

Synthesis And Biomedical Applications Of Graphene Based Material: A Review

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ABSTRACT

Graphene-based materials have emerged as highly versatile platforms due to their exceptional physicochemical properties, enabling significant advancements in biomedical science. This review summarizes recent progress in the synthesis of graphene and its derivatives, covering both top-down and bottom-up strategies that allow precise control over structure, functionality, and biocompatibility. Key biomedical applications including drug delivery, biosensing, tissue engineering, wound healing, and antimicrobial activity are critically discussed with emphasis on how graphene's unique electrical, mechanical, and surface characteristics enhance therapeutic performance. The review further highlights current challenges such as toxicity, stability, and clinical translation, offering insights into future prospects for safer and more effective graphene-based biomedical technologies.

Keywords: Graphene; Nanomaterial; Biomedical Applications; Drug Loading.

Introduction

In the 21st century, malignant tumors have become a major global health threat, ranking among the leading causes of mortality. Although multiple treatment strategies such as surgery, radiotherapy, and chemotherapy have been developed, chemotherapy remains one of the most widely used approaches. Effective chemotherapy requires both potent anticancer drugs and reliable drug delivery systems (DDSs) to minimize side effects. However, many chemotherapeutic agents are hydrophobic, exhibit low bioavailability, and suffer from poor water solubility, limited specificity, and significant side effects, ultimately reducing their therapeutic efficacy [1]. Therefore,

designing advanced DDSs capable of enhancing drug performance and improving clinical outcomes has become a critical challenge [2]. Rapid progress in nanoscience and nanotechnology has enabled the creation of novel nanomaterials, driving the development of next-generation DDSs [1, 3]. In recent years, graphene-based materials have attracted significant scientific attention, particularly for their potential in drug delivery. Since graphene an atom-thick sheet of sp^2 -hybridized carbon arranged in a honeycomb 2D lattice was first isolated in 2004, it has triggered a global “graphene boom.” Its exceptional physicochemical properties, including high mechanical strength, outstanding electrical and thermal conductivity, rapid charge-carrier mobility, large surface area, and good biocompatibility [4], make graphene a highly promising material for numerous biomedical and technological applications. These range from cancer therapy [5], medical imaging [6], and tissue engineering [7], to biosensing [8], nucleic acid extraction [9], antibacterial activity [10], and antiviral applications [11]. Within nanomedicine, graphene-based materials have emerged as innovative biomaterials capable of serving as advanced nanocarriers for drug delivery, offering solutions to several limitations associated with conventional chemotherapy [12, 13].

Since the discovery of graphene in 2004, a vast number of studies on graphene-based materials has rapidly emerged. Previous research has shown that graphene, the thinnest material known, consists of a two-dimensional sheet of sp^2 -hybridized carbon atoms and exhibits outstanding mechanical [1], electrical [1], optical [1], and thermal properties [1]. Following its initial isolation, scientific interest in graphene expanded dramatically, leading to an exponential growth in related research taken together, the remarkable physicochemical properties of graphene and its derivatives along with rapid advances in their controlled synthesis, functionalization, and biocompatibility have positioned these materials at the forefront of next-generation biomedical technologies. Despite significant progress, challenges remain in achieving standardized synthesis routes, understanding long-term biosafety, and optimizing clinical translation. This review therefore summarizes the major synthesis strategies for graphene-based materials and highlights their diverse biomedical applications, including imaging, drug and gene delivery, biosensing, antibacterial therapy, and photothermal treatment. By integrating recent developments and identifying existing limitations, we aim to provide a comprehensive foundation for future research and the rational design of graphene-based platforms for biomedical use.

Graphene synthesis

A nanoparticle represents a basic unit of nanomaterials and functions as a bridge between microscopic structures and nanoscale materials [14]. Consequently, the synthesis of graphene-related materials (GRMs) such as graphene, graphene oxide (GO), reduced graphene oxide (rGO), and graphene quantum dots (GQDs) requires efficient, scalable, and cost-effective production approaches suitable for industrial applications. Commonly employed methods include exfoliation techniques, chemical vapor deposition (CVD), solid-state carbon deposition, and the chemical reduction of graphene oxide to form graphene nanosheets [15]. The chosen synthesis route significantly influences the physicochemical, structural, and morphological characteristics of the materials, resulting in graphene-based nanomaterials with

diverse dimensions and compositions. Recent advancements in synthesis strategies emphasize controlled conditions such as high temperature and pressure, vacuum environments, improved structural precision, phase purity, and well-defined nanoscale dimensions. Widely adopted techniques for producing graphene-based nanoparticles include catalytic thermal CVD, epitaxial growth, electrochemical exfoliation, chemical reduction processes, and sol-gel-based methods [16, 17]. Chemical vapor deposition (CVD) is widely utilized in the semiconductor industry for depositing thin films with precisely controlled thicknesses. Nanoparticles produced through such methods possess increased surface energy due to their high surface-area-to-volume ratio, which enhances their reactivity and broadens their potential applications [16]. Common synthesis techniques include ball milling, CVD, and spray pyrolysis. Chemical synthesis methods, in particular, provide superior control over the physicochemical, structural, and thickness-related properties of nanomaterials, which is crucial for device fabrication. These chemical approaches are also advantageous for large-scale production and are generally more cost-effective [18]. The properties of graphene-related materials (GRMs) depend heavily on their atomic structure; for instance, liquid exfoliation methods can tailor GRM characteristics for applications in energy composites and biomedical fields. Therefore, the following techniques are commonly employed for GRM synthesis.

Chemical vapor deposition

CVD is a vacuum deposition method of depositing solid material at a high temperature to form a thin film (a layer or coating having a maximum thickness of 1 μm or less whose properties are different from bulk material) from the volatile gaseous precursors as a consequence of chemical reaction and decomposition on the substrate surface [19]. The deposition includes homogeneous gas-phase responses and/or heterogeneous chemical reactions near the proximity of a heated surface, driving the generation of powders or films. In the CVD process, polycrystalline Cu or Ni foil is commonly used as the substrate on which the graphene film is deposited, while hexane serves as an efficient liquid precursor. The substrate is placed inside a vacuum-assisted quartz furnace, where the temperature is maintained at approximately 900 $^{\circ}\text{C}$ under a flow of hydrocarbon gases. Within this environment, the precursor vapors undergo chemical reactions and decompose on the heated substrate surface. During this stage, the substrate is also annealed to promote grain growth. As the system cools, nucleation of graphene islands occurs as carbon atoms assemble on the metal surface, ultimately leading to the formation of a high-quality, crystalline graphene thin film [20]. Li et al. demonstrated the successful growth of high-quality monolayer and bilayer graphene on copper substrates using the CVD technique, achieving hole and electron mobilities of 5500 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ and 3900 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$, respectively. Their findings indicate that the surface quality of the Cu substrate, along with pretreatment procedures and microlithography steps, plays a crucial role in determining the uniformity and quality of the deposited graphene film. Moreover, the purity of the copper substrate significantly influences the number of graphene layers formed under low-pressure CVD conditions [21].

Mechanical exfoliation

Mechanical exfoliation, often referred to as mechanical cleavage, is a commonly employed top-down method for producing graphene. The technique works by overcoming the van der Waals forces that hold graphene layers together, enabling their separation without causing structural damage or leading to re-agglomeration after exfoliation [22, 23]. Early graphene films were obtained by repeatedly peeling highly oriented pyrolytic graphite, producing layers up to 10 μm thick, with individual flakes around 3 nm thick deposited onto oxidized silicon wafers. The process leverages the weak interlayer van der Waals interactions, which allow the use of simple yet effective tools such as Scotch tape, SiO_2 stamps, palladium films, and polydimethylsiloxane (PDMS) stamps to isolate high-quality graphene sheets [24]. Mechanical exfoliation provides a cost-effective and scalable approach for producing graphene, though achieving uniform size distribution and consistent crystallinity remains challenging [25]. Improvements such as polymer stamp techniques have enhanced this method, enabling the fabrication of large-area graphene sheets with better control, typically using highly ordered pyrolytic graphite (HOPG) as the source material [26, 27]. Ultrasonic exfoliation particularly liquid-assisted ultrasonication has also become a widely adopted strategy for generating graphene with tunable dimensions [28, 29]. Extensive work by Coleman's group has shown that solvent-assisted bath sonication, commonly using solvents like N-methyl-2-pyrrolidone (NMP) or dimethylformamide (DMF), can produce high-quality, defect-free graphene flakes [30]. However, careful optimization of sonication parameters and appropriate solvent selection is crucial to minimize defects and impurities, thereby improving the overall quality of graphene nanostructures. In summary, while mechanical exfoliation offers notable advantages in simplicity, cost-effectiveness, and scalability, further refinement is required to consistently yield high-quality graphene materials [31].

Chemical exfoliation

Chemical exfoliation involves separating graphite layers through oxidation or by using suitable solvents, which introduce oxygen-containing functional groups that expand the interlayer spacing and weaken the van der Waals forces holding the layers together [32, 33]. A variety of reducing solvents have been used in this process to facilitate the exfoliation of graphite into graphene, including hydrazine hydrate, N-methyl-2-pyrrolidone (NMP), methanesulfonic acid, and various ionic liquids [34]. Although hydrazine-based reducing agents are commonly employed in graphene synthesis [35], their high toxicity and explosive nature pose major concerns for large-scale applications. These limitations underscore the need for alternative reducing agents and methods that are safer, scalable, and cost-effective for commercial graphene production [36]. In recent years, green reducing agents such as ascorbic acid and plant extracts have drawn attention due to their lower environmental impact and improved safety profile. However, these eco-friendly approaches often face challenges related to efficiency and graphene quality, particularly when scaled up [37]. Ongoing research continues to focus on enhancing these methods to achieve high-quality graphene suitable for practical, large-scale applications.

Electrochemical exfoliation

Electrochemical exfoliation employs graphite as a sacrificial electrode along with various electrolytes, including HBr, HCl, HNO₃, and H₂SO₄ [38]. Among these, H₂SO₄ demonstrates the highest exfoliation efficiency in terms of processing time and achievable layer thickness. However, it commonly produces graphene with a high defect density [39]. To address this limitation, KOH has been introduced into the H₂SO₄ electrolyte to reduce its acidity and minimize the oxidation of graphite that typically occurs with H₂SO₄ alone. Pan et al. reported that applying low voltages (below 10 V) during KOH addition slowed down exfoliation and reduced efficiency [40]. To overcome this, they proposed a hybrid method combining electrochemical exfoliation with spark plasma sintering, which significantly improved overall performance. Despite this advancement, the scalability of the process for industrial-scale graphene production remains uncertain.

Furthermore, incorporating surfactants during electrochemical exfoliation has proven effective in preventing graphene flake aggregation [41]. The type of surfactant and its concentration play critical roles in ensuring compatibility with graphene and must be carefully optimized to achieve improved exfoliation outcomes. Overall, electrochemical exfoliation is regarded as a cost-effective and environmentally friendly approach for large-scale graphene synthesis. Nevertheless, challenges persist, particularly in controlling defect formation, improving exfoliation efficiency, and ensuring scalability. Future progress may depend on the development of novel electrolytes, optimization of processing parameters, and strategic design of surfactant structures to enhance both the quality and yield of graphene [42].

Reduction of Graphite Oxide

The reduction of graphite oxide is a key step aimed at removing oxygen-containing functional groups particularly C–O bonds to convert graphite oxide into graphene. A variety of reducing agents have been investigated for this transformation, allowing graphene production at relatively low temperatures and within shorter reaction times. Sodium hydrosulfite has traditionally been used as an effective reducing agent for this purpose [43]. More recently, sodium borohydride has attracted significant attention as a cost-effective and highly efficient aqueous reducing agent for graphite oxide reduction [43, 44]. Additionally, a mixed solution of acetone and sodium hypochlorite has been reported to successfully reduce graphite oxide, further broadening the range of available reduction strategies for producing high-quality graphene [43].

Thermally exfoliated graphite oxide has also been examined for graphene sheet fabrication. During thermal reduction, oxidation promotes the formation of chain-like epoxy structures across the graphite surface [45]. This structural rearrangement leads to the development of wrinkled sheets at the reaction sites. The thermal process also releases CO₂, resulting in the formation of vacancies and topological defects within the carbon lattice. These defects, including stable 5–8–5 configurations, can withstand extreme temperatures of up to 3000 K. The diffusion of single vacancies in graphene involves an energy barrier of approximately 0.94 eV, comparable to the barrier required for epoxy group transitions on graphite. Adjacent single vacancies may merge to form double vacancies such as 5–8–5 structures when surpassing an energy threshold of 1.52 eV. At room temperature, isolated carbon vacancies and epoxy

groups exhibit rapid diffusion, occurring on the order of seconds. This mobility promotes the aggregation of vacancies into linear defect structures, ultimately giving rise to the characteristic wrinkled morphology observed in the final graphene sheets [46].

Although thermal exfoliation is cost-effective and suitable for large-scale production, it often introduces substantial structural defects in reduced graphene oxide (rGO), which can degrade the overall material quality. Therefore, optimizing heating profiles and controlling the reaction atmosphere are crucial for enhancing the performance and structural integrity of thermally reduced graphene [46].

Pyrolysis

Pyrolysis is a thermochemical process used to synthesize nanostructured carbon materials by decomposing carbon-rich precursors into smaller molecular fragments in an oxygen-free environment [47, 48]. Microwave-assisted pyrolysis of biomass has emerged as an efficient pathway for graphene production, offering advantages such as low cost, short processing time, reduced energy consumption, and improved heat efficiency [49-51]. Moreover, biomass pyrolysis helps minimize environmental waste by converting materials that would otherwise end up in landfills. Recent studies have demonstrated the successful use of various biomass feedstocks for producing graphene and other carbon-based materials [52]. Common biomass sources used for graphene fabrication include wheat straw, rice husks, orange peels, ginger, cotton, corncobs, sawdust, gumwood, bamboo, and peanut shells [53, 54].

Graphene sheets can also be generated through the pyrolysis of sodium ethoxide, where sonication facilitates the detachment of graphene layers, resulting in sheets with relatively small lateral dimensions [55]. This method has similarly been reported as an effective approach for graphene extraction [54]. During biomass pyrolysis, decomposition begins around 300 °C, releasing small gas molecules as primary products, while approximately 70% of the biomass is converted into organic compounds [54].

A notable example of pyrolysis application was demonstrated by Widiatmoko et al. [56], who converted oil palm empty fruit bunches (EFB) into bio-based graphene. The process involved carbonization at 350 °C for 90 minutes under a nitrogen atmosphere, followed by graphitization at 900 °C for one hour [54].

Epitaxial Growth of Graphene

Epitaxial growth is another highly promising method for the large-scale production and commercialization of graphene. This technique involves the condensation of gaseous precursors to form a thin graphene film on a solid substrate. Silicon carbide (SiC) is one of the most widely used substrates for this purpose, enabling graphene formation at high temperatures (around 1500 °C) under ultrahigh vacuum conditions ($\sim 10^{-10}$ mbar), as first reported by Bommel et al. [56]. Epitaxially grown graphene on SiC has been successfully employed in a variety of advanced applications, including high-frequency transistors, light-emitting devices, and radiation-resistant electronics [57].

In another example, Yang et al. demonstrated the effective use of hexagonal boron nitride (h-BN) as a substrate for graphene-based nano devices. Using a plasma-

assisted deposition method, they achieved the growth of large-area graphene single crystals on h-BN with a well-controlled stacking orientation [58]. Despite these advancements, the scalability of epitaxial graphene remains constrained by the physical dimensions of the substrate, which limits macroscopic production.

Biomedical applications

Treatment of Scars and Skin Wounds

Hypertrophic scars commonly develop after burns or scald injuries, and their prevention is just as important as their treatment. Early and timely management of damaged skin is crucial, as effective wound care promotes healing and reduces the risk of secondary injuries that may lead to scarring. In recent years, numerous research groups have developed cell scaffolds, films, medical dressings, and wound bandages using graphene (Gr) and its derivatives. These materials are designed to address both primary wound healing and postoperative scar management, benefiting from graphene's antibacterial activity, low toxicity, and excellent biocompatibility. Such graphene-based materials have shown the ability to accelerate skin repair and reduce scar formation[59].

Scaffold materials are particularly important for the treatment of large or deep wounds because they help prevent infection and support cell growth. Graphene oxide (GO), in particular, has been widely used as a carrier material to enhance skin regeneration and speed up wound healing. For instance, Sadeghianmaryan fabricated PU/polycaprolactone nanocomposite scaffolds for skin tissue engineering [60]. Pourjavadi developed a double-network hydrogel composed of O-carboxymethyl chitosan (CS) and GO for use as a skin scaffold [61]. Mahmoudi designed CS/PVP fibrous membranes incorporating GO nanosheets, which can function as temporary skin grafts [62]. Additionally, Li produced drug-loaded medical dressings using barbaloin and graphene, which were shown to support wound recovery and minimize scar formation [59]. Li developed composite films composed of N-acetyl cysteine, collagen I, and graphene oxide (GO), which were shown to enhance skin regeneration following scar formation [63]. Similarly, Tang fabricated scaffolds by integrating polydopamine-reduced GO with a double-crosslinked chitosan/silk fibroin network. These scaffolds supported wound healing by promoting bioelectric signal transmission essential for cell growth while simultaneously reducing excessive reactive oxygen species (ROS), thereby aiding effective skin regeneration [64].

For antibacterial applications, Zhang designed an injectable, conductive supramolecular hydrogel composed of β -cyclodextrin (β -CD), quaternized chitosan (QCS), adamantane, and graphene oxide (GO). This hydrogel promoted epidermal regeneration and granulation tissue formation while effectively preventing pathogen infiltration at the wound site [65]. Yu developed a graphene-based, targeted photothermally activated antibacterial nanomaterial, which demonstrated strong therapeutic effects against multidrug-resistant bacteria in animal skin models [59].

Qian combined graphene with additional materials to fabricate a porous rGO-silicone rubber film that exhibited excellent wound-healing properties. Furthermore, graphene-chitosan (Gr-CS) composites showed selective antibacterial activity within acidic abscess microenvironments (pH $\approx$ 6.3), confirming their potential as highly effective targeted photothermal antibacterial agents [59].

Treatment of tumours

Currently, tumour treatment options include surgery, radiotherapy, chemotherapy, and immunotherapy. However, the search for new therapeutic strategies that offer improved efficacy with fewer side effects has become an important area of research. In this context, numerous studies have explored the potential use of graphene (Gr) and its derivatives in cancer therapy.

Photothermal therapy (PTT) is one promising approach, utilizing nanomaterials to destroy cancer cells through heat generated under light irradiation. When graphene nanolayers are introduced to cancer cells and exposed to near-infrared (NIR) light, the resulting localized heating can significantly increase cancer cell death. To better understand and optimize tissue response during PTT, Sarkar et al. developed a breast tumour model incorporating various types and concentrations of carbon nanotubes, demonstrating that these nanomaterials greatly enhance the optical absorption coefficient [66].

In another study, researchers combined gold nanorods with PEG-functionalized reduced graphene oxide (rGO) and introduced the nanocomposite into human glioblastoma astrocytoma (U87MG) cells. Upon exposure to a low-power NIR laser, the composite induced substantial tumour cell damage due to its efficient conversion of photon energy into heat. Moreover, when the nanocomposite was further modified with Tat peptide, targeted tumour selectivity was achieved, enhancing treatment precision [67]. Matai and colleagues developed a localized hydrogel patch based on an interpenetrating network of alginate and polyacrylamide, fabricated through free radical polymerization. Embedded within the patch was a hybrid nanolayer composed of gold nanorods and PVP-functionalized graphene oxide (GO). This integrated structure enabled effective thermal ablation of localized tumours while also allowing controlled, targeted delivery of chemotherapeutic drugs [68].

Drug Loading

The drug-loading capability of a material is influenced by factors such as the drug's location, release time, and concentration. Ideally, a drug should be delivered to the target site in high concentrations within a short period. Kurantowicz demonstrated that, after multiple intraperitoneal injections of graphene oxide (GO) into mice, GO tended to accumulate in aggregated forms between the abdominal skin, muscle, and peritoneal connective tissues [69].

Microneedle arrays made from chitosan–graphene (CS–Gr) nanocomposites showed excellent mechanical strength and electrical conductivity due to the incorporation of reduced graphene oxide (rGO). These arrays were able to release substantial amounts of low-molecular-weight drugs at a rapid rate, highlighting their potential as a painless drug delivery system [59]. Similarly, the addition of GO to PVA–carboxymethyl tamarind gum films resulted in the formation of an aggregated structure with improved viscoelasticity and antibacterial properties, promoting HaCaT cell proliferation. However, increasing graphene content in the film led to a reduction in drug release efficiency [70].

Ganguly developed a conductive hydrogel by incorporating green-synthesized rGO into a semi-interpenetrating hydrogel matrix using an in-situ free radical polymerization approach. This hydrogel enabled pH-responsive and electrically

stimulated drug release [71]. Altinbasak fabricated an on-demand antibacterial delivery system using rGO–polymer nanofibers, where near-infrared (NIR) irradiation controlled the release of antibiotics, offering a promising strategy for treating bacterial infections [72].

Additionally, Pagneux utilized graphene's excellent thermal conductivity by integrating rGO nanoparticles into insulin-loaded transdermal patches. By heating the nanoparticles, insulin release could be externally controlled, providing a less painful alternative to long-term injections and supporting wearable drug delivery applications [59].

Treatment of Infections

Understanding the antimicrobial and antibacterial properties of graphene is crucial for advancing its biomedical applications. Biofilm formation is commonly used to study microbial colonies [73], yet preventing microbial contamination on biofilms and related surfaces remains a significant challenge. The rise of antimicrobial resistance further complicates disease prevention and treatment, underscoring the need for innovative antimicrobial agents capable of targeting multidrug-resistant bacterial strains. Graphene-related materials (GRMs) have emerged as promising candidates in this regard [74].

Many medical devices including ventilators, urinary catheters, and dental tools—are vulnerable to microbial contamination. Incorporating antimicrobial coatings into these devices is essential for reducing infection risks. GRMs can be engineered into nanomaterial layers or surface coatings to effectively inhibit microbial growth [75]. For example, graphene- and GO-coated aluminum plates have been tested against *E. coli*, showing strong antimicrobial effects by significantly suppressing bacterial activity. Similarly, graphene nanowalls used as coatings for stainless-steel materials demonstrated substantial antibacterial performance against both Gram-positive and Gram-negative strains. Microscopic analyses indicated that the sharp edges of the nanowalls physically damaged bacterial membranes, leading to cell death [76].

Beyond their intrinsic antimicrobial properties, GRMs can also be integrated into more sophisticated formulations containing metal or metal oxide nanoparticles, polyelectrolytes, or conventional antimicrobial agents. Among these, GRM-based binary or ternary systems—such as GRMs combined with silver and/or polymers, or with ZnO and polymer matrices are among the most extensively studied antimicrobial platforms [77].

Imaging Techniques

Advancements in biomedical imaging focus on achieving higher resolution, greater tissue penetration, minimized tissue damage, faster acquisition, improved signal-to-noise ratios, and multifunctional imaging capabilities. The ability of graphene-based materials to be internalized by cells enables enhanced cellular fluorescence imaging [78, 79]. Owing to their large surface area, graphene materials can effectively carry metal ions, targeting ligands, and labeling agents, making them promising candidates for improving MRI, positron emission tomography (PET), and computed tomography (CT) imaging [80]. Additionally, their strong laser absorption and vibrational characteristics significantly enhance the quality of photoacoustic imaging (PAI).

Drug Delivery

Functionalized graphene-based materials are increasingly used in drug delivery to transport therapeutic agents directly to diseased sites while minimizing harm to healthy tissues [81]. Their release behavior can also be precisely controlled through various stimuli-responsive mechanisms [82]. Owing to their large surface area, graphene materials can load substantial amounts of drugs, while functionalization reduces toxicity and enables attachment of targeting ligands and specific therapeutic molecules.

Biosensors

Biosensors detect target biomolecules by converting changes in their concentration into electrical [83] or optical [84] signals for analysis. Functionalized graphene materials offer outstanding advantages as sensing platforms due to their high electrocatalytic activity, large surface area, mechanical strength, and stability, enabling rapid, simple, and highly sensitive biomolecular detection. Graphene's exceptionally high electron mobility—predicted to be $9.04 \times 10^3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at 300 K [85], much higher than typical 2D semiconductors such as CrS₂, MoS₂, and WS₂ [86] further enhances its suitability for advanced biosensing.

There are three types of graphene-based biosensors. The first is electric biosensors, mainly using cyclic voltammetry (CV) to monitor resistance changes caused by enzyme-mediated oxidation [83] or by binding of specific ligands such as aptamers [87], antibodies [88], and peptides. The second category includes spectrum shift-based biosensors, which detect variations in optical signals, such as NIR-induced spectral changes [174] or intrinsic colorimetric reactions [84]. The third type comprises multifunctional biosensors, which integrate multiple capabilities such as diagnosis, therapy [89], and multimodal detection [90] for advanced in vivo applications.

Photothermal Therapy

Biocompatible graphene materials, known for their strong laser absorption and excellent thermal conductivity, are well suited for photothermal therapy (PTT) [91]. In PTT, graphene-based agents are guided to the diseased site, where their light absorption and heat-conversion capabilities enable thermal ablation of the target under NIR irradiation [92, 93]. Ideally, this process should minimize harm to surrounding healthy tissues. Recent advances in the field categorize PTT approaches into two main types: basic targeting PTT and enhanced PTT.

Gene Delivery

Beyond transporting drug molecules, graphene-based materials can also function as effective carriers for gene delivery. Earlier studies have described their interactions with nucleic acids in three main ways: (1) graphene shows stronger adsorption toward single-stranded DNA (ssDNA) than double-stranded DNA (dsDNA) [91]; (2) nucleases can be inhibited due to steric protection of DNA adsorbed on graphene surfaces; and (3) small graphene sheets may intercalate into DNA and cause strand scission [94]. Additionally, reported interaction energies between graphene and nucleobases follow the order thymine (T) < cytosine (C) < adenine (A) < guanine (G)

in aqueous environments [95]. Beyond understanding these mechanisms, recent work has focused on applications such as disease detection using ssDNA-based systems and gene therapy involving plasmid DNA transfection [96] or siRNA-mediated gene silencing [97]. Importantly, concerns about genotoxicity can be addressed through appropriate functionalization strategies [94].

Future Perspectives

Despite remarkable progress in the synthesis and biomedical applications of graphene-based materials, several challenges and opportunities remain. Future research should focus on developing safer, greener, and more scalable synthesis methods that ensure uniform quality and reduce potential toxicity. Precise functionalization strategies are needed to improve biocompatibility, targeting efficiency, and controlled drug release. Advancements in *in vivo* imaging, biosensing, and multimodal therapeutic platforms will further expand the clinical potential of graphene. Long-term biosafety, degradation pathways, and standardized evaluation protocols must be established to facilitate regulatory approval and clinical translation. Integrating graphene with emerging technologies such as artificial intelligence, 3D bioprinting, and personalized medicine may enable highly tailored diagnostic and therapeutic solutions. Overall, interdisciplinary collaboration will be crucial to unlocking the full potential of graphene-based materials in next-generation biomedical applications.

Conclusion

Graphene based materials have emerged as highly versatile and promising candidates for a wide range of biomedical applications due to their exceptional mechanical strength, large surface area, tunable chemistry, and unique electronic and optical properties. Advances in synthesis and functionalization methods have enabled more precise control over their structure, biocompatibility, and performance, thereby expanding their potential in imaging, drug and gene delivery, biosensing, antibacterial therapy, tissue regeneration, and photothermal treatment. Despite these significant achievements, important challenges remain, particularly those related to large scale synthesis, reproducibility, long-term toxicity, biodegradation, and clinical translation. Continued efforts toward understanding the interactions between graphene-related materials and biological systems, developing safer and more efficient functionalization strategies, and standardizing evaluation protocols will be essential for advancing their clinical applicability. Overall, graphene-based materials represent a powerful platform for future biomedical technologies, and ongoing research is expected to unlock even broader and more impactful therapeutic and diagnostic opportunities.

References

- [1] B. Zhang, Y. Wang, G. Zhai, Biomedical applications of the graphene-based materials, *Materials Science and Engineering: C*, 61 (2016) 953-964.
- [2] S. Ahmad, M.T. Aminzai, T. Sharif, M. Sayed, S. Khan, F. Rehman, J.A. Khan, E. Yabalak, Advanced oxidation pathways for chlorophenol degradation-UV/H₂O₂ and UV/O₃ kinetics and mechanisms, *Journal of Materials Science*,

Online ISSN

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<http://amresearchreview.com/index.php/Journal/about>

- (2025) 1-35.
- [3] J. Shah, H. Sun, Z. Qiao, T. Sharif, M. Gul, Enhanced degradation of methylene blue dye using hydrothermally synthesized Nickel-doped Strontium oxide catalysts, *Brazilian Journal of Science*, 3 (2024) 13-27.
- [4] A.K. Geim, Graphene: status and prospects, *science*, 324 (2009) 1530-1534.
- [5] O. Akhavan, A. Meidanchi, E. Ghaderi, S. Khoei, Zinc ferrite spinel-graphene in magneto-photothermal therapy of cancer, *Journal of Materials Chemistry B*, 2 (2014) 3306-3314.
- [6] Y. Fazaeli, O. Akhavan, R. Rahighi, M.R. Aboudzadeh, E. Karimi, H. Afarideh, In vivo SPECT imaging of tumors by 198,199 Au-labeled graphene oxide nanostructures, *Materials Science and Engineering: C*, 45 (2014) 196-204.
- [7] O. Akhavan, E. Ghaderi, M. Shahsavari, Graphene nanogrids for selective and fast osteogenic differentiation of human mesenchymal stem cells, *Carbon*, 59 (2013) 200-211.
- [8] O. Akhavan, E. Ghaderi, R. Rahighi, Toward single-DNA electrochemical biosensing by graphene nanowalls, *ACS nano*, 6 (2012) 2904-2916.
- [9] E. Hashemi, O. Akhavan, M. Shamsara, S. Valimehr, R. Rahighi, DNA and RNA extractions from eukaryotic and prokaryotic cells by graphene nanoplatelets, *RSC Advances*, 4 (2014) 60720-60728.
- [10] O. Akhavan, E. Ghaderi, K. Rahimi, Adverse effects of graphene incorporated in TiO₂ photocatalyst on minuscule animals under solar light irradiation, *Journal of Materials Chemistry*, 22 (2012) 23260-23266.
- [11] O. Akhavan, E. Ghaderi, Escherichia coli bacteria reduce graphene oxide to bactericidal graphene in a self-limiting manner, *Carbon*, 50 (2012) 1853-1860.
- [12] V.N. Kim, Small RNAs: classification, biogenesis, and function, *Molecules and cells*, 19 (2005) 1-15.
- [13] T. Sharif, M. Ateeq, S. Ahmad, W. Ahmad, A. Zada, P. Fazil, N.S. Shah, A. Al-Anazi, J.A. Khan, S. Azizi, Degradation of Rosuvastatin by UV/H₂O₂ and UV/H₂O₂/Fe²⁺ processes: Kinetics, mechanism, toxicity and economic assessment, *Brazilian Journal of Chemical Engineering*, (2025) 1-14.
- [14] C. Dhand, N. Dwivedi, X.J. Loh, A.N.J. Ying, N.K. Verma, R.W. Beuerman, R. Lakshminarayanan, S. Ramakrishna, Methods and strategies for the synthesis of diverse nanoparticles and their applications: a comprehensive overview, *Rsc Advances*, 5 (2015) 105003-105037.
- [15] S. Mourdikoudis, R.M. Pallares, N.T. Thanh, Characterization techniques for nanoparticles: comparison and complementarity upon studying nanoparticle properties, *Nanoscale*, 10 (2018) 12871-12934.
- [16] M. El-Rafie, H.B. Ahmed, M. Zahran, Facile precursor for synthesis of silver nanoparticles using alkali treated maize starch, *International scholarly research notices*, 2014 (2014) 702396.
- [17] R.S. Dey, S. Hajra, R.K. Sahu, C.R. Raj, M. Panigrahi, A rapid room temperature chemical route for the synthesis of graphene: metal-mediated reduction of graphene oxide, *Chemical Communications*, 48 (2012) 1787-1789.
- [18] S.K. Yadav, A. Kumar, N. Mehta, Beyond Graphene Basics: A Holistic Review of Electronic Structure, Synthesis Strategies, Properties, and Graphene-based Electrode Materials for Supercapacitor Applications, *Progress in Solid State*

- Chemistry, (2025) 100519.
- [19] L. Wang, R. Lai, L. Zhang, M. Zeng, L. Fu, In situ investigating the mechanism of graphene growth by chemical vapor deposition, *ACS Materials Letters*, 4 (2022) 528-540.
- [20] A. Srivastava, C. Galande, L. Ci, L. Song, C. Rai, D. Jariwala, K.F. Kelly, P.M. Ajayan, Novel liquid precursor-based facile synthesis of large-area continuous, single, and few-layer graphene films, *Chemistry of Materials*, 22 (2010) 3457-3461.
- [21] W. Liu, H. Li, C. Xu, Y. Khatami, K. Banerjee, Synthesis of high-quality monolayer and bilayer graphene on copper using chemical vapor deposition, *Carbon*, 49 (2011) 4122-4130.
- [22] R. Mohd Firdaus, N. Berrada, A. Desforjes, A.R. Mohamed, B. Vigolo, From 2D graphene nanosheets to 3D graphene-based macrostructures, *Chemistry–An Asian Journal*, 15 (2020) 2902-2924.
- [23] R.S. Edwards, K.S. Coleman, Graphene synthesis: relationship to applications, *Nanoscale*, 5 (2013) 38-51.
- [24] S. JIE, Chemical vapor deposited graphene: Transfer and application, in, 2013.
- [25] T.H. Le, Y. Oh, H. Kim, H. Yoon, Exfoliation of 2D materials for energy and environmental applications, *Chemistry–A European Journal*, 26 (2020) 6360-6401.
- [26] F. Mahmood, S. Ashraf, M. Shahzad, B. Li, F. Asghar, W. Amjad, M.M. Omar, Graphene synthesis from organic substrates: a review, *Industrial & Engineering Chemistry Research*, 62 (2023) 17314-17327.
- [27] J. Kang, D. Shin, S. Bae, B.H. Hong, Graphene transfer: key for applications, *Nanoscale*, 4 (2012) 5527-5537.
- [28] C. Cai, N. Sang, Z. Shen, X. Zhao, Facile and size-controllable preparation of graphene oxide nanosheets using high shear method and ultrasonic method, *Journal of Experimental Nanoscience*, 12 (2017) 247-262.
- [29] F. Farjadian, S. Abbaspour, M.A.A. Sadatlu, S. Mirkiani, A. Ghasemi, M. Hoseini-Ghahfarokhi, N. Mozaffari, M. Karimi, M.R. Hamblin, Recent developments in graphene and graphene oxide: Properties, synthesis, and modifications: A review, *ChemistrySelect*, 5 (2020) 10200-10219.
- [30] M. Zhao, C. Casiraghi, K. Parvez, Electrochemical exfoliation of 2D materials beyond graphene, *Chemical Society Reviews*, 53 (2024) 3036-3064.
- [31] M. Yi, Z. Shen, A review on mechanical exfoliation for the scalable production of graphene, *Journal of Materials Chemistry A*, 3 (2015) 11700-11715.
- [32] M.T. Alshamkhani, L.K. Teong, L.K. Putri, A.R. Mohamed, P. Lahijani, M. Mohammadi, Effect of graphite exfoliation routes on the properties of exfoliated graphene and its photocatalytic applications, *Journal of Environmental Chemical Engineering*, 9 (2021) 106506.
- [33] M. Sumdani, M. Islam, A. Yahaya, S. Safie, Recent advances of the graphite exfoliation processes and structural modification of graphene: a review, *Journal of Nanoparticle Research*, 23 (2021) 253.
- [34] Q. Abbas, P.A. Shinde, M.A. Abdelkareem, A.H. Alami, M. Mirzaeian, A. Yadav, A.G. Olabi, Graphene synthesis techniques and environmental applications, *Materials*, 15 (2022) 7804.

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

- [35] H. Wang, J.T. Robinson, X. Li, H. Dai, Solvothermal reduction of chemically exfoliated graphene sheets, *Journal of the American Chemical Society*, 131 (2009) 9910-9911.
- [36] M. Liu, X. Zhang, W. Wu, T. Liu, Y. Liu, B. Guo, R. Zhang, One-step chemical exfoliation of graphite to~ 100% few-layer graphene with high quality and large size at ambient temperature, *Chemical Engineering Journal*, 355 (2019) 181-185.
- [37] F.K.F. Dos Santos, A.A.M.P. Júnior, A.L.N. Filho, C.J.N. Fonseca, D.K.M. Isidório, F.d.A. Araujo, P.H.A. Oliveira, V.F.d. Veiga Júnior, Graphene and natural products: A review of antioxidant properties in graphene oxide reduction, *International Journal of Molecular Sciences*, 25 (2024) 5182.
- [38] J. Liu, *Graphene-based composites for electrochemical energy storage*, Springer, 2017.
- [39] C.-Y. Su, A.-Y. Lu, Y. Xu, F.-R. Chen, A.N. Khlobystov, L.-J. Li, High-quality thin graphene films from fast electrochemical exfoliation, *ACS nano*, 5 (2011) 2332-2339.
- [40] Y. Gong, Y. Ping, D. Li, C. Luo, X. Ruan, Q. Fu, C. Pan, Preparation of high-quality graphene via electrochemical exfoliation & spark plasma sintering and its applications, *Applied Surface Science*, 397 (2017) 213-219.
- [41] H. Ma, Z. Shen, Exfoliation of graphene nanosheets in aqueous media, *Ceramics International*, 46 (2020) 21873-21887.
- [42] C.-H. Chuang, C.-Y. Su, K.-T. Hsu, C.-H. Chen, C.-H. Huang, C.-W. Chu, W.-R. Liu, A green, simple and cost-effective approach to synthesize high quality graphene by electrochemical exfoliation via process optimization, *Rsc Advances*, 5 (2015) 54762-54768.
- [43] B. Yuan, C. Bao, X. Qian, P. Wen, W. Xing, L. Song, Y. Hu, A facile approach to prepare graphene via solvothermal reduction of graphite oxide, *Materials Research Bulletin*, 55 (2014) 48-52.
- [44] L.G. Guex, B. Sacchi, K.F. Peuvot, R.L. Andersson, A.M. Pourrahimi, V. Ström, S. Farris, R.T. Olsson, Experimental review: chemical reduction of graphene oxide (GO) to reduced graphene oxide (rGO) by aqueous chemistry, *Nanoscale*, 9 (2017) 9562-9571.
- [45] H.C. Schniepp, J.-L. Li, M.J. McAllister, H. Sai, M. Herrera-Alonso, D.H. Adamson, R.K. Prud'homme, R. Car, D.A. Saville, I.A. Aksay, Functionalized single graphene sheets derived from splitting graphite oxide, *The journal of physical chemistry B*, 110 (2006) 8535-8539.
- [46] M.A.A. El-Khair, A.O.A. El Naga, K.Z. Elwakeel, A.M. Elgarahy, A. Priya, K.K. Yadav, A.S. Morshedy, The promise of graphene-based photocatalytic materials for wastewater remediation: A scoping review, *Coordination Chemistry Reviews*, 544 (2025) 216961.
- [47] Q. Bu, H. Morgan Jr, J. Liang, H. Lei, R. Ruan, Catalytic microwave pyrolysis of lignocellulosic biomass for fuels and chemicals, in: *Advances in bioenergy*, Elsevier, 2016, pp. 69-123.
- [48] J.E. Omoriyekomwan, A. Tahmasebi, J. Dou, R. Wang, J. Yu, A review on the recent advances in the production of carbon nanotubes and carbon nanofibers via microwave-assisted pyrolysis of biomass, *Fuel Processing Technology*,

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

- 214 (2021) 106686.
- [49] W. Liu, H. Jiang, X. Zhang, Y. Zhao, S. Sun, J. Qiao, Less defective graphene aerogel and its application in microwave-assisted biomass pyrolysis to prepare H₂-rich gas, *Journal of Materials Chemistry A*, 7 (2019) 27236-27240.
- [50] S.S. Shams, L.S. Zhang, R. Hu, R. Zhang, J. Zhu, Synthesis of graphene from biomass: a green chemistry approach, *Materials Letters*, 161 (2015) 476-479.
- [51] I. Berktaş, M. Hezarkhani, L. Haghighi Poudeh, B. Saner Okan, Recent developments in the synthesis of graphene and graphene-like structures from waste sources by recycling and upcycling technologies: a review, *Graphene Technology*, 5 (2020) 59-73.
- [52] N.Z.J. Zakaria, S. Rozali, N.M. Mubarak, S. Ibrahim, A review of the recent trend in the synthesis of carbon nanomaterials derived from oil palm by-product materials, *Biomass Conversion and Biorefinery*, 14 (2024) 13-44.
- [53] M.T.-u. Safian, U.S. Haron, M.M. Ibrahim, A review on bio-based graphene derived from biomass wastes, *BioResources*, 15 (2020) 9756.
- [54] F. Samara, K. Obaideen, M. Moyet, R. Darra, G. Venkatesh, S. Kanan, Environmental advantages and current trends of graphene-based materials for energy storage, *Energy Conversion and Management: X*, (2025) 101264.
- [55] A. Van Bommel, J. Crombeen, A. Van Tooren, LEED and Auger electron observations of the SiC (0001) surface, *Surface Science*, 48 (1975) 463-472.
- [56] R.F. Davis, G. Kelner, M. Shur, J.W. Palmour, J.A. Edmond, Thin film deposition and microelectronic and optoelectronic device fabrication and characterization in monocrystalline alpha and beta silicon carbide, *Proceedings of the IEEE*, 79 (2002) 677-701.
- [57] W. Zieba, K. Jurkiewicz, A. Burian, M. Pawlyta, S. Boncel, G.S. Szymanski, J. Kubacki, P. Kowalczyk, K. Krukiewicz, A. Furuse, High-surface-area graphene oxide for next-generation energy storage applications, *ACS applied nano materials*, 5 (2022) 18448-18461.
- [58] W. Yang, G. Chen, Z. Shi, C.-C. Liu, L. Zhang, G. Xie, M. Cheng, D. Wang, R. Yang, D. Shi, Epitaxial growth of single-domain graphene on hexagonal boron nitride, *Nature materials*, 12 (2013) 792-797.
- [59] Y. Liu, J. Ding, Q.-q. Wang, M.-l. Wen, T.-t. Tang, Y. Liu, R. Yuan, Y.-f. Li, M.-w. An, Research progress on the biomedical uses of graphene and its derivatives, *New Carbon Materials*, 36 (2021) 779-793.
- [60] A. Sadeghianmaryan, Y. Karimi, S. Naghie, H. Alizadeh Sardroud, M. Gorji, X. Chen, Electrospinning of scaffolds from the polycaprolactone/polyurethane composite with graphene oxide for skin tissue engineering, *Applied Biochemistry and Biotechnology*, 191 (2020) 567-578.
- [61] A. Pourjavadi, Z. Mazaheri Tehrani, H. Salami, F. Seidi, A. Motamedi, A. Amanzadi, E. Zayerzadeh, M. Shabanian, Both tough and soft double network hydrogel nanocomposite based on O-carboxymethyl chitosan/poly (vinyl alcohol) and graphene oxide: A promising alternative for tissue engineering, *Polymer Engineering & Science*, 60 (2020) 889-899.
- [62] N. Mahmoudi, N. Eslahi, A. Mehdipour, M. Mohammadi, M. Akbari, A. Samadikuchaksaraei, A. Simchi, Temporary skin grafts based on hybrid graphene oxide-natural biopolymer nanofibers as effective wound healing

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

- substitutes: pre-clinical and pathological studies in animal models, *Journal of Materials Science: Materials in Medicine*, 28 (2017) 73.
- [63] J. Li, C. Zhou, C. Luo, B. Qian, S. Liu, Y. Zeng, J. Hou, B. Deng, Y. Sun, J. Yang, N-acetyl cysteine-loaded graphene oxide-collagen hybrid membrane for scarless wound healing, *Theranostics*, 9 (2019) 5839.
- [64] P. Tang, L. Han, P. Li, Z. Jia, K. Wang, H. Zhang, H. Tan, T. Guo, X. Lu, Mussel-inspired electroactive and antioxidative scaffolds with incorporation of polydopamine-reduced graphene oxide for enhancing skin wound healing, *ACS applied materials & interfaces*, 11 (2019) 7703-7714.
- [65] B. Zhang, J. He, M. Shi, Y. Liang, B. Guo, Injectable self-healing supramolecular hydrogels with conductivity and photo-thermal antibacterial activity to enhance complete skin regeneration, *Chemical Engineering Journal*, 400 (2020) 125994.
- [66] S. Sarkar, A.A. Gurjarpadhye, C.G. Rylander, M. Nichole Rylander, Optical properties of breast tumor phantoms containing carbon nanotubes and nanohorns, *Journal of biomedical optics*, 16 (2011) 051304-051304-051311.
- [67] K. Turcheniuk, T. Dumych, R. Bilyy, V. Turcheniuk, J. Bouckaert, V. Vovk, V. Chopyak, V. Zaitsev, P. Mariot, N. Prevarskaya, Plasmonic photothermal cancer therapy with gold nanorods/reduced graphene oxide core/shell nanocomposites, *RSC advances*, 6 (2016) 1600-1610.
- [68] I. Matai, G. Kaur, S. Soni, A. Sachdev, S. Mishra, Near-infrared stimulated hydrogel patch for photothermal therapeutics and thermoresponsive drug delivery, *Journal of Photochemistry and Photobiology B: Biology*, 210 (2020) 111960.
- [69] N. Kurantowicz, B. Strojny, E. Sawosz, S. Jaworski, M. Kutwin, M. Grodzik, M. Wierzbicki, L. Lipińska, K. Mitura, A. Chwalibog, Biodistribution of a high dose of diamond, graphite, and graphene oxide nanoparticles after multiple intraperitoneal injections in rats, *Nanoscale research letters*, 10 (2015) 398.
- [70] I. Yadav, S.K. Nayak, V.S. Rathnam, I. Banerjee, S.S. Ray, A. Anis, K. Pal, Reinforcing effect of graphene oxide reinforcement on the properties of poly (vinyl alcohol) and carboxymethyl tamarind gum based phase-separated film, *Journal of the mechanical behavior of biomedical materials*, 81 (2018) 61-71.
- [71] S. Ganguly, P. Das, P.P. Maity, S. Mondal, S. Ghosh, S. Dhara, N.C. Das, Green reduced graphene oxide toughened semi-IPN monolith hydrogel as dual responsive drug release system: rheological, physicomachanical, and electrical evaluations, *The Journal of Physical Chemistry B*, 122 (2018) 7201-7218.
- [72] I. Altinbasak, R. Jijie, A. Barras, B. Golba, R. Sanyal, J. Bouckaert, D. Drider, R. Bilyy, T. Dumych, S. Paryzhak, Reduced graphene-oxide-embedded polymeric nanofiber mats: an “on-demand” photothermally triggered antibiotic release platform, *ACS Applied Materials & Interfaces*, 10 (2018) 41098-41106.
- [73] K. Schilcher, A.R. Horswill, Staphylococcal biofilm development: structure, regulation, and treatment strategies, *Microbiology and Molecular Biology Reviews*, 84 (2020) 10.1128/mmbr.00026-00019.
- [74] H. Mohammed, A. Kumar, E. Bekyarova, Y. Al-Hadeethi, X. Zhang, M. Chen, M.S. Ansari, A. Cochis, L. Rimondini, Antimicrobial mechanisms and

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

- effectiveness of graphene and graphene-functionalized biomaterials. A scope review, *Frontiers in bioengineering and biotechnology*, 8 (2020) 465.
- [75] A.D. Staneva, D.K. Dimitrov, D.N. Gospodinova, T.G. Vladkova, Antibiofouling activity of graphene materials and graphene-based antimicrobial coatings, *Microorganisms*, 9 (2021) 1839.
- [76] S. Pandit, K. Gaska, R. Kádár, I. Mijakovic, Graphene-based antimicrobial biomedical surfaces, *ChemPhysChem*, 22 (2021) 250-263.
- [77] V. Ahmad, M.O. Ansari, Antimicrobial activity of graphene-based nanocomposites: synthesis, characterization, and their applications for human welfare, *Nanomaterials*, 12 (2022) 4002.
- [78] K. Liu, J.-J. Zhang, F.-F. Cheng, T.-T. Zheng, C. Wang, J.-J. Zhu, Green and facile synthesis of highly biocompatible graphene nanosheets and its application for cellular imaging and drug delivery, *Journal of Materials Chemistry*, 21 (2011) 12034-12040.
- [79] C. Peng, W. Hu, Y. Zhou, C. Fan, Q. Huang, Intracellular imaging with a graphene-based fluorescent probe, *Small*, 6 (2010) 1686-1692.
- [80] J. Lin, Y. Huang, P. Huang, Graphene-based nanomaterials in bioimaging, *Biomedical applications of functionalized nanomaterials*, (2018) 247-287.
- [81] L. Feng, Z. Liu, Graphene in biomedicine: opportunities and challenges, *Nanomedicine*, 6 (2011) 317-324.
- [82] K. Yang, L. Feng, Z. Liu, Stimuli responsive drug delivery systems based on nano-graphene for cancer therapy, *Advanced drug delivery reviews*, 105 (2016) 228-241.
- [83] C. Shan, H. Yang, D. Han, Q. Zhang Q, A. Ivaska and L. Niu, *Biosens. Bioelectron*, 25 (2010) 1070.
- [84] Y. Song, K. Qu, C. Zhao, J. Ren, X. Qu, Graphene oxide: intrinsic peroxidase catalytic activity and its application to glucose detection, *Advanced Materials*, 22 (2010) 2206-2210.
- [85] Y. Su, S. Cao, L.-B. Shi, P. Qian, Investigation of biaxial strain behavior and phonon-limited mobility for γ graphyne: First-principles calculation, *Journal of Applied Physics*, 130 (2021).
- [86] H. Chang, H. Wang, K.-K. Song, M. Zhong, L.-B. Shi, P. Qian, Origin of phonon-limited mobility in two-dimensional metal dichalcogenides, *Journal of Physics: Condensed Matter*, 34 (2021) 013003.
- [87] Z. Hao, Y. Luo, C. Huang, Z. Wang, G. Song, Y. Pan, X. Zhao, S. Liu, An intelligent graphene-based biosensing device for cytokine storm syndrome biomarkers detection in human biofluids, *Small*, 17 (2021) 2101508.
- [88] M.-S. Chae, J. Kim, D. Jeong, Y. Kim, J.H. Roh, S.M. Lee, Y. Heo, J.Y. Kang, J.H. Lee, D.S. Yoon, Enhancing surface functionality of reduced graphene oxide biosensors by oxygen plasma treatment for Alzheimer's disease diagnosis, *Biosensors and Bioelectronics*, 92 (2017) 610-617.
- [89] S.W. Park, J. Kim, M. Kang, W. Lee, B.S. Park, H. Kim, S.Y. Choi, S. Yang, J.H. Ahn, S. Yang, Epidural electrotherapy for epilepsy, *Small*, 14 (2018) 1801732.
- [90] D. Kuzum, H. Takano, E. Shim, J.C. Reed, H. Juul, A.G. Richardson, J. De Vries, H. Bink, M.A. Dichter, T.H. Lucas, Transparent and flexible low noise

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

- graphene electrodes for simultaneous electrophysiology and neuroimaging, *Nature communications*, 5 (2014) 5259.
- [91] C.N.R. Rao, A.K. Sood, *Graphene: synthesis, properties, and phenomena*, John Wiley & Sons, 2013.
- [92] K. Yang, S. Zhang, G. Zhang, X. Sun, S.-T. Lee, Z. Liu, Graphene in mice: ultrahigh in vivo tumor uptake and efficient photothermal therapy, *Nano letters*, 10 (2010) 3318-3323.
- [93] M. Guo, J. Huang, Y. Deng, H. Shen, Y. Ma, M. Zhang, A. Zhu, Y. Li, H. Hui, Y. Wang, pH-responsive cyanine-grafted graphene oxide for fluorescence resonance energy transfer-enhanced photothermal therapy, *Advanced Functional Materials*, 25 (2015) 59-67.
- [94] H. Ren, C. Wang, J. Zhang, X. Zhou, D. Xu, J. Zheng, S. Guo, J. Zhang, DNA cleavage system of nanosized graphene oxide sheets and copper ions, *ACS nano*, 4 (2010) 7169-7174.
- [95] N. Varghese, U. Mogera, A. Govindaraj, A. Das, P.K. Maiti, A.K. Sood, C. Rao, Binding of DNA nucleobases and nucleosides with graphene, *ChemPhysChem*, 10 (2009) 206-210.
- [96] L. Feng, S. Zhang, Z. Liu, Graphene based gene transfection, *Nanoscale*, 3 (2011) 1252-1257.
- [97] Y. Qu, F. Sun, F. He, C. Yu, J. Lv, Q. Zhang, D. Liang, C. Yu, J. Wang, X. Zhang, Glycyrrhetic acid-modified graphene oxide mediated siRNA delivery for enhanced liver-cancer targeting therapy, *European Journal of Pharmaceutical Sciences*, 139 (2019) 105036.