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Graphene as a promising material in orthodontics: A review

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Abstract

Graphene is an extraordinary material with unique mechanical, chemical, and thermal properties. Additionally, it boasts high surface area and antimicrobial properties, making it an attractive option for researchers exploring innovative materials for biomedical applications. Although there have been various studies on graphene applications in different biomedical fields, limited reviews have been conducted on its use in dentistry, and no reviews have focused on its application in the orthodontic field. This review aims to present a comprehensive overview of graphene-based materials, with an emphasis on their antibacterial mechanisms and the factors that influence these properties. Additionally, the review summarizes the dental applications of graphene, spotlighting the studies of its orthodontic application as they can be used to enhance the antibacterial and mechanical properties of orthodontic materials such as adhesives, archwires, and splints. Also, they can be utilized to enhance bone remodeling during orthodontic tooth movement. An electronic search was carried out in Scopus, PubMed, Science Direct, and Wiley Online Library digital database platforms using graphene and orthodontics as keywords. The search was restricted to English language publications without a time limit. This review highlights the need for further laboratory and clinical research using graphene-based materials to improve the properties of orthodontic materials to make them available for clinical use.

Keywords:

Antimicrobial properties, dentistry, graphene, graphene-based material, orthodontic

Introduction

Carbon is extensively utilized in various scientific disciplines owing to its abundant presence and diverse structural configurations.[1] Nanomaterials made of carbon are currently receiving much attention in biomedicine.[2] Carbon nanomaterials can be categorized into various dimensional structures. Zero-dimensional structures (material with all X, Y, and Z dimensions in nanoscale levels) encompass carbon dots and fullerenes and one-dimensional structures such as nanotubes. Additionally, graphene represents a two-dimensional carbon structure.[3] Furthermore, a hybrid of carbon nano components gives rise to three-dimensional structures.[4]

Graphene is one of the strongest and thinnest materials that arise from single crystalline carbon arranged in a honeycomb pattern.[5-7] They possess unique mechanical, chemical, and thermal characteristics with high surface area and antimicrobial properties.[8] Graphene and its derivatives have many biomedical applications as they can easily be functionalized and modified, producing different graphene-based materials.[8-10]

Following their isolation in 2004, graphene and its derivatives have become a promising material for biomaterial research,[11] and the unique physical and chemical properties of graphene-based materials[12] attract their dental application.[13] They have been investigated in many fields and excessively researched for biomedical applications such as tissue engineering, drug delivery, and cancer treatment.[14] In recent years, with the advancement of properties of graphene-based material, they have been

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widely investigated in the field of dentistry.[15] The unique antibacterial and mechanical properties of graphene-based materials encourage researchers to investigate them in orthodontics. To date, there has been no review summary of their specific application in orthodontics.

In this review, we summarized the main graphene derivatives, the mechanism of their antibacterial properties and the factors influencing them. We further summarized their possible application in dentistry, application to enhance bone remodeling, and potential application in orthodontic materials including adhesive, archwire, and acrylic.

Information Sources, Search Strategy, and Study Selection

An electronic search was carried out in Scopus, PubMed, Science Direct, and Wiley Online Library digital database platforms using graphene and orthodontics as keywords. The search was restricted to English language publications without a time limit. A total of 524 publications were identified from PubMed (51), Scopus (20), Science Direct (320), and Wiley Online Library (133) databases. The removal of 14 duplicated studies resulted in 510 studies; among them 487 studies were excluded from the research after assessing the title and abstract (121 were not relevant to the topic, 181 review articles, 127 book chapters, 10 conference review articles, and 48 others). The remaining 23 studies were retrieved and screened by the first author, and this process resulted in the exclusion of 12 studies (4 were not available as full text and 8 were not relevant to the topic). One study was selected and added after screening the references of the selected studies. Therefore, this resulted in the inclusion of 12 studies in the current review [Figure 1]. Any concern regarding the selection of studies was resolved by discussion with the second author.

Types of Graphene-Based Materials

The structures of graphene derivatives are similar; however, they have distinct physicochemical properties resulting from a slight structure variation.[16] They can be classified according to layer numbers, dimensions, and functional surface modification. In addition to single and few-layer graphene, they have two essential derivatives: graphene oxide and reduced graphene oxide.[15]

Graphene is a bi-dimensional, single-layer carbon-based hexagonal structure,[17] they are produced by the exfoliation of graphite as it represents their basic structure. Also, graphene can be deposited utilizing chemical vapor.[18]

Graphene oxide is a highly oxidative flake-like water-soluble graphene derivative with carboxyl, epoxy, and hydroxyl functional groups.[19,20] It is usually produced by the exfoliation of graphite oxide.[7] The partial reduction of the oxygen group from graphene oxide will generate reduced graphene oxide[21,22] with an intermediate structure between graphene and graphene oxide.[23] Additionally, graphene materials can be functionalized by physical or chemical processes utilizing the defect sites, and this can be achieved by nitrogen and fluorine atoms; also, functionalization can be performed with amino, hydroxyl, or carboxyl functional groups,[17] metal nanoparticles to produce graphene nanocomposite.[19] The physicochemical properties of graphene material can be enhanced with functionalization[24,25] [Figure 2].

Proposed Antibacterial Mechanism of Graphene-Based Materials

Numerous graphene-based materials have antibacterial properties from different physical and chemical processes [Figure 3]. Besides minimizing bacterial adhesion,[26,27] these processes involve:

1. *Membrane stress*: The strong interaction between graphene-based material and lipid molecule[21,22] leads to the extraction of phospholipid from the bacterial membrane, destroying the bacterial cells while maintaining cell integrity.[26,28]
2. *Oxidative stress*: In the presence of bacteria, graphene material can produce reactive oxygen species (such as hydrogen peroxide, hydroxyl radical, or superoxide radical), which can destroy bacteria by the evolution of lipid peroxide as they contact bacterial membranes.[29] That leads to oxidation and degradation of different bacterial parts including nucleic acid, protein, and membrane components,[26,30] and reducing their proliferation ability.[31]
3. *Electron transfer*: Graphene behaves as an electron receptor, extracting electrons from the bacterial membrane and damaging their integrity.[5,28]
4. *Wrapping isolation*: Graphene sheets can surround the bacteria, isolating them from their growth media and preventing the crossing of nutrients to bacteria and subsequent inhibition of their growth.[32,33] This antibacterial mechanism is reversible, and the viability can be recovered by bacterial separation from graphene materials.[34]
5. *Nano knife effect*: Bacterial damage can occur by direct contact of bacteria with the sharp edge of graphene layers,[30,35] damaging the bacterial wall integrity and leading to leakage of cellular content,[36] such as protein, phospholipids, ribonucleic acid (RNA), and deoxynucleic acid (DNA).[30]

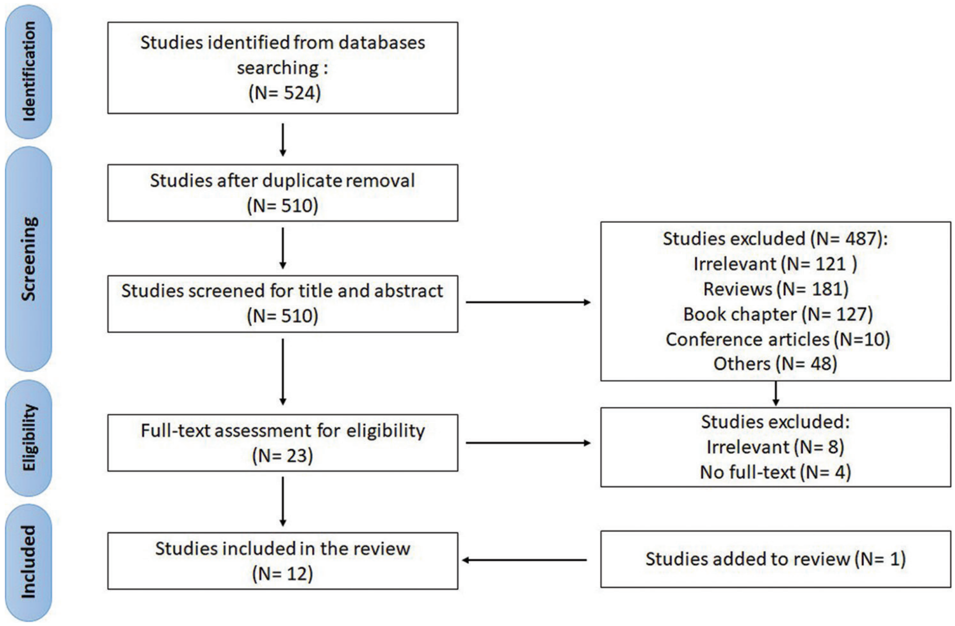

Figure 1: Flow diagram for literature searches

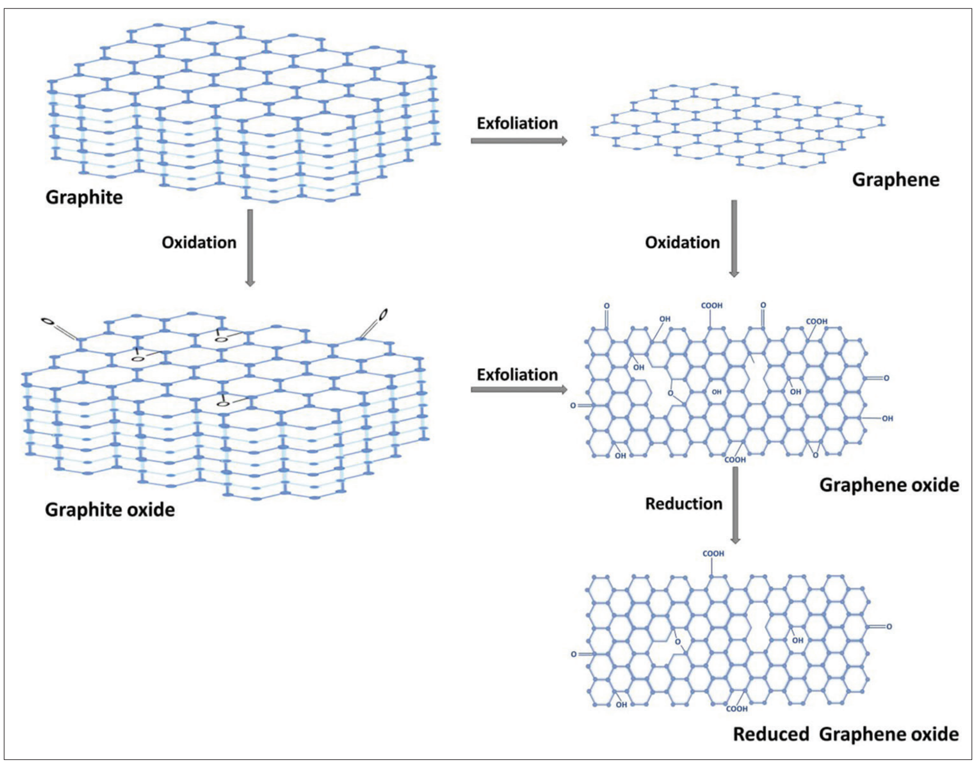

Figure 2: Structure of graphite and graphene-based materials

Factors and Circumstances Determining the Antibacterial Properties of Graphene-Based Materials

The biomedical research community has recently shown considerable interest in the antibacterial properties of graphene and their derivatives,[37] many researchers evaluated the antibacterial behavior of graphene-based material against gram-positive and gram-negative bacteria such as *S. aureus*,[32,38-40] *E. coli*,[34,39-42] *P. aeruginosa*,[38,39] and *P. syringae*.[43]

The interaction between bacteria and graphene materials can be affected by several factors:

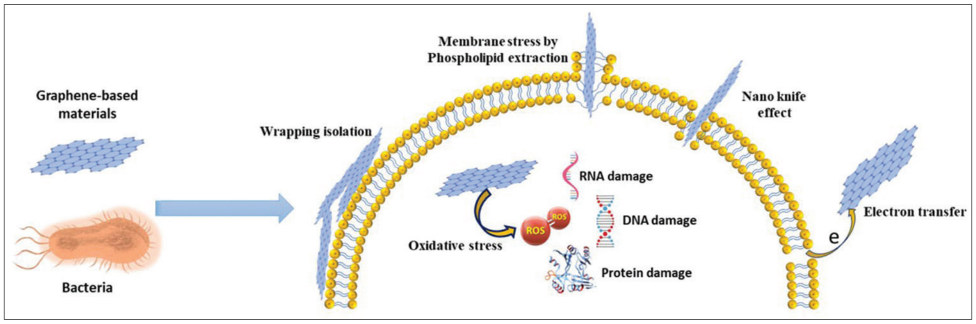

Figure 3: Antibacterial mechanism of graphene-based materials

1. *Physiochemical characteristics of graphene material:* larger sheet sizes provide better bacterial isolation,[20,44] while smaller sheet sizes have better mechanical disruption properties with more production of reactive oxygen species[27,45] and more effortless penetration of phospholipid layer.[36] Additionally, fewer layers show the utmost antibacterial properties[28,46] as higher graphene accumulation and thickness are observed with increasing layers, reducing the interaction with microorganisms.[36] However, antibacterial efficacy can be improved with a smooth surface as bacterial colonization and biofilm formation mainly increase on rough surfaces.[26,45]
2. *Exposure condition:* The antibacterial properties of graphene materials depend on their concentration and exposure time[38,41] and mainly occur in aerobic conditions, as the presence of oxygen is necessary for the production of reactive species.[26,46]
3. *Type and shape of bacteria:* The antibacterial mechanism of graphene materials varies with different types, sizes, and shapes of bacteria.[25,26,28] The damage of cell membranes by graphene oxide is more effective on gram-positive bacterial with thin cytoplasmic membranes,[38] while oxidative stress is responsible for the antibacterial properties of reduced graphene oxide on gram-negative bacteria with more resistant cytoplasmic membranes.[28,32]
4. *Surface modification of graphene material:* Graphene functionalization with hydroxyl or epoxy group reduces bacterial proliferation compared to the carboxylic-rich group.[27] Also, the antibacterial property of graphene material can be enhanced by surface modification with antibiotics, enzymes, metal ions/oxide, or polymers.[5,11,33] Therefore, graphene oxide has higher antibacterial properties when compared to other graphene materials as they possess more functional groups.[41,42]

Application of Graphene and Its Derivatives in Dentistry

Many researchers investigated the antibacterial properties of graphene-based material to oral pathogens; some of these investigations are summarized in Table 1. The improved synthesis and promising characteristics of various graphene-based materials, together with their antibacterial properties, have attracted researchers in different fields of dentistry,[9,69] including [Figure 4]:

Regenerative dentistry and tissue engineering

Orofacial tissue is characterized by a unique structure[70] with minimal self-regeneration properties,[71] which challenges their regeneration by tissue engineering.[14] Nanomaterials, with their small size, large surface area, and biocompatibility, promote cell differentiation and proliferation, making them a candidate biomaterial for tissue regeneration.[72]

Various studies concluded that graphene and its derivative show multi-differentiation ability, including dental pulp,[73] bone marrow,[74] cementum,[75] and periodontal ligament stem cell regeneration.[76] So, they can be used for synthesizing or coating scaffolds to improve their repairing and regeneration properties.[15,77]

Improvement of dental material performance

Besides the antibacterial characteristics, the physiochemical and mechanical characteristics of graphene and its derivative can be utilized to improve the properties of various dental materials.[78] Several studies investigated adding graphene-based material into polymers,[79] glass ionomer cement,[49,80] composite,[81,82] primers,[83] implant materials,[84] and adhesives.[85]

Prevention and management of dental caries

Dental caries is a multifactorial, biofilm-mediated common dental disease. The process of caries development starts with the chemical disintegration of dental tissue due to acid generation through the metabolism of dietary carbohydrates by bacterial attachment to the tooth surface as a biofilm,[86] giving rise to subsurface demineralization, which progresses to caries if untreated.[87]

The antibacterial properties of graphene-based material against *Streptococcus mutans* are utilized by various dental materials to prevent biofilm formation and reduce demineralization and caries development.[88,89]

Table 1: Studies investigated the antibacterial properties of graphene-based materials against oral pathogens

Author	Year	Bacteria	Graphene-based material	Findings of the study
Zanni *et al.*[47]	2016	*S. mutans*	Zinc oxide nanorods decorated with graphene nanoplatelets	The developed nanomaterial can reduce planktonic bacterial viability in a dose-dependent pattern (99.9% with the highest concentration) and inhibit bacterial biofilm formation.
Bregnocchi *et al.*[35]	2017	*S. mutans*	Graphene nanoplatelets	Graphene nanoplatelets can combine the antibacterial properties of graphene-based nanomaterials and the antiadhesion properties of two-dimensional graphene material. They can be used as a filler for antimicrobial dental adhesives without affecting their mechanical properties.
He *et al.*[48]	2017	*S. mutans*	Graphene oxide nanosheets	Graphene oxide nanosheets can effectively reduce living bacterial cells and inhibit biofilm development, but they have minimum effect on mature biofilm.
Sun *et al.*[49]	2018	*S. mutans*	Fluorinated graphene	The bacterial colony count decreases with increasing fluorinated graphene, and the antibacterial rate is up to 85.27% with fluorinated graphene.
Wu *et al.*[50]	2018	*S. mutans*	Reduced graphene oxide, silver nanocomposite	The modified nanocomposite has auspicious antibacterial properties against *S. mutans* to prevent dental caries.
Pulingam *et al.*[38]	2019	*E. faecalis*	Graphene oxide	The antibacterial characteristic of graphene oxide is concentration and time-dependent, with most bacterial inhibition of gram-positive bacteria occurring by wrapping isolation.
Qin *et al.*[51]	2020	*S. mutans, P. gingivalis and F. nucleatum*	Graphene Oxide	The bacterial biofilm in contaminated titanium surfaces can be removed using graphene oxide with brushing, with enhanced osteogenic potential providing a possible treatment for peri-implantation.
Martini *et al.*[52]	2020	*E. faecalis*	Graphene oxide	Graphene oxide observed acceptable adhesion to root dentin with the ability to inhibit bacterial biofilm formation and development.
Wu *et al.*[53]	2020	*S. mutans*	Nano graphene oxide with antisense vicR RNA	The developed material can reduce biofilm aggregation and exopolysaccharide production within the biofilm.
Zhao *et al.*[54]	2020	*S. mutans*	Graphene oxide	Graphene oxide exhibited a concentration-dependent, highly effective (about 80%) antibacterial activity against biofilm and planktonic form of *S. mutans*
Guo *et al.*[55]	2021	*S. mutans, P. gingivalis and F. nucleatum*	Graphene Oxide	Graphene oxide can be used as an antibacterial coating for Polyetheretherketone dental implants to reduce implant-related complications.
Jang *et al.* 2021[56]	2021	*S. mutans*	Graphene oxide	Zirconia coated with graphene oxide can inhibit bacterial adhesion with stimulation of proliferation and stimulation of osteoblast.
Lu *et al.*[57]	2021	*S. mutans*	Graphene oxide nanosheets	The antibacterial properties of graphene oxide nanosheets are concentration and time-dependent, and infrared irradiation can enhance their antibacterial properties to 98%.
Mao *et al.*[58]	2021	*S. mutans*	Graphene oxide-copper nanocomposites	The investigated nanocomposite has antibacterial properties with low cytotoxicity.
Trusek and Kijak[59]	2021	*E. faecalis*	Graphene oxide	Enzymes encapsulated with graphene oxide can act as antibiotic drug carriers and effectively inhibit the growth of bacteria sensitive to antibiotics.
Wei *et al.*[60]	2021	*S. mutans, P. gingivalis and F. nucleatum*	Graphene	Graphene-reinforced dental implant has antimicrobial properties with convenient fibroblast response.
Cheng *et al.*[61]	2022	*S. mutans and P. gingivalis*	Graphene oxide	The peptide-loaded graphene oxide coating of dental implant pretend to have excellent antibacterial characteristics with no cytotoxic effect.
Gamal *et al.*[62]	2022	*S. mutans*	Graphene oxide	Antibacterial properties can be achieved by including graphene oxide nanoparticles within the composition of self-etch adhesive without affecting the bond strength.
Gao *et al.*[63]	2022	*S. mutans, P. gingivalis and F. nucleatum*	Graphene oxide	The graphene oxide coating of dental implants has antibacterial properties against gram-positive and gram-negative bacteria with adequate cytocompatibility.
Salgado *et al.*[64]	2022	*S. mutans*	Graphene	The dental resin modified with graphene effectively inhibits bacterial growth and adhesion to the resin surface.
Eskandari *et al.*[65]	2023	*E. faecalis*	Graphene oxide	Combining graphene oxide and double antibiotic paste improves root canal disinfection and could be considered a promising intracanal antibacterial medication.

Contd...

Table 1: Contd...

Author	Year	Bacteria	Graphene-based material	Findings of the study
Kim *et al.*[66]	2023	*E. faecalis*	Graphene oxide Reduced graphene oxide	The antibacterial characteristic of graphene oxide and reduced graphene oxide is similar, while the cytotoxicity of reduced graphene oxide is lower than graphene oxide; therefore, the reduced graphene oxide can be used as a more effective antibacterial agent.
Kim *et al.*[67]	2023	*E. faecalis*	Reduced graphene oxide	Combining apigenin and reduced graphene oxide could be an effective endodontic antibacterial disinfectant agent.
Park *et al.*[68]	2023	*S. mutans and P. gingivalis*	Graphene oxide	The infrared irradiation of graphene oxide with photothermal characteristics can reduce bacterial adhesion, minimizing peri-implantation when used as a dental implant coating.

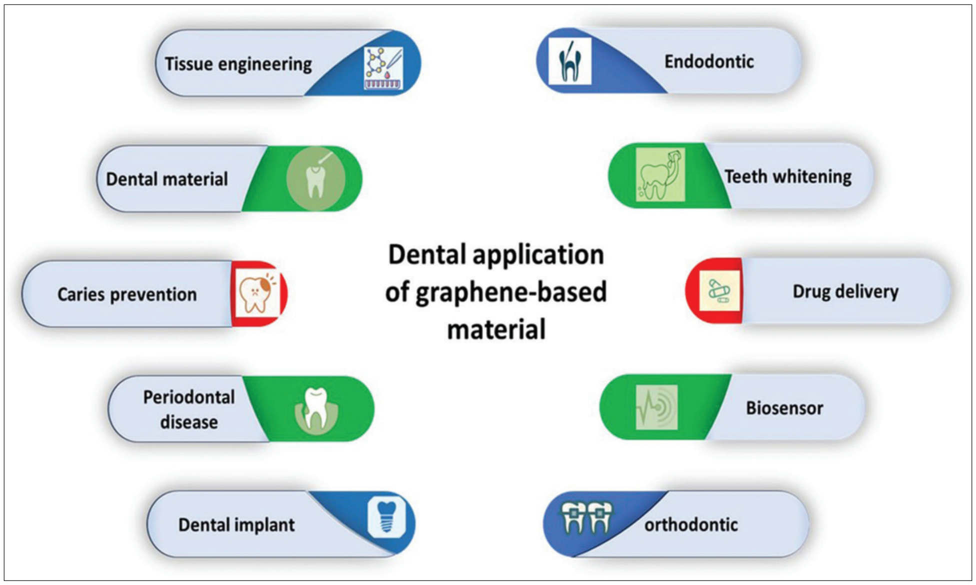

Figure 4: Dental application of graphene-based materials

Periodontal disease management

Periodontitis is a chronic inflammatory disease stimulated by oral pathogens.[90] It leads to the gradual breakdown of the hard and soft tissues of the periodontal structure, with the loss of alveolar bone and periodontal ligament attachment.[91,92]

Periodontal pathogens can be suppressed by graphene and its derivative to control infection and prevent tissue destruction.[15,88] Several research concluded that graphene-based materials are highly effective against *P. gingivalis*,[51,55,93] the leading bacteria responsible for periodontal disease.[94] Additionally, graphene derivatives can be utilized for guided tissue and bone regeneration. This can be achieved by increasing the biocompatibility of collagen membranes,[95] promoting periodontal stem cell regeneration,[76,96] or a combination of both.[88]

Dental implant coating

A successful dental implant requires optimal osteointegration at the hard tissue interface and intimate gingival attachment at the soft tissue interface to prevent bacterial infiltration since bacterial contamination may cause implant failure by promoting peri-implantation. Graphene materials can modify the implant surface to improve their biocompatibility[6] and enhance osteointegration[97] with outstanding antibacterial properties.[51,55,61]

Endodontic treatment

Root canal treatment aims to biomechanically clean the infected root canal system by destroying intracanal pathogens, decontaminating infected tissue, and avoiding further infection. The leading cause of endodontic failure is a persistent infection or reinfection in the root canal.[98]

Studies are carried out to improve the properties of endodontic sealer,[99] obturation material,[100] bioactive cement,[101] and irrigation material[102] with graphene derivatives, to enhance their antibacterial and mechanical properties.[9,78]

Teeth whitening

With the increased awareness of dental esthetics, tooth whitening is highly requested as one of the conservative procedures to enhance dental appearance. This can be achieved by physical stain removal or chemically using hydrogen peroxide to whiten the tooth.[103] Besides their widespread use of teeth whitening, they have side effects, including tooth sensitivity and gingival irritation.[104]

With graphene materials, the efficacy of hydrogen peroxide in tooth whitening can be raised while reducing side effects and shortening treatment time.[16]

Drug delivery

The control drug delivery system allows the release of active materials to specific organs at the required concentration with minimal side effects.[105] Graphene materials, with their large surface area, outstanding chemical properties, and biocompatibility, make them promising materials for controlled drug delivery of anticancer, antibiotic, genes, and other pharmaceutical drugs.[106]

Despite the well-known ability of graphene materials as drug carriers in the biomedical field, few studies investigated this property for dental applications.[77] The effective concentration and gradual drug release can be achieved by employing graphene oxide as a drug delivery system for bone morphogenetic protein[107] and antibiotics.[15,59]

Graphene-based biosensors

The large surface area, biocompatibility with the excellent signal response of graphene, and their derivatives encourage their use in biosensor synthesis as they can be used for the detection of antibodies, DNA, proteins, and enzymes.[108]

Graphene-based biosensors are researched for detecting bacterial and viral markers in the oral cavity. Also, they are effective in the early detection of cancer biomarkers in saliva.[15,16]

Potential Application of Graphene-Based Materials in Orthodontic

Due to their unique physiochemical and antibacterial properties, graphene materials are also investigated to improve the properties of orthodontic materials [Figure 5]. Table 2 summarizes some of the studies of graphene and its derivative in the orthodontic field.

The use of graphene-based material in orthodontic adhesive system

Successful orthodontic treatment is based on enhancing dental esthetic and function by correcting the occlusion[121] without influencing the health of the teeth and the supporting tissue.[122] Fixed orthodontic appliance and their accessories act as a plaque retentive factor that makes maintaining oral hygiene difficult and increases the risk of enamel demineralization and the development of white spot lesions.[123] Since the white spot lesion is visible to the naked eye, it can damage the esthetic outcome of orthodontic treatment.[110]

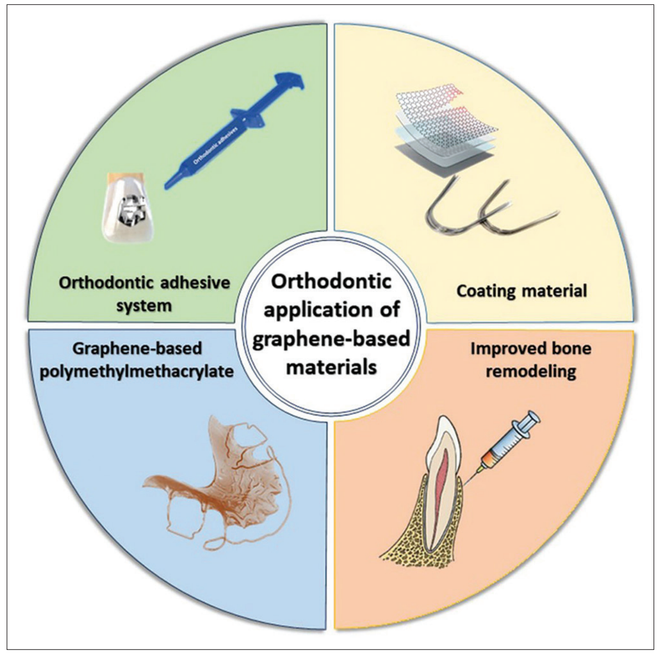

Figure 5: Orthodontic application of graphene-based materials

Preventive treatment of white spot lesions can be accomplished by patient training in tooth brushing and fluoride gargling. These methods require patient cooperation, which is usually unpredictable.[124] Graphen-based materials with unique properties can be incorporated into orthodontic adhesives to improve their biological and mechanical properties. The addition of graphene-based materials to orthodontic adhesive was investigated in many studies. The incorporation of 0.25 wt.% of graphene oxide into orthodontic adhesive shows antibacterial properties against *s. mutans* of 31% and 47% after 1 and 30 days, with the acceptable bond strength and adhesive remanent index.[112] Another study investigated orthodontic adhesive dopped with 5 wt.% of graphene oxide; the result of the study showed the modified adhesive has antibacterial properties against *s. mutans* with proper shear bond strength and adhesive remanent index.[114] A study by Pourhajibagher *et al.*[118] found that the total bacterial count was reduced for up to 30 days by modifying orthodontic adhesive by 5 and 10 wt.% of nano-graphene oxide. Furthermore, Lee *et al.*[109] concluded that adding a 5% mixture of graphene oxide and bioactive glass observed higher antibacterial and remineralization characteristics. Also, the addition of graphene oxide and fluorinated graphite to high-flow orthodontic adhesive is researched by Nam *et al.*[110] and reported inhibition in bacterial growth with enhancement of remineralization properties. Additionally, modifying orthodontic adhesive with 5% curcumin-reduced nano-graphene oxide has no

Table 2: Summary of the studies that used graphene-based materials in orthodontic materials

Author	Year	The used graphene materials	Method	Material type	The conclusion of the study
Lee *et al.*[109]	2018	Graphene oxide and bioactive glass	Microhardness, SBS, ARI, cytotoxicity, antibacterial, anti-demineralization tests	Orthodontic adhesive	The modified adhesive has appropriate mechanical and biological properties.
Nam *et al.*[110]	2019	Fluoridated graphite and bioactive glass	Microhardness, SBS, antibacterial, cytotoxicity, fluorine dissolution, remineralization test	Orthodontic adhesive	The modified resin has physical stability and biological safety for clinical use to prevent WSL.
Mallick and Arunachalam[111]	2019	Graphene nanoplatelet	TEM, XRD, FESEM, FTIR, TGA, XPS, nanoindentation and corrosion resistance	Nitinol wire	There is an improvement in corrosion resistance with graphene coating and post-deposition annealing can increase the coating strength
Alnatheer *et al.*[112]	2021	Graphene oxide	SBS, ARI, cytotoxicity, antimicrobial tests	Orthodontic adhesive	The modified adhesive has superior antimicrobial and mechanical properties.
Ghorbanzadeh *et al.*[113]	2021	Curcumin-reduced nano-graphene oxide	SBS, antimicrobial test	Orthodontic adhesive	The modified adhesive has no adverse effect on SBS with improved antimicrobial activity.
Pourhajibagher and Bahador[114]	2021	Graphene oxide	SBS, ARI, antimicrobial tests	Orthodontic adhesive	Improved antibacterial properties with no effect on SBS and ARI
Sawan *et al.*[115]	2021	Graphene nanoplatelets and silver nanoparticles	SBS, ARI, cytotoxicity, antibacterial tests	Orthodontic adhesive	The modified adhesive has potential antibacterial properties
Jiao *et al.*[116]	2022	Reduced graphene oxide	Observation and analysis of tooth movement, evaluation of osteogenesis	Gelatin-reduced graphene oxide	The gelatin-reduced graphene oxide promotes bone remodeling
Pan *et al.*[117]	2022	Graphene sheet	Friction test, immersion test	Orthodontic archwire	The coated wire has improved friction and wear performance
Pourhajibagher *et al.*[118]	2022	Graphene oxide	Cytotoxicity, antimicrobial tests	Orthodontic adhesive	A modified adhesive has antimicrobial activity against *streptococcus mutans*
Wang *et al.*[119]	2022	Graphene sheet	TEM, Raman spectroscopy, hardness, young module, Fretting wear test	Orthodontic archwire	The modified archwire has a low friction coefficient and a low wear rate
Barbur *et al.*[120]	2023	Graphene oxide with (silver or zinc oxide)	SEM, compressive strength, bending resistance, and tensile strength test	Orthodontic occlusal splint	The graphene based polymethylmethacrylate has good mechanical properties making it a promising material for future use

SBS=shear bond strength, ARI=adhesive remnant index, WSL=white spot lesion, TEM=transmission electron microscope, XRD=X-ray diffractometer, FESEM=field emission scanning electron microscope, FTIR=Fourier transform infrared spectroscopy, TGA=thermogravimetric analysis, XPS=X-ray photoelectron spectroscopy, SEM=scanning electron microscope

adverse effect on antibacterial characteristics or physical and mechanical properties.[113] The incorporation of a methacrylate-based bonding agent with 0.25 wt.% of graphene nanoplatelets functionalized by silver nanoparticles showed sustained enhancement of antibacterial behavior with acceptable bond strength.[115]

The use of graphene-based material as coating material

Fixed orthodontic appliances comprise brackets, archwire, and axillaries.[125] Orthodontic therapy depends on the bracket sliding along the archwire to produce tooth movement;[126] however, tooth movement may be opposed by the frictional force between the bracket and archwire.[127,128] Therefore, controlling friction is advantageous regarding treatment duration, desirable movement,[129] and minimizing root resorption.[130] With the advancement of nanotechnology, they improve orthodontic archwire mechanical and biological properties by coating them with nanomaterials.[131]

Among the graphene-based material, graphene sheet was used by Wang *et al.*[119] as a coating for stainless steel archwire using a plasma sputtering deposition system, the coated archwire showed a remarkable reduction of wear rate and friction coefficient, proposing an advantage for orthodontic tooth movement. Another study investigated the stable and static friction of stainless steel archwire coated with graphene sheets under wet and dry conditions; a low friction coefficient was observed in the wet condition of artificial saliva. Although the friction manner observed some impairment when immersed in wet conditions for a prolonged time, they still followed a moderate friction coefficient after a 30-day immersion in artificial saliva.[117] Additionally, the researched graphene coating of nitinol wire reported enhancement of corrosion resistance, and the coating strength can be enhanced by post-deposition annealing in a vacuum environment. Similarly, the coating of nickel-titanium alloy with graphene oxide was studied by Dai *et al.*,[132] who concluded that graphene oxide coating can reduce corrosion in artificial saliva and also show antibacterial characteristics against *S. mutans*.

Application of graphene-based materials to improve bone remodeling

Conventional orthodontic treatment is a lengthy procedure, and there is increasing interest in speeding up orthodontic tooth movement and reducing the duration of treatment.[133] During orthodontic treatment, the main limiting factor for tooth movement is bone remodeling around the teeth.[116]

Biocompatible gelatin of reduced graphene oxide was synthesized by Jiao *et al.*[134] and evaluated for its ability to modify bone remodeling in a mouse orthodontic tooth movements model; they found that local injection of gelatin-reduced graphene oxide can accelerate tooth movement with more neovascularization and osteoclastic bone resorption without affecting the survival life of animals.[116]

Graphene-based polymethylmethacrylate

Polymethylmethacrylate is a transparent polymer with wide application in dentistry and orthodontics,[135] it can be utilized for the fabrication of myofunctional appliances, occlusal splints, retainers, bite guards, and bite planes.[136] Despite their popular use, they have many drawbacks such as poor mechanical characteristics, polymerization shrinkage, and poor antibacterial properties.[137] Therefore, several studies have been carried out to improve the polymethylmethacrylate properties using different materials.[136,138] Graphene-based materials are among the researched materials to improve the mechanical[139] and antibacterial properties of polymethylmethacrylate.[140] Commercially available orthodontic polymethylmethacrylate (Orthocryl) was modified by Barbur *et al.*,[120] using 2% graphene oxide-silver and 1% graphene oxide-zinc oxide, after preparation of polymethylmethacrylate by salt and pepper methods, they evaluated for mechanical properties. Modified polymethylmethacrylate has excellent mechanical properties, with the possibility of clinical use in the future.

Conclusion and Future Perspective

According to this review, the following can be concluded in terms of the potential use of graphene-based material in the dental field:

1. The improvement of the antibacterial properties of dental materials, which can be beneficial in the control and management of dental caries, periodontal disease, root canal infection, and peri-implantitis.
2. The physiochemical and mechanical characteristics of graphene-based materials can be used to improve the mechanical properties of dental materials.
3. They might be utilized for enhancing the ability of dental tissue regeneration.
4. They can also be used for drug delivery, biosensors, and teeth whitening.

The application of graphene-based materials in orthodontics is in the primitive stage; however, the available evidence shows that:

1. The antibacterial properties of the orthodontic adhesive system can be improved by the addition of graphene-based materials. This could have a positive role in maintaining good oral hygiene and prevention of white spot lesions during orthodontic treatment.
2. Graphene-based material can be included within or used as a coating of orthodontic material to improve its mechanical properties, such as controlling the archwire-brackets friction.
3. Graphene-based material can be utilized to modify bone remodeling during orthodontic movement.

However, there are limited *in vitro* studies in orthodontic application of graphene-based material with a lack of *in vivo* studies. Hence, the provided and discussed evidence can enhance researchers to develop novel orthodontic applications for graphene-based materials to improve the mechanical and antibacterial properties of orthodontic materials. Also, they can be investigated to enhance dental tissue regeneration, which can be beneficial for both acceleration and retention of orthodontic tooth movement. Additionally, enough clinical studies are required to utilize this material in market-oriented investigation areas to become available for clinical use in the future.

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Conflicts of interest

There are no conflicts of interest.

References

1. Castro-Rojas MA, Vega-Cantu YI, Cordell GA, Rodriguez-Garcia A. Dental applications of carbon nanotubes. Molecules 2021;26:4423.
2. Mousavi SM, Yousefi K, Hashemi SA, Afsa M, BahranI S, Gholami A, *et al.* Renewable carbon nanomaterials: Novel resources for dental tissue engineering. Nanomaterials 2021;11:2800.
3. Singh J, Nayak P, Singh G, Khandai M, Sarangi RR, Kar MK. Carbon nanostructures as therapeutic cargoes: Recent developments and challenges. C-J CARBON RES 2022;9:3.
4. Rizwan M, Shoukat A, Ayub A, Razzaq B, Tahir MB. Types and classification of nanomaterials. In: Tahir MB, Sagir M, Asiri AM, editors. Nanomaterials: Synthesis, Characterization, Hazards and Safety. Elsevier; 2021. p. 31-54.

5. Kumar P, Huo P, Zhang R, Liu B. Antibacterial properties of graphene-based nanomaterials. Nanomaterials (Basel) 2019;9:737.
6. Hashim NC, Frankel D, Nordin D. Graphene oxide-modified hydroxyapatite nanocomposites in biomedical applications: A review. Ceramics-Silikáty 2019;63:426-48.
7. Sujiono EH, Zabrian D, Dahlan M, Amin B, Agus J. Graphene oxide based coconut shell waste: Synthesis by modified Hummers method and characterization. Heliyon 2020;6:e04568.
8. Nica IC, Stan MS, Popa M, Chifiriuc MC, Pircalabioru GG, Lazar V, *et al.* Development and biocompatibility evaluation of photocatalytic TiO2/reduced graphene oxide-based nanoparticles designed for self-cleaning purposes. Nanomaterials (Basel) 2017;7:279.
9. Gupta S, Mittal N, Agrawal A, Kumar P. Grapheme: An asset or a black box to dentistry: A review. J Oral Health Dent 2022;4:318-22.
10. Jampilek J, Kralova K. Advances in biologically applicable graphene-based 2D nanomaterials. Int J Mol Sci 2022;23:6253.
11. Williams A, Moore E, Thomas A, Johnson J. Graphene-based materials in dental applications: Antibacterial, biocompatible, and bone regenerative properties. Int J Biomater 2023;2023:8803283.
12. Maiti D, Tong X, Mou X, Yang K. Carbon-based nanomaterials for biomedical applications: A recent study. Front Pharmacol 2019;9:1401.
13. Vijay R, Mendhi J, Prasad K, Xiao Y, MacLeod J, Ostrikov K, *et al.* Carbon nanomaterials modified biomimetic dental implants for diabetic patients. Nanomaterials (Basel) 2021;11:2977.
14. Guazzo R, Gardin C, Bellin G, Sbricoli L, Ferroni L, Ludovichetti FS, *et al.* Graphene-based nanomaterials for tissue engineering in the dental field. Nanomaterials (Basel) 2018;8:349.
15. Li X, Liang X, Wang Y, Wang D, Teng M, Xu H, *et al.* Graphene-based nanomaterials for dental applications: Principles, current advances, and future outlook. Front Bioeng Biotechnol 2022;10:804201.
16. Tahriri M, Del Monico M, Moghanian A, Tavakkoli Yaraki M, Torres R, Yadegari A, *et al.* Graphene and its derivatives: Opportunities and challenges in dentistry. Mater Sci Eng C 2019;102:171-85.
17. Plachá D, Jampilek J. Graphenic materials for biomedical applications. Nanomaterials (Basel) 2019;9:1758.
18. Bacakova L, Pajorova J, Tomkova M, Matejka R, Broz A, Stepanovska J, *et al.* Applications of nanocellulose/nanocarbon composites: Focus on biotechnology and medicine. Nanomaterials 2020;10:196.
19. Lawal AT. Graphene-based nano composites and their applications. A review. Biosens Bioelectron 2019;141:111384.
20. Xia M-Y, Xie Y, Yu C-H, Chen G-Y, Li Y-H, Zhang T, *et al.* Graphene-based nanomaterials: The promising active agents for antibiotics-independent antibacterial applications. J Control Release 2019;307:16-31.
21. Szunerits S, Boukherroub R. Antibacterial activity of graphene-based materials. J Mater Chem B 2016;4:6892-6912.
22. Linklater DP, Baulin VA, Juodkazis S, Ivanova EP. Mechano-bactericidal mechanism of graphene nanomaterials. Interface Focus 2018;8:20170060.
23. Raslan A, Del Burgo LS, Ciriza J, Pedraz JL. Graphene oxide and reduced graphene oxide-based scaffolds in regenerative medicine. Int J Pharm 2020;580:119226.
24. Mohammed H, Kumar A, Bekyarova E, Al-Hadeethi Y, Zhang X, Chen M, *et al.* Antimicrobial mechanisms and effectiveness of graphene and graphene-functionalized biomaterials. A scope review. Front Bioeng Biotechnol 2020;8:465.
25. Tegou E, Magana M, Katsogridaki AE, Ioannidis A, Raptis V, Jordan S, *et al.* Terms of endearment: Bacteria meet graphene nanosurfaces. Biomaterials 2016;89:38-55.
26. Zhang T, Tremblay P-L. Graphene: An antibacterial agent or a promoter of bacterial proliferation? iScience 2020;23:101787.
27. Radhi A, Mohamad D, Abdul Rahman FS, Abdullah AM, Hasan H. Mechanism and factors influence of graphene-based nanomaterials antimicrobial activities and application in dentistry. J Mater Res Technol 2021;11:1290-307.
28. Yaragalla S, Bhavitha KB, Athanassiou A. A review on graphene based materials and their antimicrobial properties. Coatings 2021;11:1197.
29. Krishnamoorthy K, Veerapandian M, Zhang L-H, Yun K, Kim SJ. Antibacterial efficiency of graphene nanosheets against pathogenic bacteria via lipid peroxidation. J Phys Chem C 2012;116:17280-7.
30. Mei L, Zhu S, Yin W, Chen C, Nie G, Gu Z, *et al.* Two-dimensional nanomaterials beyond graphene for antibacterial applications: Current progress and future perspectives. Theranostics 2020;10:757-81.
31. Dutta T, Sarkar R, Pakhira B, Ghosh S, Sarkar R, Barui A, *et al.* ROS generation by reduced graphene oxide (rGO) induced by visible light showing antibacterial activity: Comparison with graphene oxide (GO). RSC Adv 2015;5:80192-5.
32. Sengupta I, Bhattacharya P, Talukdar M, Neogi S, Pal SK, Chakraborty S. Bactericidal effect of graphene oxide and reduced graphene oxide: Influence of shape of bacteria. Colloids Interface Sci Commun 2019;28:60-8.
33. Ji H, Sun H, Qu X. Antibacterial applications of graphene-based nanomaterials: Recent achievements and challenges. Adv Drug Deliv Rev 2016;105:176-89.
34. Perreault F, De Faria AF, Nejati S, Elimelech M. Antimicrobial properties of graphene oxide nanosheets: Why size matters. ACS Nano 2015;9:7226-36.
35. Bregnocchi A, Zanni E, Uccelletti D, Marra F, Cavallini D, De Angelis F, *et al.* Graphene-based dental adhesive with anti-biofilm activity. J Nanobiotechnology 2017;15:89.
36. Zou X, Zhang L, Wang Z, Luo Y. Mechanisms of the antimicrobial activities of graphene materials. J Am Chem Soc 2016;138:2064-77.
37. Yousefi M, Dadashpour M, Hejazi M, Hasanzadeh M, Behnam B, de la Guardia M, *et al.* Anti-bacterial activity of graphene oxide as a new weapon nanomaterial to combat multidrug-resistance bacteria. Mater Sci Eng C 2017;74:568-81.
38. Pulingam T, Thong KL, Ali ME, Appaturi JN, Dinshaw IJ, Ong ZY, *et al.* Graphene oxide exhibits differential mechanistic action towards Gram-positive and Gram-negative bacteria. Colloids Surf B Biointerfaces 2019;181:6-15.
39. Karahan HE, Wei L, Goh K, Liu Z, Birer Ö, Dehghani F, *et al.* Bacterial physiology is a key modulator of the antibacterial activity of graphene oxide. Nanoscale 2016;8:17181-9.
40. Liu Y, Wen J, Gao Y, Li T, Wang H, Yan H, *et al.* Antibacterial graphene oxide coatings on polymer substrate. Appl Surf Sci 2018;436:624-30.
41. Liu S, Zeng TH, Hofmann M, Burcombe E, Wei J, Jiang R, *et al.* Antibacterial activity of graphite, graphite oxide, graphene oxide, and reduced graphene oxide: Membrane and oxidative stress. ACS Nano 2011;5:6971-80.
42. Hu W, Peng C, Luo W, Lv M, Li X, Li D, *et al.* Graphene-based antibacterial paper. ACS Nano 2010;4:4317-23.
43. Chen J, Peng H, Wang X, Shao F, Yuan Z, Han H. Graphene oxide exhibits broad-spectrum antimicrobial activity against bacterial phytopathogens and fungal conidia by intertwining and membrane perturbation. Nanoscale 2014;6:1879-89.
44. Yu C-H, Chen G-Y, Xia M-Y, Xie Y, Chi Y-Q, He Z-Y, *et al.* Understanding the sheet size-antibacterial activity relationship of graphene oxide and the nano-bio interaction-based physical mechanisms. Colloids Surf B Biointerfaces 2020;191:111009.
45. Hegab HM, ElMekawy A, Zou L, Mulcahy D, Saint CP, Ginic-Markovic M. The controversial antibacterial activity of graphene-based materials. Carbon 2016;105:362-76.
46. Gungordu Er S, Edirisinghe M, Tabish TA. Graphene-based nanocomposites as antibacterial, antiviral and antifungal agents. Adv Healthc Mater 2023;12:2201523.

47. Zanni E, Chandraiahgari CR, De Bellis G, Montereali MR, Armiento G, Ballirano P, *et al.* Zinc oxide nanorods-decorated graphene nanoplatelets: A promising antimicrobial agent against the cariogenic bacterium *Streptococcus mutans*. Nanomaterials 2016;6:179.
48. He J, Zhu X, Qi Z, Wang L, Aldalbahi A, Shi J, *et al.* The inhibition effect of graphene oxide nanosheets on the development of *Streptococcus mutans* biofilms. Part Part Syst Charact 2017;34:1700001.
49. Sun L, Yan Z, Duan Y, Zhang J, Liu B. Improvement of the mechanical, tribological and antibacterial properties of glass ionomer cements by fluorinated graphene. Dent Mater 2018;34:e115-27.
50. Wu R, Zhao Q, Lu S, Fu Y, Yu D, Zhao W. Inhibitory effect of reduced graphene oxide-silver nanocomposite on progression of artificial enamel caries. J Appl Oral Sci 2018;27:e20180042.
51. Qin W, Wang C, Jiang C, Sun J, Yu C, Jiao T. Graphene oxide enables the reosteogenesis of previously contaminated titanium *in vitro*. J Dent Res 2020;99:922-9.
52. Martini C, Longo F, Castagnola R, Marigo L, Grande NM, Cordaro M, *et al.* Antimicrobial and antibiofilm properties of graphene oxide on *Enterococcus faecalis*. Antibiotics 2020;9:692.
53. Wu S, Liu Y, Zhang H, Lei L. Nano-graphene oxide with antisense vicR RNA reduced exopolysaccharide synthesis and biofilm aggregation for *Streptococcus mutans*. Dent Mater J 2020;39:278-86.
54. Zhao M, Shan T, Wu Q, Gu L. The antibacterial effect of graphene oxide on *Streptococcus mutans*. J Nanosci Nanotechnol 2020;20:2095-103.
55. Guo C, Lu R, Wang X, Chen S. Graphene oxide-modified polyetheretherketone with excellent antibacterial properties and biocompatibility for implant abutment. Macromol Res 2021;29:351-9.
56. Jang W, Kim H-S, Alam K, Ji M-K, Cho H-S, Lim H-P. Direct-deposited graphene oxide on dental implants for antimicrobial activities and osteogenesis. Int J Nanomedicine 2021;16:5745-54.
57. Lu B-Y, Zhu G-Y, Yu C-H, Chen G-Y, Zhang C-L, Zeng X, *et al.* Functionalized graphene oxide nanosheets with unique three-in-one properties for efficient and tunable antibacterial applications. Nano Res 2021;14:185-90.
58. Mao M, Zhang W, Huang Z, Huang J, Wang J, Li W, *et al.* Graphene oxide-copper nanocomposites suppress cariogenic *Streptococcus mutans* biofilm formation. Int J Nanomedicine 2021;16:7727-39.
59. Trusek A, Kijak E. Drug carriers based on graphene oxide and hydrogel: Opportunities and challenges in infection control tested by amoxicillin release. Materials 2021;14:3182.
60. Wei J, Qiao S, Zhang X, Li Y, Zhang Y, Wei S, *et al.* Graphene-reinforced titanium enhances soft tissue seal. Front Bioeng Biotechnol 2021;9:665305.
61. Cheng Q, Lu R, Wang X, Chen S. Antibacterial activity and cytocompatibility evaluation of the antimicrobial peptide Nal-P-113-loaded graphene oxide coating on titanium. Dent Mater J 2022;41:905-15.
62. Gamal W, Alrafee SA, Sayed A. The effect of incorporating graphene oxide nanoparticles within self-etch adhesive on the antibacterial properties and shear bond strength. Egypt Dent J 2022;68:3733-40.
63. Gao Y, Kang K, Luo B, Sun X, Lan F, He J, *et al.* Graphene oxide and mineralized collagen-functionalized dental implant abutment with effective soft tissue seal and romotely repeatable photodisinfection. Regen Biomater 2022;9:rbac024.
64. Salgado H, Gomes AT, Duarte AS, Ferreira JM, Fernandes C, Figueiral MH, *et al.* Antimicrobial activity of a 3D-printed polymethylmethacrylate dental resin enhanced with graphene. Biomedicines 2022;10:2607.
65. Eskandari F, Abbaszadegan A, Gholami A, Ghahramani Y. The antimicrobial efficacy of graphene oxide, double antibiotic paste, and their combination against *Enterococcus faecalis* in the root canal treatment. BMC Oral Health 2023;23:20.
66. Kim M-A, Rosa V, Min K-S. Effect of two graphene derivatives on *Enterococcus faecalis* biofilms and cytotoxicity. Dent Mater J 2023;42:211-7.
67. Kim M-A, Min K-S. Combined effect of apigenin and reduced graphene oxide against *Enterococcus faecalis* biofilms. J Oral Sci 2023;65:163-7.
68. Park L, Kim H-S, Jang W, Ji M-K, Ryu J-H, Cho H, *et al.* Antibacterial evaluation of zirconia coated with plasma-based graphene oxide with photothermal properties. Int J Mol Sci 2023;24:8888.
69. Kulshrestha S, Khan S, Meena R, Singh BR, Khan AU. A graphene/zinc oxide nanocomposite film protects dental implant surfaces against cariogenic *Streptococcus mutans*. Biofouling 2014;30:1281-94.
70. Abou Neel EA, Chrzanowski W, Salih VM, Kim H-W, Knowles JC. Tissue engineering in dentistry. J Dent 2014;42:915-28.
71. Olaru M, Sachelarie L, Calin G. Hard dental tissues regeneration—approaches and challenges. Materials (Basel) 2021;14:2558.
72. Zheng X, Zhang P, Fu Z, Meng S, Dai L, Yang H. Applications of nanomaterials in tissue engineering. RSC Adv 2021;11:19041-8.
73. Li Y, Yang L, Hou Y, Zhang Z, Chen M, Wang M, *et al.* Polydopamine-mediated graphene oxide and nanohydroxyapatite-incorporated conductive scaffold with an immunomodulatory ability accelerates periodontal bone regeneration in diabetes. Bioact Mater 2022;18:213-27.
74. Daneshmandi L, Barajaa M, Tahmasbi Rad A, Sydlik SA, Laurencin CT. Graphene-based biomaterials for bone regenerative engineering: A comprehensive review of the field and considerations regarding biocompatibility and biodegradation. Adv Healthc Mater 2021;10:2001414.
75. Vera-Sánchez M, Aznar-Cervantes S, Jover E, Garcia-Bernal D, Onate-Sanchez RE, Hernández-Romero D, *et al.* Silk-fibroin and graphene oxide composites promote human periodontal ligament stem cell spontaneous differentiation into osteo/cementoblast-like cells. Stem Cells Dev 2016;25:1742-54.
76. Park J, Park S, Kim JE, Jang K-J, Seonwoo H, Chung JH. Enhanced osteogenic differentiation of periodontal ligament stem cells using a graphene oxide-coated poly (ε-caprolactone) scaffold. Polymers 2021;13:797.
77. Nizami MZI, Takashiba S, Nishina Y. Graphene oxide: A new direction in dentistry. Appl Mater Today 2020;19:100576.
78. Liu C, Tan D, Chen X, Liao J, Wu L. Research on graphene and its derivatives in oral disease treatment. Int J Mol Sci 2022;23:4737.
79. Sahm BD, Teixeira ABV, Dos Reis AC. Graphene loaded into dental polymers as reinforcement of mechanical properties: A systematic review. Jpn Dent Sci Rev 2023;59:160-6.
80. Al-Qahtani YM. Impact of graphene oxide and silver diamine fluoride in comparison to photodynamic therapy on bond integrity and microleakage scores of resin modified glass ionomer cement to demineralized dentin. Photodiagnosis Photodyn Ther 2021;33:102163.
81. Moldovan M, Dudea D, Cuc S, Sarosi C, Prodan D, Petean I, *et al.* Chemical and structural assessment of new dental composites with graphene exposed to staining agents. J Funct Biomater 2023;14:163.
82. Velo MMdAC, Filho FGN, de Lima Nascimento TR, Obeid AT, Castellano LC, Costa RM, *et al.* Enhancing the mechanical properties and providing bioactive potential for graphene oxide/montmorillonite hybrid dental resin composites. Sci Rep 2022;12:10259.
83. Khan AA, Al-Khureif AA, Saadaldin SA, Mohamed BA, Musaibah AS, Divakar DD, *et al.* Graphene oxide-based experimental silane primers enhance shear bond strength between resin composite and zirconia. Eur J Oral Sci 2019;127:570-6.

84. Zhang C, Wang F, Jiang Z, Lan J, Zhao L, Si P. Effect of graphene oxide on the mechanical, tribological, and biological properties of sintered 3Y–ZrO2/GO composite ceramics for dental implants. Ceram Int 2021;47:6940-6.
85. Ilie N, Serfoezoe NE, Prodan D, Diegelmann J, Moldovan M. Synthesis and performance of experimental resin-based dental adhesives reinforced with functionalized graphene and hydroxyapatite fillers. Mater Des 2022;221:110985.
86. Wong A, Subar PE, Young DA. Dental caries: An update on dental trends and therapy. Adv Pediatr 2017;64:307-30.
87. Chanachai S, Chaichana W, Insee K, Benjakul S, Aupaphong V, Panpisut P. Physical/mechanical and antibacterial properties of orthodontic adhesives containing calcium phosphate and nisin. J Funct Biomater 2021;12:73.
88. Nizami MZI, Yin IX, Lung CYK, Niu JY, Mei ML, Chu CH. *In vitro* studies of graphene for management of dental caries and periodontal disease: A concise review. Pharmaceutics 2022;14:1997.
89. Zhang OL, Niu JY, Yin IX, Yu OY, Mei ML, Chu CH. Bioactive materials for caries management: A literature review. Dent J 2023;11:59.
90. Ibraheem LM, Ahmmad BZ, Dhafer AM, Dhafer JM. Effect of diabetes mellitus on periodontal health status, salivary flow rate and salivary pH in patients with chronic periodontitis. J Baghdad Coll Dent 2020;32:12-6.
91. Sedghi LM, Bacino M, Kapila YL. Periodontal disease: The good, the bad, and the unknown. Front Cell Infect Microbiol 2021;11:1210.
92. Zaki SM, Ahmed MA, Hameed HM. Periodontal health status of patients with maxillary chronic rhinosinusitis (part 1: Clinical study). J Baghdad Coll Dent 2018;30:59-65.
93. He J, Zhu X, Qi Z, Wang C, Mao X, Zhu C, *et al.* Killing dental pathogens using antibacterial graphene oxide. ACS Appl Mater Interfaces 2015;7:5605-11.
94. Mei F, Xie M, Huang X, Long Y, Lu X, Wang X, *et al.* Porphyromonas gingivalis and its systemic impact: Current status. Pathogens 2020;9:944.
95. Radunovic M, De Colli M, De Marco P, Di Nisio C, Fontana A, Piattelli A, *et al.* Graphene oxide enrichment of collagen membranes improves DPSCs differentiation and controls inflammation occurrence. J Biomed Mater Res A 2017;105:2312-20.
96. Gao W, Liang Y, Wu D, Deng S, Qiu R. Graphene quantum dots enhance the osteogenic differentiation of PDLSCs in the inflammatory microenvironment. BMC Oral Health 2023;23:331.
97. Suo L, Jiang N, Wang Y, Wang P, Chen J, Pei X, *et al.* The enhancement of osseointegration using a graphene oxide/chitosan/hydroxyapatite composite coating on titanium fabricated by electrophoretic deposition. J Biomed Mater Res Part B Appl Biomater 2019;107:635-45.
98. Yamaguchi M, Noiri Y, Itoh Y, Komichi S, Yagi K, Uemura R, *et al.* Factors that cause endodontic failures in general practices in Japan. BMC Oral Health 2018;18:70.
99. Nizami MZI, Gorduysus M, Shinoda-Ito Y, Yamamoto T, Nishina Y, Takashiba S, *et al.* Graphene oxide-based endodontic sealer: An *in vitro* study. Acta Med Okayama 2022;76:715-21.
100. Singh AA, Makade CS, Krupadam RJ. Graphene nanoplatelets embedded polymer: An efficient endodontic material for root canal therapy. Mater Sci Eng C 2021;121:111864.
101. Dubey N, Rajan SS, Bello YD, Min KS, Rosa V. Graphene nanosheets to improve physico-mechanical properties of bioactive calcium silicate cements. Materials 2017;10:606.
102. Sharma DK, Bhat M, Kumar V, Mazumder D, Singh SV, Bansal M. Evaluation of antimicrobial efficacy of graphene silver composite nanoparticles against *E. faecalis* as root canal irrigant: An *ex-vivo* study. Int J Pharm Med Res 2015;3:267-72.
103. Irusa K, Alrahaem IA, Ngoc CN, Donovan T. Tooth whitening procedures: A narrative review. Dent Rev 2022;2:100055.
104. Epple M, Meyer F, Enax J. A critical review of modern concepts for teeth whitening. Dent J 2019;7:79.
105. Adepu S, Ramakrishna S. Controlled drug delivery systems: Current status and future directions. Molecules 2021;26:5905.
106. Bai RG, Husseini GA. Chapter 11 - Graphene-based drug delivery systems. In: Unnithan AR, Sasikala ARK, Park CH, Kim CS, editors. Biomimetic Nanoengineered Materials for Advanced Drug Delivery. Elsevier; 2019. p. 149-68.
107. La WG, Jin M, Park S, Yoon HH, Jeong GJ, Bhang SH, *et al.* Delivery of bone morphogenetic protein-2 and substance *P* using graphene oxide for bone regeneration. Int J Nanomedicine 2014;9(Suppl 1):107-16.
108. Peña-Bahamonde J, Nguyen HN, Fanourakis SK, Rodrigues DF. Recent advances in graphene-based biosensor technology with applications in life sciences. J Nanobiotechnology 2018;16:75.
109. Lee SM, Yoo KH, Yoon SY, Kim IR, Park BS, Son WS, *et al.* Enamel anti-demineralization effect of orthodontic adhesive containing bioactive glass and graphene oxide: An *in-vitro* study. Materials 2018;11:1728.
110. Nam HJ, Kim YM, Kwon YH, Kim IR, Park BS, Son WS, *et al.* Enamel surface remineralization effect by fluorinated graphite and bioactive glass-containing orthodontic bonding resin. Materials 2019;12:1308.
111. Mallick M, Arunachalam N. Electrophoretic deposited graphene based functional coatings for biocompatibility improvement of Nitinol. Thin Solid Films 2019;692:137616.
112. Alnatheer M, Alqerban A, Alhazmi H. Graphene oxide-modified dental adhesive for bonding orthodontic brackets. Int J Adhes Adhes 2021;110:102928.
113. Ghorbanzadeh R, Vaziri AS, Bahador A. Antimicrobial properties and shear bond strength of composite used in orthodontics following the addition of curcumin-reduced nanographene oxide. Avicenna J Clin Microbiol Infect 2021;8:139-44.
114. Pourhajibagher M, Bahador A. Orthodontic adhesive doped with nano-graphene oxide: Physico-mechanical and antimicrobial properties. Folia Med 2021;63:413-21.
115. Sawan NM, AlSagob EI, Ben Gassem AA, Alshami AA. Graphene functionalized with nanosilver particle-modified methacrylate-based bonding agent improves antimicrobial capacity and mechanical strength at tooth orthodontic bracket interface. Polym Compos 2021;42:5850-8.
116. Jiao D, Wang J, Yu W, Zhang K, Zhang N, Cao L, *et al.* Biocompatible reduced graphene oxide stimulated BMSCs induce acceleration of bone remodeling and orthodontic tooth movement through promotion on osteoclastogenesis and angiogenesis. Bioact Mater 2022;15:409-25.
117. Pan Z, Zhou Q, Wang P, Diao D. Robust low friction performance of graphene sheets embedded carbon films coated orthodontic stainless steel archwires. Friction 2022;10:142-58.
118. Pourhajibagher M, Ghorbanzadeh R, Salehi-Vaziri A, Bahador A. *In vitro* assessments of antimicrobial potential and cytotoxicity activity of an orthodontic adhesive doped with nano-graphene oxide. Folia Med (Plovdiv) 2022;64:110-6.
119. Wang P, Luo X, Qin J, Pan Z, Zhou K. Effect of graphene sheets embedded carbon films on the fretting wear behaviors of orthodontic archwire–bracket contacts. Nanomaterials (Basel) 2022;12:3430.
120. Barbur I, Opris H, Colosi HA, Baciut M, Opris D, Cuc S, *et al.* Improving the mechanical properties of orthodontic occlusal splints using nanoparticles: Silver and zinc oxide. Biomedicines 2023;11:1965.
121. Sardana D, Zhang J, Ekambaram M, Yang Y, McGrath CP, Yiu CKY. Effectiveness of professional fluorides against enamel white spot lesions during fixed orthodontic treatment: A systematic review and meta-analysis. J Dent 2019;82:1-10.
122. Vineesha CM, Varma DPK, Bhupathi PA, Priya CP, Anoosha M, Harsha G. Comparative evaluation of antibacterial effects of

nanoparticle-incorporated orthodontic primer: An *in vitro* study. J Indian Orthod Soc 2021;55:390-8.
123. Ferreira CJ, Leitune VCB, Balbinot GS, Degrazia FW, Arakelyan M, Sauro S, *et al.* Antibacterial and remineralizing fillers in experimental orthodontic adhesives. Materials (Basel) 2019;12:652.
124. Wang N, Yu J, Yan J, Hua F. Recent advances in antibacterial coatings for orthodontic appliances. Front Bioeng Biotechnol 2023;11:1093926.
125. Nabbat SA, Yassir YA. A clinical comparison of the effectiveness of two types of orthodontic aligning archwire materials: A multicentre randomized clinical trial. Eur J Orthod 2020;42:626-34.
126. Arici N, Akdeniz BS, Oz AA, Gencer Y, Tarakci M, Arici S. Effectiveness of medical coating materials in decreasing friction between orthodontic brackets and archwires. Korean J Orthod 2021;51:270-81.
127. Dragomirescu A-O, Bencze M-A, Vasilache A, Teodorescu E, Albu C-C, Popoviciu NO, *et al.* Reducing friction in orthodontic brackets: A matter of material or type of ligation selection? *in-vitro* comparative study. Materials (Basel) 2022;15:2640.
128. Aldabagh DJ, Alzubaydi TL, Alhuwaizi AF. Surface characterization of stainless steel 316L coated with various nanoparticle types. Int J Biomater 2023;2023:3997281.
129. Zakrzewski W, Dobrzynski M, Dobrzynski W, Zawadzka-Knefel A, Janecki M, Kurek K, *et al.* Nanomaterials application in orthodontics. Nanomaterials 2021;11:337.
130. Gracco A, Dandrea M, Deflorian F, Zanella C, De Stefani A, Bruno G, *et al.* Application of a molybdenum and tungsten disulfide coating to improve tribological properties of orthodontic archwires. Nanomaterials 2019;9:753.
131. Yun Z, Qin D, Wei F, Xiaobing L. Application of antibacterial nanoparticles in orthodontic materials. Nanotechnol Rev 2022;11:2433-50.
132. Dai D, Zhou D, He L, Wang C, Zhang C. Graphene oxide nanocoating for enhanced corrosion resistance, wear resistance and antibacterial activity of nickel-titanium shape memory alloy. Surf Coat Technol 2022;431:128012.
133. Dipalma G, Patano A, Ferrara I, Viapiano F, Netti A, Ceci S, *et al.* Acceleration techniques for teeth movements in extractive orthodontic therapy. Appl Sci 2023;13:9759.
134. Jiao D, Cao L, Liu Y, Wu J, Zheng A, Jiang X. Synergistic osteogenesis of biocompatible reduced graphene oxide with methyl vanillate in BMSCs. ACS Biomater Sci Eng 2019;5:1920-36.
135. Gamal R, Gomaa YF, Mahroos A. Evaluation of an experimental poly-methyl methacrylate/nano graphene oxide composite. Indian J Public Health Res Dev 2020;11:1766-71.
136. Zafar MS. Prosthodontic applications of polymethyl methacrylate (PMMA): An update. Polymers (Basel) 2020;12:2299.
137. Hassan M, Asghar M, Din SU, Zafar MS. Thermoset polymethacrylate-based materials for dental applications. In: Grumezescu V, Grumezescu MA, editors. Materials for Biomedical Engineering. Elsevier; 2019. p. 273-308.
138. Teimoorian M, Mirzaie M, Tashakkorian H, Gholinia H, Alaghemand H, Pournajaf A, *et al.* Effects of adding functionalized graphene oxide nanosheets on physical, mechanical, and anti-biofilm properties of acrylic resin: *In vitro*-experimental study. Dent Res J (Isfahan) 2023;20:37.
139. Kausar A. Poly (methyl methacrylate) nanocomposite reinforced with graphene, graphene oxide, and graphite: A review. Polym-Plast Technol Mater 2019;58:821-42.
140. Lee JH, Jo JK, Kim DA, Patel KD, Kim HW, Lee HH. Nano-graphene oxide incorporated into PMMA resin to prevent microbial adhesion. Dent Mater 2018;34:e63-72.