need sophisticated designs to alter their characteristics by adjusting the number and kind of flaws present. Several attempts, however, have been made to fix these problems (Yuan et al. 2023).

## 9.5 Future Perspectives and Research Directions

### 9.5.1 Development of Novel Bio-based Nanomaterial

In terms of exploring new applications in dentistry, several experimental studies have exhibited promising reports in the novel application of nanomaterials. Nano-PS and PS-carrying nanoparticles have lately been developed to overcome the problem of PS dye's shallow penetration into bacterial biofilm, which can enhance the antibacterial effectiveness of following photodynamic therapy. This technique is a newly introduced antibacterial tool in dentistry that does result in the development of antibiotic resistance (Badran et al. 2023; Tan et al. 2023). Huang et al. proposed a new method to clear the smear layer in endodontic treatment, which involves the use of nano and submicron diamond along with intracanal oscillation irrigation, which can improve endodontic treatment outcomes (Huang et al. 2023). According to the research done by Sethi et al. (2023), they demonstrated that a quercetin-loaded titanium nanocomposite coating applied over the surface of healing abutments can serve in the treatment of inflammation and the prevention of infection, contributing to the long-term success of implant restorations. Patients with a prior history of periodontal disease may benefit greatly from this strategy.

### 9.5.2 Advancements in Nanofabrication Techniques

Additive manufacturing (AM) is 3D printing in which nanomaterials are combined with host materials (such as ceramics or polymers) has resulted in a mutually beneficial approach, and the resulting composite biomaterials have been developed (De et al. 2008). although the main benefit of 3D printing compared to conventional manufacturing methods is its capacity to quickly generate highly precise and complex scaffolds tailored to the patient's needs (Kang et al. 2016). Totu et al. (2017) utilized an SLA printer to construct a dental prosthesis that incorporated $TiO_2$ nanoparticles ranging from 56 to 170 nm in size at a concentration of 0.4%. The prosthesis exhibited impressive antibacterial properties, effectively limiting the growth of the candida Scotti strain. Chen et al. conducted an additional study in which they employed an SLA 3D printer to produce composite resins that integrated $TiO_2$ nanoparticles (ranging: 30–40 nm) to enhance the material's antibacterial properties. 3D-printed components exhibited better and stronger bactericidal effects, ultimately eradicating nearly a whole group of bacterial pathogens (specifically *S. aureus* and *E. coli*) in just 12 h, even in dark conditions (Chen et al. 2018). In general, significant advancements may be made with the use of 3D printing to enhance the compatibility, dispersal, and safety of nanomaterials (Zhang et al. 2022a).

### 9.5.3 Addressing Safety Concerns and Improving Biocompatibility

The safety of nanomaterials is of paramount concern in the fields of dentistry and medicine. Although nanomaterials offer many advantages, such as improved mechanical properties and antibacterial effects, some issues still need to be addressed. One of the most significant concerns is biocompatibility, which defines the ability of a material to function within the human body without causing adverse effects. Additionally, human safety is a critical issue, as these materials may have toxic effects on human cells and tissues. Ethical considerations also need to be considered, particularly in terms of the potential long-term effects of nanotechnology on community health and environmental issues. Furthermore, economic-related problems, such as the cost of producing and using these materials, need to be considered. Various studies have investigated the cytotoxicity and potential hazards of nanomaterials, including various nanoparticles used in esthetics (Kim et al. 2022), restorative (Fierascu 2022), implantology (Li et al. 2022), and endodontics (Özdemir and Kopac 2022). However, there is no consensus on the safety of these materials, and more research is needed to fully understand their effects. Therefore, it is important for the dental community to continue monitoring the safety and efficacy of nanomaterials and to use them only when they are safe and effective.

## 9.6 Conclusion

### 9.6.1 Outlook for the Future Development and Implementation of These Materials in Dental Practice

Nanomaterials derived from biological sources have recently been hailed as a material promising for dental care. They have been applied in various dental areas, such as composite restorations, dental implants, and tissue regeneration. Additionally, advancements in nanofabrication techniques, for instance, 3D-printing technology has enabled the manufacture of highly precise and complex dental restorations, while the incorporation of nanomaterials has enhanced the physical properties and antibacterial effects of dental supplies such as patient-specific dental restorations, increasing patient comfort and satisfaction while reducing treatment times and costs.

### 9.6.2 Future Directions for Research in the Field of Biobased Nanomaterials in Dentistry

However, safety concerns related to nanomaterials still exist, and their implications on human health and the environment require more study. Despite these concerns, bio-based dental materials might benefit greatly from the use of nanoparticles due to their ability to increase compatibility, dispersion, and decrease toxicity. Therefore, continued research and development in this field is crucial to ensure these materials' safe and effective application in dentistry. The dental industry as a whole might be profoundly affected by research into and use of bio-based nanomaterials, offering improved treatments, greater patient comfort, and better oral health outcomes. Continued research, development, and regulatory oversight will be key to realizing this potential.

### 9.6.3 Final Thoughts on the Potential Impact of Biobased Nanomaterials on the Field of Dentistry

The field of biobased nanomaterials in dentistry is evolving through several horizons. Study of long-term safety and potential harms to community health and environmental issues and further development of medication delivery systems, gene therapy, and other cutting-edge dental uses. Integration of nanotechnology with digital dentistry can further enhance the accuracy of dental restorations and procedures. Lastly, researchers can investigate the cost-effectiveness of using biobased nanomaterial and determine the feasibility of their widespread use. Further research and development of nanotechnology in dentistry can grow dental care standards and promote oral health and patient comfort.

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