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Graphene in Prosthodontics: A Comprehensive Review

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ABSTRACT

Graphene, a two-dimensional carbon nanomaterial, has developed as a groundbreaking substance in biomedical and dental fields because it has remarkable mechanical strength, extensive surface area, electrical and thermal conductivity, and excellent biocompatibility. This review examines the structure, characteristics, synthesis techniques, and biological interactions of graphene and its derivatives—such as graphene oxide (GO) and reduced graphene oxide (rGO)—with an emphasis on prosthodontics. Numerous studies have established graphene's antimicrobial properties, cytocompatibility, and its probability to enhance dental materials like PMMA, glass ionomer cements, and bioactive cements. Dental composites augmented with graphene exhibit enhanced mechanical, thermal, and antibacterial properties, rendering them appropriate for denture bases, restorative materials, and implant coatings. Additionally, graphene-based scaffolds facilitate stem cell proliferation and osteogenic differentiation, indicating potential in tissue engineering and regenerative dentistry. Nevertheless, in spite of its advantages, issues including production scalability, material consistency, and long-term biosafety must be addressed before clinical application. Future investigations will ascertain how graphene-based materials can be refined for safer, stronger, and more effective prosthodontic solutions.

KEYWORDS: Graphene, graphene oxide, graphene synthesis, tissue engineering,

I. INTRODUCTION

Nanotechnology represents a multidisciplinary domain dedicated to the design, synthesis, and utilization of materials and devices through the manipulation of matter at the nanoscale (1–100 nm). At this scale, materials display unique physical, chemical, and biological characteristics, facilitating revolutionary progress in fields such as medicine, electronics, energy, and environmental conservation(1).

Graphene nanotechnology pertains to the utilization of graphene—a monolayer of sp^2-bonded carbon atoms organized in a two-dimensional honeycomb structure—at the nanoscale. Its remarkable electrical conductivity, thermal stability, mechanical strength, flexibility, and extensive surface area render it a highly promising material in various technological domains(1).

Carbon, a plentiful and adaptable element, creates nanostructures in zero-, one-, two-, and three-dimensional forms. Graphene sheets, generally measuring less than 10 nm in thickness, are recognized as the thinnest and strongest materials available. Furthermore, graphene shows promise in disease diagnosis, targeted drug and gene delivery, cancer treatment, and bioimaging(2)

HISTORY OF GRAPHENE:

In the 18th century, Antoine Lavoisier identified carbon as a distinct element. In the 20th century, the discovery of its allotropes—diamond, graphite, and later graphene—boosted carbon’s role in science and technology (1). The isolation of fullerene in 1985 and carbon nanotubes in 1991 marked significant advances in carbon nanomaterials (1). In 2004, Andre Geim and Konstantin Novoselov at the University of Manchester isolated single-layer graphene using mechanical exfoliation with adhesive tape. Their discovery earned them the Nobel Prize in Physics in 2010. The term "graphene" was later officially adopted by IUPAC to describe monolayer graphite structures (3).

CHEMISTRY OF GRAPHENE:

Graphene is a single atom-thick layer of sp^2-hybridized carbon atoms arranged in a two-dimensional honeycomb lattice, with a carbon–carbon bond length of approximately 0.142 nm. As an allotrope of carbon—alongside diamond, carbon nanotubes, and fullerenes—graphene is composed entirely of carbon atoms in a planar structure (3).

Graphene and Its Derivatives:

Graphene-related materials can be classified based on the number of layers (e.g., mono- or multi-layered) or by chemical modification into three main types:

- Graphene Oxide (GO)
- Reduced Graphene Oxide (rGO)
- Nitrogen-Doped Graphene (N-G) (3)

Graphene Oxide (GO):

GO is a single-layer material derived from graphite oxide, typically synthesized via the Hummer's method through acid–base treatment and sonication. It contains various oxygenated functional groups—such as hydroxyl, epoxide, carbonyl, and carboxyl—which disrupt its electrical conductivity and make it hydrophilic.(5)

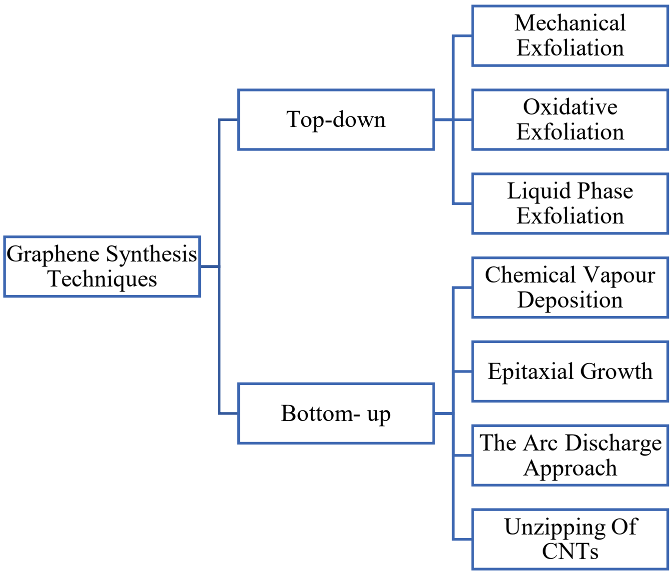
Reduced Graphene Oxide (rGO):

rGO is obtained by reducing GO using chemical, thermal, photo, or microwave-assisted processes. This reduction removes a significant portion of the oxygen groups, restoring partial electrical conductivity and making rGO structurally closer to pristine graphene. rGO serves as an intermediate material between graphene and GO, with improved conductivity but retained surface reactivity (5).

MANUFACTURING OF GRAPHENE:

The crude synthesis of graphene by chemical deposition began in the early 1970s. The mechanical exfoliation technique using scotch tape was the first widely accepted method of producing high-quality graphene for research analysis. Subsequently large-scale commercial applications of graphene, such as chemical exfoliation, mechanical exfoliation, and chemical synthesis.(9)

A detailed summary of the manufacturing of graphene using various techniques:



Flow Chart 1: Methods of Graphene synthesis(9)

TOP-DOWN METHODS:

Mechanical exfoliation/cleavage:

In this approach, graphite consists of graphene layers that are bonded by Van der Waals forces, and the exfoliation technique leverages this characteristic by disrupting those weak bonds(6)

Oxidative exfoliation:

Oxidative exfoliation method has been utilized mostly in order to obtain GO. Following this process, rGO and pristine graphene can be obtained by reducing oxygen thermally, electrochemically, or chemically. The chemical oxidation method is the most preferred method for the production of GQDs as it is simple and efficient. However, among these the most widely used approach is Hummer's method.

Liquid-Phase Exfoliation:

In this method, Gt disperses in a suitable liquid, then exfoliation is performed and lastly, pure graphene is obtained with the aid of high intensive ultrasound.(6)

BOTTOM-UP METHODS:

Chemical vapor deposition (CVD):

In this method, graphene is synthesized by a graphite target or catalytic decomposition of hydrocarbons on the surface of a metallic catalyst. An advantage of this method is the absence or low amount of metallic residuals.

Epitaxial Growth:

Another method of synthesizing graphene is to prepare it on silicon carbide (SiC) under certain conditions, at 1200–1600 °C temperature and under vacuum. At high temperatures, Si sublimates and graphene growth occurs by collecting carbon atoms and forming sp2 form.

The Arc discharge approach:

The arc discharge technique has been utilized in the past for the synthesis of carbon nanotubes (CNTs) and fullerenes; more recently, it has been modified for the generation of few-layered graphene(6)

Unzipping Of CNTs:

The unzipping of CNTs methodology, it is also useful to produce few-layered graphene and single layer graphene.(6)

PROPERTIES OF GRAPHENE:

Since its discovery in 2004 by Nobel laureates Geim and Novoselov, graphene has gained more interest because of its unique physical, mechanical, and chemical properties.(8)

- Thinnest, strongest, and stiffest imaginable material.
- Almost transparent.
- Most stretchable crystal (20% elasticity).
- Recording thermal conductivity.
- Highest current density at room temperature.
- Completely impermeable.
- Highest intrinsic mobility (100 times more than in Si).
- Conducting electricity in the limit of no electrons.
- Large surface area (~2600 m2 g−1).
- Longest mean free path at room temperature (micron range).

Biological properties of graphene:

Biocompatibility:

The clinical introduction of any novel biomedical material requires it to be biocompatible, meaning it should not provoke adverse biological responses upon contact with living tissues. The biocompatibility of graphene-based nanomaterials (GFNs) is influenced by several factors, including morphology, surface charge, shape, size, and number of layers, as well as the functional groups attached to their surface. These parameters affect cellular uptake and the material's interaction with biomolecules such as proteins and micronutrients.(7)

Biodegradability:

The biodegradability of graphene and its derivatives is vital for assessing their safety in biomedical applications. Prof. Bianco and his team demonstrated that myeloperoxidase (MPO)—an enzyme secreted by neutrophils—can effectively degrade graphene oxide (GO) in the presence of hydrogen peroxide (H_2O_2)(2). In ex vivo studies, both single- and few-layer graphene, synthesized via aqueous methods, were exposed to MPO. The enzyme successfully oxidized and degraded the graphene structures. This suggests that dispersible graphene materials may undergo natural enzymatic degradation in vivo. These findings highlight the potential for safe clearance of graphene by immune mechanisms(7).

APPLICATIONS OF GRAPHENE IN DENTISTRY:

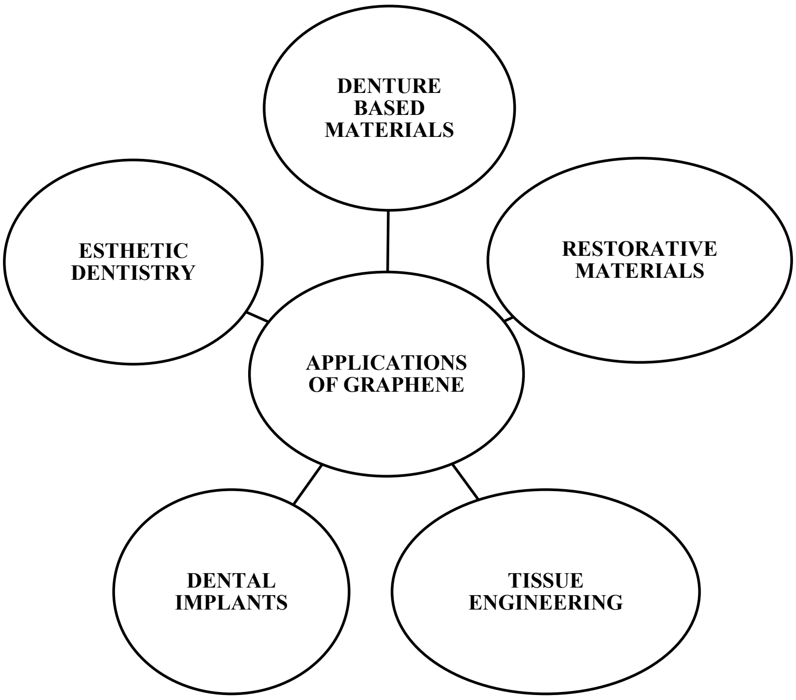


Figure 2 : Applications of graphene in dentistry

GRAPHENE IN DENTURE BASED MATERIALS:

Polymethyl methacrylate (PMMA) has remained the most commonly used denture base material since its introduction by Walter Wright in 1937, later described by Peyton FA in

1975(10). For over eight decades, PMMA has been preferred due to its aesthetic appeal, chemical stability, light weight, water resistance, and cost-effectiveness (1,10). However, despite these advantages, PMMA exhibits poor mechanical strength, low flexural resistance, and limited antimicrobial activity, making it prone to fractures, cracks, and denture stomatitis (1).

To overcome these limitations, graphene incorporated into PMMA, graphene enhances its mechanical durability, flexural strength, and biocompatibility, while imparting antibacterial properties that may help prevent denture-related infections such as stomatitis(1).

GRAPHENE IN RESTORATIVE MATERIALS:

Cements and filling materials:

Glass ionomer cements (GICs) have long been used in restorative dentistry for their biocompatibility, fluoride release, and chemical adhesion to tooth structures. However, they are limited by poor mechanical strength and insufficient antibacterial activity, often leading to secondary caries(11). To address these issues, nano-fillers and bioactive additives like fluoride-functionalized graphene (FG) have been incorporated into GICs. FG, improves mechanical strength, reduces porosity and microcracks, and enhances antibacterial activity—making the composite more resistant to erosion and microbial invasion(11).

Root canal irrigants:

Persistent root canal infection is endodontic treatment failure, highlighting the need for effective irrigation that disinfects while preserving dentin(4). Indocyanine green (ICG), a photosensitizer, has shown promise but is limited by poor stability and aggregation. When added with graphene oxide (GO), ICG exhibits improved bioavailability and antibacterial action, effectively reducing E. faecalis and S. mutans(4). Additionally, graphene-silver nanoparticle composites have demonstrated disinfection efficacy comparable to 3% sodium hypochlorite, but with significantly reduced cytotoxicity to bone and soft tissues—offering a safer alternative in endodontic therapy(4).

Crown materials:
Dental ceramics are layered restorations prone to brittle fracture, primarily due to micro-crack formation within the veneer layer. These cracks propagate under stress, often leading to clinical failure(12). Reinforcing ceramics with nanoparticles has emerged as a key strategy to improve their mechanical properties. Among them, graphene—used alone or in hybrid form with carbon nanotubes (CNTs)—has shown remarkable potential. Its incorporation enhances the toughness, strength, and electrical conductivity of ceramic composites, offering a promising alternative to CNTs(13). Graphene-reinforced ceramics not only improve fracture resistance but also open possibilities for electrically responsive dental materials in advanced prosthetic applications.

GRAPHENE IN TISSUE ENGINEERING:
Tissue engineering aims to restore or improve tissue function by combining cells, scaffolds, and biochemical signals. Scaffolds are central to this process, providing a 3D matrix for cell migration, adhesion, proliferation, and differentiation, while also retaining essential growth factors(14). In dentistry, dental tissue regeneration is particularly difficult due to the limited healing capacity of structures like the dental pulp, which is encased in mineralized tissue and has restricted blood supply(14). These materials enhance stem cell adhesion, support cell proliferation, and promote osteogenic differentiation in various cell lines, including BMSCs, PDLCs, and DPSCs(15), significantly increases the expression of osteogenic markers such as RUNX2, COL1, and OCN, particularly when scaffold stiffness is optimized(4).

GRAPHENE IN DENTAL IMPLANTS:
Dental implants are integral to oral rehabilitation, restoring function and aesthetics by replacing missing teeth. Their long-term success depends on osseointegration, a direct structural and functional bond between the implant and surrounding bone. While titanium (Ti) implants are the gold standard due to their biocompatibility and reliability, pure titanium lacks sufficient mechanical strength and wear resistance, making it prone to deformation and fatigue under occlusal load(16). To address these limitations, titanium alloys like Ti-6Al-4V are used for improved strength, fatigue resistance, and osseointegration(16). Recently, graphene-based surface coatings has ability to enhance implant performance. Graphene offers superior mechanical durability, corrosion resistance, and biocompatibility. Its electrical conductivity may also enhance cell signaling and healing at the implant site(17,18).
Graphene oxide (GO)-coated Ti implants demonstrate improved osteogenic differentiation, cell proliferation, and antibacterial activity—especially when functionalized with silver nanoparticles or antibiotics—offering dual benefits of bone integration and infection prevention(17,18).-
Despite its promising potential, with several challenges needing resolution before clinical application. One major issue is mechanical failure in graphene-based implants, often attributed to defects introduced during production, which vary with synthesis methods. Another key concern is in vivo toxicity, as the biological behaviour and safety of graphene depend heavily on its physicochemical properties(2). Therefore, the two primary limitations hindering its clinical translation are the need for standardized production protocols and more comprehensive toxicological evaluations.

II. CONCLUSIONS AND FUTURE PERSPECTIVE

Graphene and its derivatives offer immense potential in dentistry due to their exceptional mechanical strength, biocompatibility, and functionalization capabilities. Their incorporation into dental composites, scaffolds, and implant coatings enhances durability, bioactivity, and tissue regeneration. However, challenges remain, including material consistency, nanoparticle agglomeration, and incomplete understanding of long-term biocompatibility. Future research should aim to develop scalable and cost-effective synthesis methods, alongside targeted functionalization strategies for dental use. Exploring graphene's role in drug delivery, antimicrobial therapy, and gene modulation could transform oral healthcare. With interdisciplinary collaboration, graphene-based nanomaterials are poised to drive the next generation of personalized, efficient, and safe dental treatments.

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