

Graphene Nanomaterials: A Potential Game-Changer in Medicine

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Abstract: Graphene is made up of carbon atoms arranged in a single, hexagon-shaped lattice. It is one of the best carriers for pharmaceutical product formulations because of its many uses and unique characteristics, including its strength and structure, which make it a good choice in many formulations, and its particle size, which provides a higher surface area. Among the many potential biomedical applications, graphene has been studied in depth in pharmaceuticals as an additive and a carrier. Graphene also has antimicrobial properties, which make it unique and therefore can be used in nanomedicines as well. Graphene-based materials offer a new generation of drug-delivery vehicles that provide controlled release, target-specific delivery, enhanced bioavailability, and reduced systemic toxicity. Graphene oxide and its derivatives, such as reduced graphene oxide and its quantum dots, have shown excellent drug-delivery capabilities. Producing graphene-based formulations for drug delivery systems, whether as carriers in new methods or traditional ones on a large scale, presents major challenges. Ensuring these materials are safe and compatible with the body over time is crucial. Future research in medicine and drug delivery must focus on understanding and fixing these issues to make graphene safe for widespread use. Moreover, upcoming research should focus on developing nanoparticle formulations with increased specificity and sensitivity towards the target site, as well as the ability to release and respond at the site of action.

Keywords: graphene; reduced graphene oxide; graphene quantum dots; nanoscaffolds; regenerative medicine; anticancer; nano carrier; nanoparticles.

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1. Introduction

When carbon atoms are arranged as a hexagonal lattice, they form a two-dimensional product known as graphene. A single layer of carbon atoms makes graphene the thinnest material known to man, and its hexagonal lattice makes it special. Due to its unique properties, graphene is an exceedingly promising material for applications in electronics, thermodynamics, energy conservation, engineering, space, and even medical science [1,2]. It is the perfect material for use across a range of sectors due to its excellent strength, greater surface area, and conductivity. Graphene distinguishes itself from other materials due to several special qualities.

For instance, graphene has a tensile strength that is more than 200 times that of stainless steel [3-5].

Additionally, it has high electrical and thermal conductivity, making it ideal for energy storage systems and electronics. Wearable technology and other applications can benefit from graphene and its derivatives, which offer high flexibility and low weight. There are many potential uses for graphene because of its unique properties [5,6].

Electronics is one of the most promising fields, where graphene's high conductivity enables faster, more effective devices. Since it can conduct both heat and electricity, it can also be used in energy storage systems such as batteries and supercapacitors to increase efficiency [7]. Additionally, due to its flexibility and lightweight nature, graphene is ideal for use in fitness trackers and other wearable technologies. Water filtration systems, sensors for detecting contaminants or chemicals in the environment, and even medical implants that might track a patient's health in real time are additional potential applications [8-10].

Due to its unique properties and ease of integration into the human body, graphene is also an ideal material for sensors and medical equipment. This could lead to the development of cutting-edge medical implants that track a patient's health in real time and provide doctors with useful information for better treatment options [11]. Additionally, graphene may enhance the efficiency of solar and battery cells, making renewable energy sources more practical and affordable. As scientists continue to investigate the extensive applications of graphene, this material will become increasingly important in shaping our world in the coming years [12-16].

1.1. Importance of graphene and its derivatives in medicinal and therapeutic applications.

Graphene's unique properties make it an excellent material for a variety of medical applications. Due to its high surface area and biocompatibility, graphene is the material of choice for pharmaceutical applications and drug delivery systems, even though its conductivity and flexibility make it useful for the development of biosensors and implantable devices [17-21]. Besides lowering the risk of infections, graphene- and derivative-based coatings have demonstrated the potential to inhibit bacterial growth on medical equipment. Furthermore, graphene's ability to improve the resolution of medical imaging techniques could lead to more accurate diagnoses and better treatment outcomes. Graphene will likely transform medicine as its potential is further investigated, improving patient outcomes and altering the way that healthcare is currently provided [22].

The main objective of this review article is to rediscover and research from the literature about the potential effect of graphene on the field of medicine and drug delivery systems. With its exceptional properties, graphene has already shown promise in various applications, including medical imaging. By enhancing the resolution of medical imaging techniques, graphene could enable more accurate diagnoses and better treatment outcomes for patients. Furthermore, graphene's unique properties could lead to the development of novel, advanced medical devices that are more efficient and effective than current technologies. Ongoing research into graphene's potential indicates that this material can completely transform healthcare as we know it, ultimately leading to better patient outcomes and a shift in how we treat medical conditions.

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1.2. History of graphene and its associated forms.

A British chemist named Benjamin Collins Brodie first discovered graphene in 1859 [23], and subsequently, Wallace and his team worked on theoretical research for many years [24]. However, since Novoselov *et al.* [25] used the Scotch tape method to produce a single-layer graphene material, it has attracted the scientific community's interest. The chronology of significant occasions in the development of graphene and its derivatives is shown in Figure 1 [26-28].

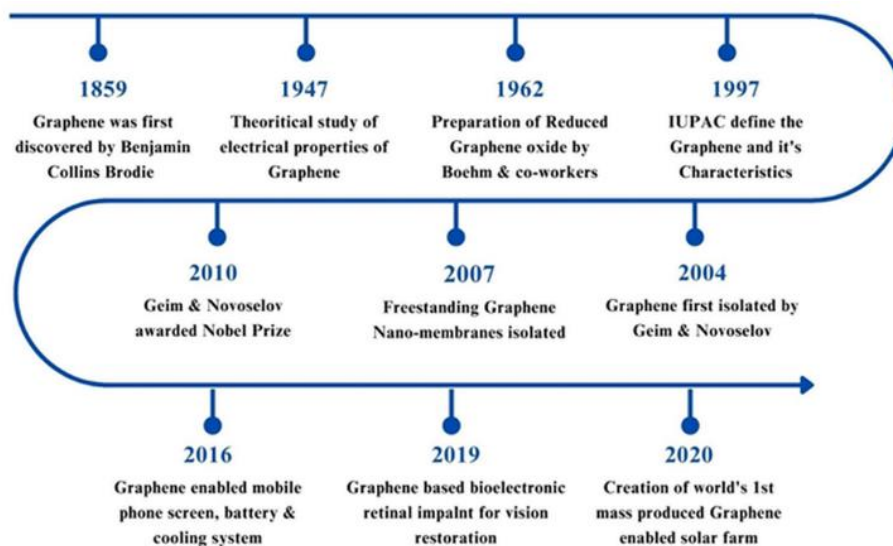


Figure 1. History of the development of graphene and its derivatives.

In 2004, Geim Andre, Novoselov Konstantin, and their group won the Nobel Prize in Physics for their work on the discovery and isolation of graphene. Since then, due to its distinct properties, graphene has been the focus of extensive research across the pharmaceutical and other sectors. Despite being flexible and lightweight, it is highly powerful. More effectively than any other known material, it conducts heat and electricity. Graphene has a higher surface area, making it ideal for sensors and other applications. One of the most promising and innovative uses of graphene lies in the fields of electronics and mechanics. Graphene- and derivative-based transistors have the potential to be much faster and more energy-efficient than traditional silicon-based transistors in the current era, and they most effectively meet the requirements of the engineering field. Additionally, graphene will be used to create flexible screens and touchscreens that are more robust and thinner than those made with existing technologies. Graphene has potential applications in energy storage in addition to electronics.

Recently, there has been significant interest in graphene and its derivative nanomaterials due to their applications in biotechnology, medicine, and other interdisciplinary fields. Even with the enormous progress and research that have been made thus far, there is still much to be done in several areas regarding the various biomedical applications of graphene, as well as the development and application of its substitutes in other research [7, 29-35].

1.3. Structure of graphene.

The carbon atoms in the single-layer graphene sheet are arranged in a honeycomb pattern. Each carbon atom in graphene is linked covalently to three other carbon atoms in the structure. Because of these covalent bonds, graphene is extremely stable and has a high tensile

strength, the amount of force with which something can be stretched before it breaks. Since all atoms are on the surface of a single-layer graphene, it can be accessed from both sides. As a result, there is more interaction with the molecules due to the close proximity [36-41]. The Structure of graphene (a) chemical structure and (b) 2-dimensional structure is shown in Figure 2 [42-44].

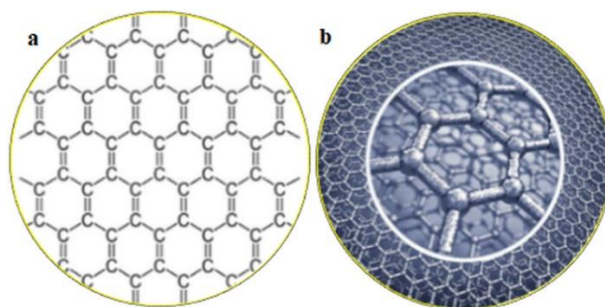


Figure 2. Structure of graphene (a) chemical structure; (b) 2-dimensional structure.

1.4. Synthesis of graphene.

Graphene and its derivatives are currently produced using a variety of techniques. In 2004 [25] and 2005 [45], graphene and other materials, such as molybdenum disulfide and hexagonal boron nitride, were first exfoliated from their bulk counterparts. Scotch tape first produced graphene by mechanically exfoliating graphite, which resulted in the formation of very fine and thin graphene flakes in a variety of particle sizes down to the micron level [4, 46-47]. This method for producing graphene is one of the best ways to obtain the highest-quality graphene. The synthesis of graphene oxide and reduced graphene oxide, which are depicted in Figure 3, is necessary for the mass production of graphene on a wafer scale. A variety of techniques, including "top-down" and "bottom-up" approaches, have been used to synthesize graphene.

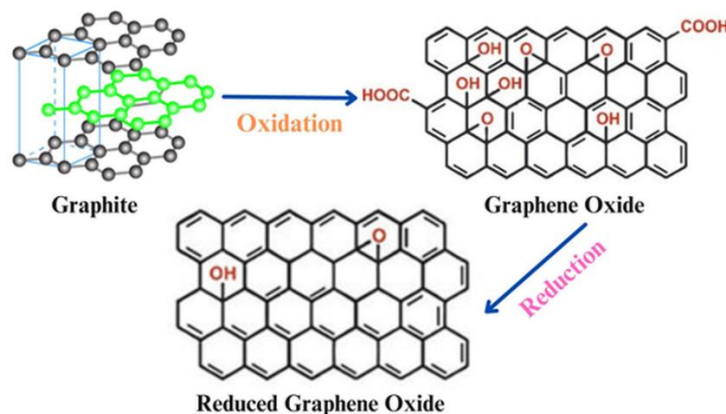


Figure 3. Synthesis of graphene oxide and reduced graphene oxide.

Every graphene manufacturing process has drawbacks as well as advantages. Figure 4 displays various graphene manufacturing techniques [48]. The starting material used in graphene synthesis is also crucial because it may affect the thickness of the resulting graphene, the effective particle size, and the number of layers [26,27].

Graphene can be synthesized in any way, depending on its purity, the desired particle size, and the desired result. In the previous stage, numerous approaches for making graphitic films have been discovered and evaluated [40, 49-52]. Although research on few-layer graphite was conducted in 1975 and the material was developed on a single platinum crystal using a

chemical breakdown method, it was not identified as graphene because there were no methods for characterizing it, or possibly because of its limited potential applications [53].

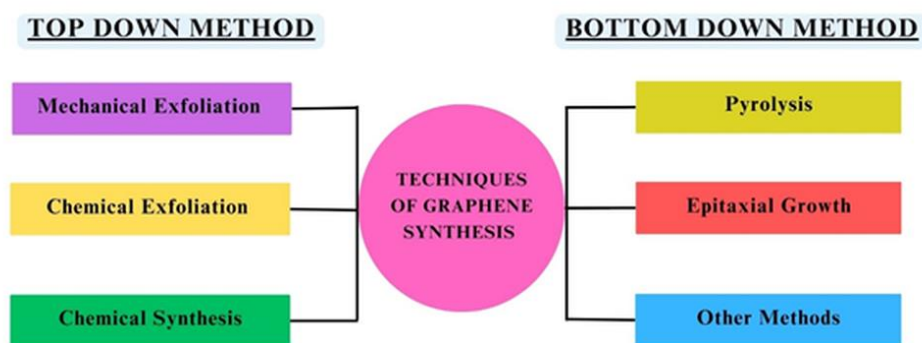


Figure 4. Techniques of graphene synthesis.

To minimize the potentially harmful and lethal effects of chemical agents used during the synthesis of graphene, researchers have developed eco-friendly methods using phytoextract biomolecules and microbes [54,55]. Traditionally, the majority of synthesis methodologies employed chemical reducing agents. GBN surface functionalization is a crucial step for expanding its use in biomedicine. Using various macromolecules and polymers, such as chitosan, polyethylene glycol (PEG), proteins, and enzymes, researchers examined how to enhance biocompatibility, solubility, and selectivity [56].

There is difficulty isolating the substrate and then placing it on the other insulating substrate. In the past, the electronic characteristics of graphitic flakes were left unexplored due to the challenge of transferring and isolating them onto insulating substrates. However, in the late 1990s, Ruoff and his teammates attempted to address this obstacle by mechanically rubbing patterned islands on highly oriented pyrolytic graphite (HOPG) to separate tiny graphitic flakes onto SiO₂ substrates. Despite their efforts, there was insufficient information on the electrical properties of these flakes. This was altered in 2005 when Kim and his colleagues used a comparable approach to describe the electrical characteristics of graphene and its derivatives effectively. Graphene research, however, did not develop rapidly until Geim and his colleagues isolated graphene on a SiO₂ substrate and examined its electrical properties [25, 57-58].

Following the material's discovery in 2004, numerous strategies and techniques were developed and applied to produce thin films of graphitic and few-layer graphene. Graphene's 2D crystals were experimentally visible when thin flakes of graphene and other materials, such as niobium diselenide, hexagonal boron nitride, and molybdenum disulfide, were first separated from their bulk counterparts between 2004 and 2005. However, Scotch and his colleagues from the same research group were the first to synthesize graphene by mechanically exfoliating graphite, which produced micron-sized flakes [4, 47]. This technique was a good way to create graphene with the highest quality, but it is still only feasible on a small scale. To produce graphene at wafer scale for mass production, another appropriate technique is needed.

1.5. Graphene derivatives as delivery carriers.

1.5.1. Delivery to the gene.

The conjugation of polyethyleneimine (PEI) and plasmid DNA (pDNA) has been widely used to deliver genes. Graphene oxide does this by altering its surface, where gene transfer from the gene to the cell is accomplished through electrostatic complexation [59-62].

Compared with PEI/pDNA complexes, the covalent GO conjugates with linear [63] and branched PEI62 showed high gene transfection efficacy with reduced cytotoxicity. The PEI-GO combination was also successfully used to demonstrate the sequential administration of small interfering RNA (siRNA) targeting the B-cell lymphoma 2 (Bcl-2) gene, combined with doxorubicin, into immortalized human HeLa cells, resulting in enhanced therapeutic efficiency. For the efficient delivery of anticancer medications and pDNA, respectively, a recently developed chitosan-functionalized graphene oxide complex was created by incorporating chitosan onto the graphene oxide surface [63,64]. Gene delivery through graphene modification is shown in Figure 5.

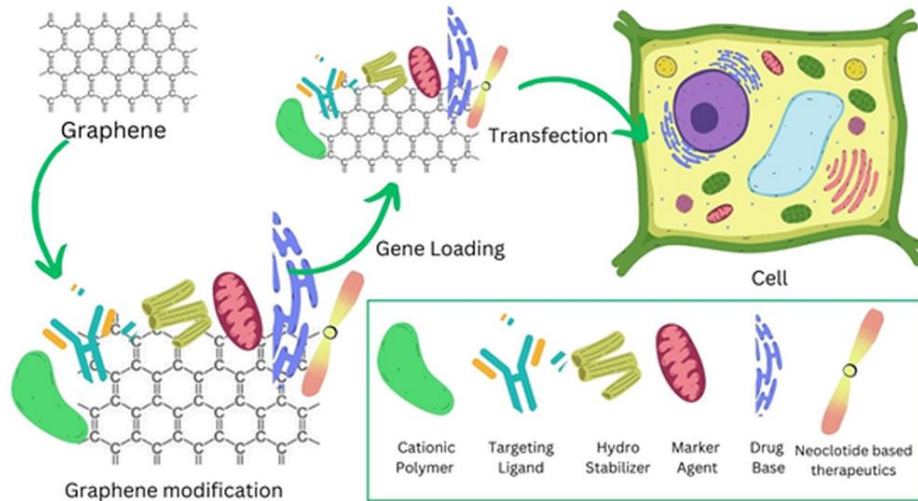


Figure 5. Gene delivery through graphene modification.

1.5.2. Drug delivery to small molecules.

The delivery of small molecules is facilitated by graphene oxide and its derivatives, but pH-dependent solubility poses a challenge for pH-responsive administration. For example, doxorubicin-loaded graphene oxide complexes showed pH-responsive release of doxorubicin from the graphene oxide, due to doxorubicin's higher solubility at lower pH [65]. Additionally, folic acid conjugation with nanographene oxide uses this advantage to deliver doxorubicin and camptothecin to cancer cells in a pH-responsive manner (Figure 6) [66]. Ibuprofen and 5-fluorouracil, both drugs with altered solubility (e.g., hydrophilicity), were delivered to the specific site via pH-responsive release, complexed with graphene oxide [67].

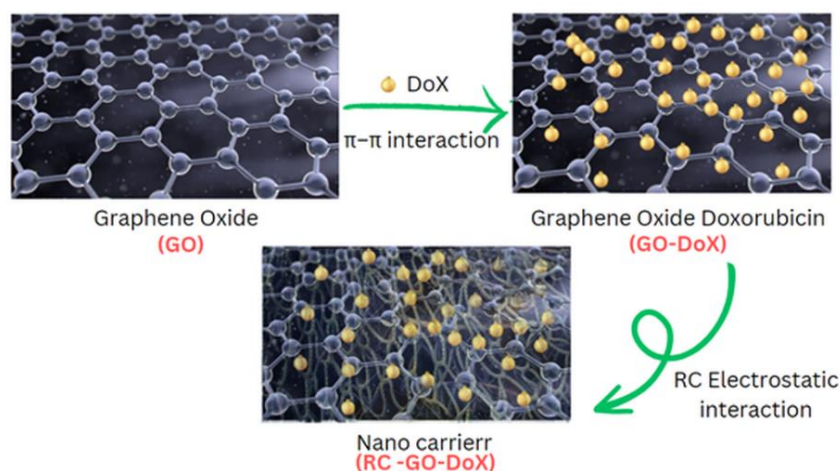


Figure 6. Delivery of doxorubicin with graphene oxide as a carrier.

1.5.3. Cancer treatment with therapeutic modalities.

Nanographene oxide conjugated to six-arm polyethylene glycol for effective hydrophobic drug delivery has been successfully applied to cancer cells, resulting in higher cellular uptake and higher therapeutic efficiency [68-69]. Besides their use as carriers, nanographene oxide derivatives have been used for photothermal therapy due to their strong near-IR (NIR) absorption. The high therapeutic activity of the PEG-GO conjugate was shown in the *in vivo* cancer xenograft models [70]. A recent investigation found that the phototherapeutic effects of nanographene and its oxide derivatives stem from the induction of oxidative stress, mitochondrial depolarization, and activation of the apoptotic process, all of which lead to apoptosis and cell death [71].

The PEG-GO complex is used as a doxorubicin carrier in combination with chemical and photothermal therapy to enhance therapeutic efficacy [72]. When folic acid is conjugated to PEG-GO, a photosensitizer porphyrin is also loaded, enabling a blend of photodynamic and photothermal therapy with the capacity to target cancer cells [73]. Based on photothermal and photocatalytic therapy, graphene/TiO₂ nanohybrid composite also demonstrated higher therapeutic efficiency [74]. Functionalized PEG with graphene oxide in drug delivery to cancer cells is shown in Figure 7.

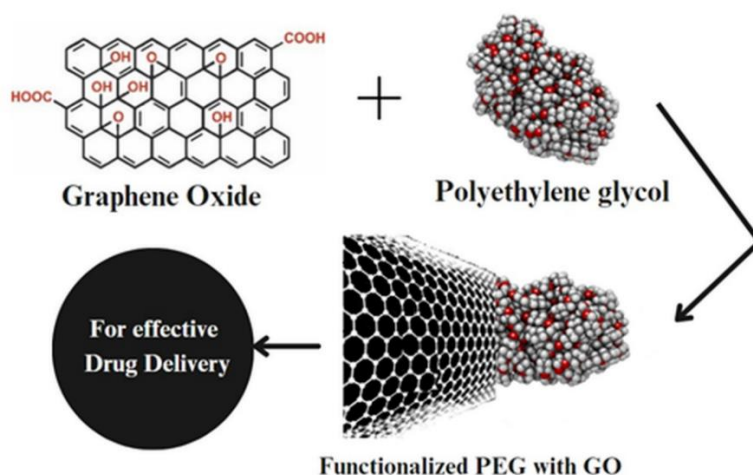


Figure 7. Functionalized PEG with graphene oxide in drug delivery to cancer cells.

1.5.4. Behavior of graphene on bacterial cell growth.

The reduced graphene oxide and graphene oxide products demonstrated the effect of inhibiting bacterial growth [75]. Both gram-positive and gram-negative bacterial cell walls were found to be inhibited by reduced graphene oxide and graphene oxide nanowalls. Because of the more effective charge transfer of reduced graphene oxide with bacterial cells, the antibacterial impact of reduced graphene oxide nanowalls was greater than that of graphene oxide nanowalls [76]. Oxidation and oxidative stress cause membrane rupture due to the antibacterial activity of graphene oxide and its derivatives [77]. However, prior studies have shown that bacteria grew more easily on graphene surfaces than on other surfaces [78]. Recent studies indicate that bacterial growth on graphene oxide can be modified by varying experimental conditions. The behavior of graphene on the surfaces of bacterial cell growth is shown in Figure 8.

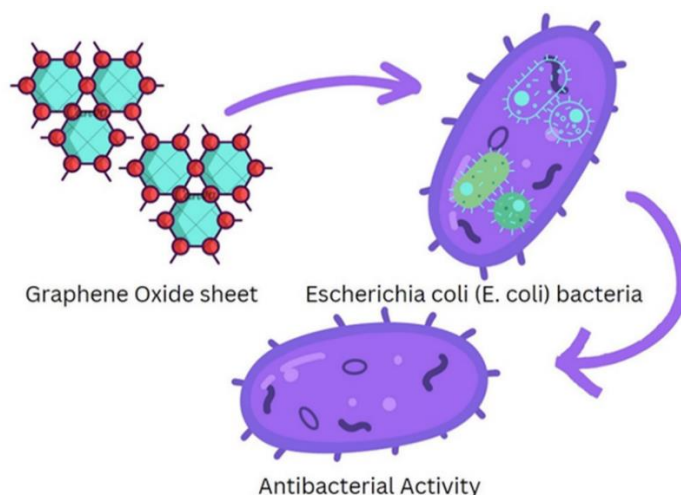


Figure 8. Behavior of graphene on the surfaces of bacterial cell growth – antibacterial activity.

1.5.5. Graphene-based scaffolds for mammalian cell culture.

For this investigation, mammalian cells were selected and cultivated on graphene and its derivatives. For example, the behavior of NIH-fibroblasts-3T3 was investigated on a range of carbon nanomaterial-coated substrates, including graphene oxide, carbon nanotubes, and reduced graphene oxide. Carbon nanomaterial-coated substrates exhibit high biocompatibility, further improving gene transfection efficiency [79]. Additionally, graphene and chitosan hybrid films showed promise for tissue repair and improved tissue function in engineering [80]. In contrast to polystyrene culture plates, neurite sprouting and overgrowth were equally promoted on graphene surfaces [81]. Stem cells are essential to the biology of living things because of the diversity of cell types that allow them to self-repair in organs and continue to develop and renew ontogeny. In regenerative medicine, or "stem cell therapy," stem cells are considered state-of-the-art therapeutic instruments. One of the vital research areas in stem cell research is the disparity of stem cells into desirable cell lines. Graphene's electrical conductivity and biocompatibility make it a popular choice for stem cell differentiation and culture.

The use of nanotechnology in the pharmaceutical industry has accelerated significantly in recent years. Graphene, a honeycomb structure component with two-dimensional carbon atoms, is a promising nanoparticle for the development of novel drug delivery systems and biological applications. With an emphasis on its properties, applications, and recent advances, graphene shows potential for use in the development of innovative pharmaceutical formulations. The hybrid film formation of graphene and chitosan in tissue engineering is shown in Figure 9.

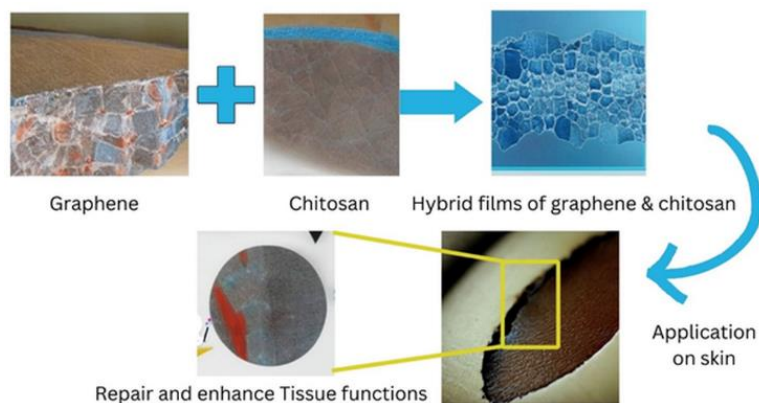


Figure 9. The formation of hybrid films of graphene and chitosan in tissue engineering.

2. Properties of Graphene

Graphene and its derivatives have unique properties that make them suitable and preferred choices for pharmaceutical formulations. Graphene and its substitute materials exhibit optical, mechanical, catalytic, thermal, electronic, and biological properties, and are therefore preferred for small-molecule drug delivery, bioassays, biomolecule recognition, and molecular medicine [82]. Graphene and its derivatives are atomic-thin, allowing fluids to permeate. The honeycomb structure of graphene enables size-selective transport through its nanochannels between adjacent graphene sheets [83-85].

2.1. High surface area.

Because of its high surface area (2600 m²/g), graphene enables pharmaceutical formulations to exhibit improved drug release characteristics and higher drug loading capacities [85].

2.2. Excellent electrical conductivity.

Because of its high electrical conductivity, graphene is a preferred material for electroresponsive drug delivery systems that use an external electric field to control drug release. Graphene has a very high electrical conductivity of 80×10^6 S/m or 10^6 S/m, depending on the source. This is because the electron mobility in graphene is 140 times greater than that of silicon. The electrical conductivity of graphene and the resistivity of current flow are inversely connected [86]. A monolayer flake of graphene is synthesized by deposition of chemical vapor on the copper, which exhibits an electrical conductivity of $1.46 \pm 0.82 \times 10^6$ S/m². The literature indicates that graphene nanocomposites have a low percolation threshold and exhibit better conductivity [87].

2.3. Elasticity and mechanical strength.

Graphene is a suitable material for the development of flexible, novel drug delivery systems due to its exceptional mechanical strength and elasticity. Young's modulus of graphene (1000 GPa) is quite high and is very similar to the elastic constant of the covalent connections between carbon atoms [88]. The literature indicates that graphene and its derivatives are highly resistant to temperatures up to 1000 K due to their mechanical properties [89].

2.4. Good molecule absorption.

Graphene can efficiently adsorb a wide range of compounds, including medicines, proteins, and nucleic acids, making it easier to deliver these molecules to specific locations in the body due to its extensive surface area and unique chemical properties [90-94]. A team of researchers developed a novel drug-delivery technique that uses graphene strips as "flying carpets" to gradually deliver two anticancer drugs to cancer cells. Each treatment targets a different part of the cancer cell where it would be most effective [94].

3. Graphene-Based Pharmaceutical Formulations

Graphene and its derivatives have been used to develop a variety of medicinal formulations, such as topical gels, ointments, and nanoconjugates.

3.1. Topical gels and ointments.

In comparison to traditional topical formulations, graphene-based topical formulations display improved drug penetration through the skin and offer better therapeutic effects. Graphene can be used in topical gels and ointments to improve the stability and shelf life of active pharmaceutical ingredients (APIs). Graphene has shown promising results in improving the effectiveness of topical gels and ointments for skin care applications. By incorporating graphene into these products, it is possible to improve their therapeutic efficacy and reduce systemic side effects, thanks to graphene's antibacterial properties, anti-inflammatory effects, and ability to promote wound healing. Moreover, graphene-based topical gels and ointments have the potential to enhance the delivery of active ingredients to the affected area, resulting in faster, more effective treatment. Thus, integrating graphene with topical applications marks a significant advancement in the study and development of skincare products. Further research on this subject should lead to even more creative applications of graphene in topical treatments for a range of skin disorders [95-98].

3.2. Nanoconjugate.

The graphene surface is coupled to other functional groups, drug molecules, or targeted ligands to form graphene nanoconjugates. These nanoconjugates offer several benefits, including greater therapeutic efficacy and fewer adverse effects, thanks to their higher solubility, prolonged circulation time, and targeted drug delivery [99].

The synthesis of graphene nanoconjugates involves the covalent or non-covalent functionalization of graphene with various molecules or nanoparticles. Covalent functionalization includes the formation of covalent bonds between the surface of graphene and the functional molecules, while non-covalent functionalization includes the adsorption or electrostatic interaction between graphene and the functional molecules [100].

Due to their superior properties and potential applications across a variety of fields, including electronics, healthcare, and energy storage, graphene nanoconjugates have attracted significant attention. Graphene's covalent functionalization makes it an attractive choice for biosensors and drug delivery systems, as it enables fine control over surface chemistry and the attachment of specific functional groups. However, non-covalent functionalization offers an easier, less invasive way to modify graphene's properties, especially for electrical applications. Using the previously mentioned characterization techniques to understand the structure and properties of graphene nanoconjugates is crucial to enhancing their performance. Overall, the development of graphene nanoconjugates has paved the way for new lines of inquiry and innovation across several areas, making it an intriguing topic of study with a wide range of potential applications [75, 101].

4. Applications of Graphene in Drug Delivery

Drug delivery systems based on graphene have demonstrated promise across a range of applications, including cancer treatment, antimicrobial therapy, and regenerative medicine.

4.1. Cancer therapy.

Chemotherapeutic agents can be delivered to tumor cells only using graphene-based nanocomposites, minimizing their damaging side effects on patients' healthy cells.

Additionally, the photothermal and photodynamic properties of graphene can be used to treat cancer, where the drug is released in response to light and reactive oxygen species are produced, killing tumor cells. Graphene has several advantages over traditional cancer therapies, including its ability to target cancer cells, thereby reducing its toxicity to healthy cells [102]. Its unique properties also make it an ideal material for drug delivery, imaging, and sensing in cancer therapy. In addition, graphene and its derivatives have been shown to enhance the effectiveness of chemotherapy drugs by reducing their side effects. Overall, graphene has great potential for cancer therapy and could improve the lives of millions of people worldwide affected by this disease [103-104]. The use of graphene and its substitutes in cancer therapy is presented in Table 1.

Table 1. Application of graphene and its derivatives in cancer therapy.

Cancer and its types	Drugs used in studies	Drugs and carriers in therapy	References
Brain cancer	1,3-bis(2-chloroethyl)-1-nitroso urea	graphene oxide and poly(acrylic acid)	[105]
Brain cancer	Camptothecin	graphene oxide (GO) and poly(N, N-diethylacrylamide)	[106]
Brain cancer	Doxorubicin	GO-PEG-Tf (Transferrin)	[107]
Brain cancer	Epirubicin	NMGO-PEG	[108]
Breast cancer	Doxorubicin with Camptothecin	Acid Folic with nGO	[109]
Breast cancer	Camptothecin	GO-PVA	[110]
Breast cancer	Doxorubicin	GN-PF127 (Pluronic F127)	[111]
Breast cancer	Tomography of TRC105, Positron Emission	Graphene oxide	[112]
Breast cancer	Fluorescence imaging	Graphene oxide-Iron oxide nanoparticles-Poly(amidoamine) dendrimers-Cyanine 5 dye	[113]
Breast cancer	Photoacoustic imaging	Reduced graphene oxide	[114]
Breast cancer	Computed Tomography	graphene oxide	[115]
Cervical cancer	Chlorin e6	GO-PEG	[116]
Cervical cancer	US imaging with CT scanning	Graphene oxide-Gold nanoparticles-Polylactic acid	[117]
Cervical cancer	Doxorubicin	Reduced Graphene Oxide-Cholesteryl Hyaluronic Acid	[118]
Cervical cancer	Doxorubicin, fluorescence imaging	GO-QDs	[119]
Cervical cancer	Curcumin, Camptothecin, Paclitaxol, and Doxorubicin	Nile red lipophilic fluorescent dye-C-folate.	[120]
Cervical cancer	Doxorubicin	GO-PEI	[121]
Cervical cancer	Doxorubicin	PEG-GO/Cus	[122]
Cervical cancer	Fluorescence and MR scanning	Fluorescent and magnetic graphene)	[123]
Lung cancer	Paclitaxel	GO	[124]
Skin cancer	Signal Transducer and Activator of Transcription-siRNA	Graphene Oxide-Polyethyleneimine-Polyethylene Glycol	[125]

4.2. Antimicrobial therapy.

Due to its intrinsic antibacterial qualities, graphene and its derivatives are excellent for developing antimicrobial compositions. Additionally, the coupling of graphene with antimicrobial substances can further enhance their effectiveness, enabling lower dosages and reducing the risk of resistance [126]. Graphene has also been found to possess antimicrobial properties, making it a promising candidate for the development of new antimicrobial treatments. The current antimicrobial therapies are facing challenges due to the emergence of drug-resistant microorganisms. Thus, there is a crucial requisite to form new antimicrobial agents that can effectively combat these pathogens [127-129]. Graphene's antimicrobial activity is attributed to its ability to disrupt the cells of microorganisms. It can also generate reactive oxygen species that can damage microbial DNA and proteins. Studies have shown that graphene can effectively inhibit the growth of various microorganisms, including bacteria, viruses, and fungi. Additionally, graphene is effective against drug-resistant bacteria, such as

MRSA. The possible uses of graphene as an antimicrobial agent are vast and varied [130]. The use of graphene and its substitutes in antimicrobial therapy is presented in Table 2.

Table 2. Application of graphene and its derivatives in antimicrobial therapy.

Name of the synthesis process	Drug used in studies	Carriers in therapy	Reference
Seeded-growth rGO-AuNPs	Carbamazepine	rGO-AuNPs	[131]
Sequential reduction method N2 doped graphene-AuNPs	Ondansetron	N ₂ -doped graphene-AuNPs	[132]
Chemical reduction in micro GO-AuNPs	Tegafur	GO-AuNPs	[133]
Eco-friendly chemical rGO-AuNPs	Tetracycline	rGO-AuNPs	[134]
Reductive deposition process rGO-AuNPs	Graphene Derivatives	rGO-AuNPs	[135]
Chemical reduction	6-thioguanine (6-TG) and 5-fluorouracil (5-FU)	Graphene-AuNPs	[136]
Solution-based chemical reduction	Diclofenac	Graphene-AuNPs	[137]
Green synthesis method	Cisplatin	GO-AuNPs	[138]
Electrostatic self- assembly	Cisplatin	Graphene-AuNPs	[138]
Wet impregnation thermal reduction method	Doxorubicin	Graphene-AuNPs	[139]
Sonochemical reduction	Doxorubicin	Graphene-AuNPs	[139]
simultaneous reduction	Folic acid (FA)	Graphene-AuNPs	[140]

4.3. Regenerative medicine.

Graphene is a desirable material for tissue engineering scaffolds and stem cell therapies due to its biocompatibility and ability to enhance cell adhesion, proliferation, and differentiation. Graphene-based implants have shown promise in promoting bone regeneration, while graphene-based scaffolds can be used to engineer tissues such as skin, cartilage, and muscle. Additionally, graphene's ability to carry drugs and other therapeutic agents could revolutionize drug delivery systems in regenerative medicine. As research into the uses of graphene in regenerative medications continues, it is clear that this material has the potential to transform the field and improve patient health [141]. Graphene applications in tissue-engineering scaffolds for regenerative medicine are presented in Table 3.

Table 3. Graphene application in tissue engineering scaffolds in regenerative medicine.

Material	Analysis	Outcomes	Reference
Carbon nanotubes and graphene	In vitro co-culture of bone mesenchymal stem cells (BMSCs) and in vivo implantation.	Cells in PLLA composite scaffolds with 3 wt% graphene displayed greater expression of proteins linked to osteogenesis, calcium deposition, and type I collagen production.	[142]
Substrate Coated with Graphene Oxide	In vitro osteogenic differentiation of human bone marrow.	On the Ti/GO substrate, human BMMSCs differentiated more osteogenically than on the Ti substrate.	[143]
Graphene oxide-calcium phosphate nanocomposites	Quantitative measurements on bone nodule formation and the immunofluorescence.	In comparison to the separate or combined effects of GO and CaP, the GO-CaP nanocomposite demonstrated greater osteoinductivity.	[144]
Reduced graphene oxide nanoribbon	Immunofluorescence and Alizarin Red analysis.	The osteogenic development of BMSC is accelerated by graphene nanogrids and matches the patterns of the nanogrids.	[145]
Graphene hydrogel	Colorimetric assay	Cell multiplication and adhesion are made possible by graphene 3D hydrogel, demonstrating the graphene hydrogel scaffolds' biocompatibility.	[146]

8. Conclusion

Graphene's remarkable properties and adaptability make it a promising platform for developing innovative pharmaceutical formulations. Despite persistent obstacles, graphene and its alternative materials hold promise for revolutionizing drug delivery, regenerative medicine, and other biomedical applications. Recent studies and technological advancements provide evidence for this. Graphene will be increasingly valuable in the pharmaceutical industry as our

knowledge of its interactions with biological systems expands, potentially leading to new treatments and better patient outcomes.

Author Contributions

Conceptualization, S.B.M. and P.K.V.; Writing-Original draft preparation, S.B.M., P.K.V., and K.V.; Writing-review and editing, S.B.M. and G.J.; Supervision, R.A.G. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
GN	Graphene
rGO	Reduced Graphene Oxide
GQDs	Graphene Quantum Dots
GA	Graphene Aerogel
GNs	Graphene Nanosheets
TR-GO	Thermally Reduced Graphene Oxide
GO	Graphene Oxide
NPs	Nanoparticles
GBNs	Graphene-Based Nanomaterials
PEG	Polyethylene Glycol
PVP	Polyvinylpyrrolidone
DNA	Deoxyribonucleic Acid
HOPG	Highly Oriented Pyrolytic Graphite
pDNA	Plasmid Dna
PEI	Polyethyleneimine

Abbreviation	Definition
DOX	Doxorubicin
CS-GO	Chitosan-Functionalized Go
CPT	Captothecin
FA-NGO	Folic Acid Conjugated-Nanogo
6-arm PEG	Six-Arm Polyethyleneglycol
NIH3T3	Embryonic Mouse Fibroblast Cell Line
TPa	Terapascal
GPa	Grade-Point-Average
K	Kelvin
APIs	Active Pharmaceutical Ingredients
BCNU	1,3-bis(2-chloroethyl)-1-nitroso Urea
GO-PAA	Graphene Oxide Modified By Polyacrylic Acid
GO-PDEA	Graphene oxide (GO) Functionalized Poly(2-(diethylamino) Ethyl methacrylate)
GO-PEG-Tf	Graphene Oxide - Polyethylene glycol - Transferrin
NMGO-PEG	Magnetic Nanographene Oxide - Polyethylene Glycol
GO-PVA	Graphene Oxide - Polyvinyl Alcohol
GO-QDs	Graphene Oxide - Quantum Dots
CNT	Carbon Nanotube
CVD	Chemical Vapor Deposition
Cfu	Colony Forming Unit
AuNC	Gold Nanocrystal
AuNP	Gold Nanoparticle
AuNS	Gold Nanostructure
SERS	Surface Enhanced Raman Spectroscopy/Scattering
3D	Three-Dimensional
2D	Two Dimensional
TEM	Transmission Electron Microscopy
nGO	Nano Graphene Oxide
SEM	Scanning Electron Microscopy

References

- Gomes, P.V.R.; Azeredo, N.F.; Garcia, L.M.; Zambiasi, P.J.; Morselli, G.R.; Ando, R.A.; Otubo, L.; Lazar, D.R.; de Souza, R.F.; Rodrigues, D.F.; Neto, A.O. Layered graphene/hexagonal boron nitride nanosheets (Gr/h-BNNs) applied to the CO₂ photoconversion into methanol. *Appl. Mater. Today*. **2022**, *29*, 101605, <https://doi.org/10.1016/j.apmt.2022.101605>.
- Raju, A.P.A.; Lewis, A.; Derby, B.; Young, R.J.; Kinloch, I.A.; Zan, R.; Novoselov, K.S. Wide-Area Strain Sensors based upon Graphene-Polymer Composite Coatings Probed by Raman Spectroscopy. *Adv. Funct. Mater.* **2014**, *24*, 2865–2874, <https://doi.org/10.1002/adfm.201302869>.
- Alshamkhani, M.T.; Teong, L.K.; Putri, L.K.; Mohamed, A.R.; Lahijani, P.; Mohammadi, M. Effect of graphite exfoliation routes on the properties of exfoliated graphene and its photocatalytic applications. *J. Environ. Chem. Eng.* **2021**, *9*, 106506, <https://doi.org/10.1016/j.jece.2021.106506>.
- Balandin, A.A.; Ghosh, S.; Bao, W.; Calizo, I.; Teweldebrhan, D.; Miao, F.; Lau, C.N. Superior thermal conductivity of single-layer graphene. *Nano Lett.* **2008**, *8*, 902–907, <https://doi.org/10.1021/nl0731872>.
- Xue, Y.; Liu, J.; Chen, H.; Wang, R.; Li, D.; Qu, J.; Dai, L. Nitrogen-doped graphene foams as metal-free counter electrodes in high-performance dye-sensitized solar cells. *Angew Chem Int Ed Engl.* **2012**, *51*, 12124–12127, <https://doi.org/10.1002/anie.201207277>.
- Novoselov, K.S.; Geim, A.K.; Morozov, S.V.; Jiang, D.; Katsnelson, M.I.; Grigorieva, I.V.; Dubonos, S.V.; Firsov, A.A. Two-dimensional gas of massless Dirac fermions in graphene. *Nature* **2005**, *438*, 197–200, <https://doi.org/10.1038/nature04233>.
- Zhu, Y.; Murali, S.; Cai, W.; Li, X.; Suk, J.W.; Potts, J.R.; Ruoff, R.S. Graphene and graphene oxide: synthesis, properties, and applications. *Adv. Mater.* **2010**, *22*, 3906–3924, <https://doi.org/10.1002/adma.201001068>.
- Lee, C.; Wei, X.; Kysar, J.W.; Hone, J. Measurement of the elastic properties and intrinsic strength of monolayer graphene. *Science* **2008**, *321*, 385–388, <https://doi.org/10.1126/science.1157996>.
- Papageorgiou, D.G.; Kinloch, I.A.; Young, R.J. Graphene/elastomer nanocomposites. *Carbon* **2015**, *95*, 460–484, <https://doi.org/10.1016/j.carbon.2015.08.055>.

10. Wang, X.; Zhi, L.; Müllen, K. Transparent, conductive graphene electrodes for dye-sensitized solar cells. *Nano Lett.* **2008**, *8*, 323–327, <https://doi.org/10.1021/nl072838r>.
11. Lin, Y.M.; Jenkins, K.A.; Valdes-Garcia, A.; Small, J.P.; Farmer, D.B.; Avouris, P. Operation of graphene transistors at gigahertz frequencies. *Nano Lett.* **2009**, *9*, 422–426, <https://doi.org/10.1021/nl803316h>.
12. Bunch, J.S.; van der Zande, A.M.; Verbridge, S.S.; Frank, I.W.; Tanenbaum, D.M.; Parpia, J.M.; Craighead, H.G.; McEuen, P.L. Electromechanical resonators from graphene sheets. **2007**, *315*, 490–493, <https://doi.org/10.1126/science.1136836>.
13. Yoo, J.J.; Balakrishnan, K.; Huang, J.; Meunier, V.; Sumpter, B.G.; Srivastava, A.; Conway, M.; Reddy, A.L.; Yu, J.; Vajtai, R.; Ajayan, P.M. Ultrathin planar graphene supercapacitors. *Nano Lett.* **2011**, *11*, 1423–1427, <https://doi.org/10.1021/nl200225j>.
14. Patchkovskii, S.; Tse, J.S.; Yurchenko, S.N.; Zhechkov, L.; Heine, T.; Seifert, G. Graphene nanostructures as tunable storage media for molecular hydrogen. *Proc. Natl. Acad. Sci. U.S.A.* **2005**, *102*, 10439–10444, <https://doi.org/10.1073/pnas.0501030102>.
15. Farhana, K.; Kadirgama, K.; Subramonian, S.; Ramasamy, D.; Samykan, M.; Mahamude, A.S.F. Applications of Graphene Nanomaterials in Energy Storage—A State-of-Art Short Review. In Proceedings of the Technological Advancement in Mechanical and Automotive Engineering, Singapore, 2023//, Ismail, M.Y., Mohd Sani, M.S., Kumarasamy, S., Hamidi, M.A., Shaari, M.S., Eds.; Springer, Singapore, **2023**; pp. 595-609, https://doi.org/10.1007/978-981-19-1457-7_46.
16. Miao, X.; Tongay, S.; Petterson, M.K.; Berke, K.; Rinzler, A.G.; Appleton, B.R.; Hebard, A.F. High efficiency graphene solar cells by chemical doping. *Nano Lett.* **2012**, *12*, 2745–2750, <https://doi.org/10.1021/nl204414u>.
17. Jia, X.; Campos-Delgado, J.; Terrones, M.; Meunier, V.; Dresselhaus, M.S. Graphene edges: a review of their fabrication and characterization. *Nanoscale* **2011**, *3*, 86–95, <https://doi.org/10.1039/c0nr00600a>.
18. Shen, J.; Zhu, Y.; Yang, X.; Li, C. Graphene quantum dots: emergent nanolights for bioimaging, sensors, catalysis and photovoltaic devices. *Chem. Commun.* **2012**, *48*, 3686-99, <https://doi.org/10.1039/C2CC00110A>.
19. Xu, Y.; Sheng, K.; Li, C.; Shi, G. Self-assembled graphene hydrogel via a one-step hydrothermal process. *ACS nano* **2010**, *4*, 4324–4330, <https://doi.org/10.1021/nn101187z>.
20. Wu, Z.S.; Sun, Y.; Tan, Y.Z.; Yang, S.; Feng, X.; Müllen, K. Three-dimensional graphene-based macro- and mesoporous frameworks for high-performance electrochemical capacitive energy storage. *J. Am. Chem. Soc.* **2012**, *134*, 19532–19535, <https://doi.org/10.1021/ja308676h>.
21. Farhana, K.; Kadirgama, K.; Rahman, M.M.; Ramasamy, D.; Noor, M.M.; Najafi, G.; Samykan, M.; Mahamude, A.S. Improvement in the performance of solar collectors with nanofluids—A state-of-the-art review. *Nano-Struct. Nano-Objects* **2019**, *18*, 1-21, <https://doi.org/10.1016/j.nanoso.2019.100276>.
22. Mahamude, A.S.F.; Harun, W.S.W.; Kadirgama, K.; Ramasamy, D.; Farhana, K.; Saleh, K.; Yusaf, T. Experimental Study on the Efficiency Improvement of Flat Plate Solar Collectors Using Hybrid Nanofluids Graphene/Waste Cotton. *Energies* **2022**, *15*, 2309, <https://doi.org/10.3390/en15072309>.
23. Shahriari, S.; Sastry, M.; Panjkar, S.; Singh Raman, R.K. Graphene and Graphene Oxide as a Support for Biomolecules in the Development of Biosensors. *Nanotechnol. Sci. Appl.* **2021**, *14*, 197–220, <https://doi.org/10.2147/NSA.S334487>.
24. Wallace, P.R. The band theory of graphite. *Phys. Rev.* **1947**, *71*, 622, <https://doi.org/10.1103/PhysRev.71.622>.
25. Novoselov, K.S.; Geim, A.K.; Morozov, S.V.; Jiang, D.; Zhang, Y.; Dubonos, S.V.; Grigorieva, I.V.; Firsov, A.A. Electric field effect in atomically thin carbon films. *Science* **2004**, *306*, 666–669, <https://doi.org/10.1126/science.1102896>.
26. Muthoosamy, K.; Manickam, S. State of the art and recent advances in the ultrasound-assisted synthesis, exfoliation and functionalization of graphene derivatives. *Ultrason. Sonochem.* **2007**, *39*, 478–493, <https://doi.org/10.1016/j.ultsonch.2017.05.019>.
27. Dreyer, D.R.; Ruoff, R.S.; Bielawski, C.W. From conception to realization: an historical account of graphene and some perspectives for its future. *Angewandte Chemie* **2010**, *49*, 9336–9344, <https://doi.org/10.1002/anie.201003024>.
28. “With collaboration, possibility is limitless”: Graphene Flagship to join Euro Nano Forum 2023. Available online: <https://graphene-flagship.eu/materials/news/with-collaboration-possibility-is-limitless-graphene-flagship-to-join-euro-nano-forum-2023/> (accessed on 3 December **2024**).

29. Lin, J.; Chen, X.; Huang, P. Graphene-based nanomaterials for bioimaging. *Adv. Drug Deliv. Rev.* **2016**, *105*, 242–254, <https://doi.org/10.1016/j.addr.2016.05.013>.
30. Garrido, M.; Naranjo, A.; Pérez, E.M. Characterization of emerging 2D materials after chemical functionalization. *Chem. Sci.* **2024**, *15*, 3428–3445, <https://doi.org/10.1039/d3sc05365b>.
31. Kim, T.H.; Lee, T.; El-Said, W.A.; Choi, J.W. Graphene-Based Materials for Stem Cell Applications. *Materials* **2015**, *8*, 8674–8690, <https://doi.org/10.3390/ma8125481>.
32. Ren, H.; Tang, M.; Guan, B.; Wang, K.; Yang, J.; Wang, F.; Wang, M.; Shan, J.; Chen, Z.; Wei, D.; Peng, H.; Liu, Z. Hierarchical Graphene Foam for Efficient Omnidirectional Solar-Thermal Energy Conversion. *Adv Mater.* **2017**, *29*, 1702590, <https://doi.org/10.1002/adma.201702590>.
33. Kothandam, G.; Singh, G.; Guan, X.; Lee, J.M.; Ramadass, K.; Joseph, S.; Benzigar, M.; Karakoti, A.; Yi, J.; Kumar, P.; Vinu, A. Recent Advances in Carbon-Based Electrodes for Energy Storage and Conversion. *Adv. Sci.* **2023**, *10*, e2301045. <https://doi.org/10.1002/advs.202301045>.
34. Lin, H.; Buerki-Thurnherr, T.; Kaur, J.; Wick, P.; Pelin, M.; Tubaro, A.; Carniel, F.C.; Tretiach, M.; Flahaut, E.; Iglesias, D.; Vázquez, E.; Cellot, G.; Ballerini, L.; Castagnola, V.; Benfenati, F.; Armirotti, A.; Sallustrau, A.; Taran, F.; Keck, M.; Bussy, C.; Bianco, A. Environmental and Health Impacts of Graphene and Other Two-Dimensional Materials: A Graphene Flagship Perspective. *ACS Nano* **2024**, *18*, 6038–6094, <https://doi.org/10.1021/acsnano.3c09699>.
35. Dasari Shareena, T.P.; McShan, D.; Dasmahapatra, A.K., Tchounwou, P.B. A Review on Graphene-Based Nanomaterials in Biomedical Applications and Risks in Environment and Health. *Nano-Micro Lett.* **2018**, *10*, 53, <https://doi.org/10.1007/s40820-018-0206-4>.
36. Dujardin, E.; Ebbesen, T.W.; Hiura, H.; Tanigaki, K. Capillarity and wetting of carbon nanotubes. *Science* **1994**, *265*, 1850–1852, <https://doi.org/10.1126/science.265.5180.1850>.
37. Yang, G.; Li, L.; Lee, W.B.; Ng, M.C. Structure of graphene and its disorders: a review. *STAM* **2018**, *19*, 613–648, <https://doi.org/10.1080/14686996.2018.1494493>.
38. Al Faruque, M.A.; Syduzzaman, M.; Sarkar, J.; Bilisik, K.; Naebe, M. A Review on the Production Methods and Applications of Graphene-Based Materials. *Nanomaterials* **2021**, *11*, 2414, <https://doi.org/10.3390/nano11092414>.
39. Sanchez, J.; Lamichhane, B.; Sutherland, K.; Kattel, S.; Xu, F. Initial Carbonation of Ni(111) Surfaces. *ACS Appl. Mater. Interfaces* **2025**, *17*, 5439–5445, <https://doi.org/10.1021/acсами.4c16639>.
40. Eizenberg, M.; Blakely, J.M. Carbon interaction with nickel surfaces: Monolayer formation and structural stability. *J Chem Phys.* **1979**, *71*, 3467–3477, <https://doi.org/10.1063/1.43873>.
41. Shim, G.; Kim, M. G.; Park, J.Y.; Oh, Y.K. Graphene-based nanosheets for delivery of chemotherapeutics and biological drugs. *Adv. Drug Deliv. Rev.* **2016**, *105*, 205–227, <https://doi.org/10.1016/j.addr.2016.04.004>.
42. McCann, E. Electronic Properties of Monolayer and Bilayer Graphene. In *Graphene Nanoelectronics: Metrology, Synthesis, Properties and Applications*, Raza, H., Ed.; Springer Berlin Heidelberg: Berlin, Heidelberg, **2012**; pp. 237–275, https://doi.org/10.1007/978-3-642-22984-8_8.
43. Novoselov, K.S.; Jiang, D.; Schedin, F.; Booth, T.J.; Khotkevich, V.V.; Morozov, S.V., Geim, A.K. Two-dimensional atomic crystals. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 10451–10453, <https://doi.org/10.1073/pnas.0502848102>.
44. Boehm HP, Setton R, Stumpp E. Nomenclature and terminology of graphite intercalation compounds (IUPAC Recommendations 1994). *Pure Appl. Chem.* **1994**, *66*, 1893–1901, <http://dx.doi.org/10.1351/pac199466091893>.
45. Jana, A.; Scheer, E.; Polarz, S. Synthesis of graphene-transition metal oxide hybrid nanoparticles and their application in various fields. *Beilstein J. Nanotechnol.* **2017**, *8*, 688–714, <https://doi.org/10.3762/bjnano.8.74>.
46. Eizenberg, M.; Blakely, J.M. Carbon interaction with nickel surfaces: Monolayer formation and structural stability. *J. Chem. Phys.* **1979**, *71*, 3467–77, <https://doi.org/10.1063/1.438736>.
47. Lang, B. A LEED study of the deposition of carbon on platinum crystal surfaces. *Surf. Sci.* **1975**, *53*, 317–29, [https://doi.org/10.1016/0039-6028\(75\)90132-6](https://doi.org/10.1016/0039-6028(75)90132-6).
48. Agharkar, M.; Kochrekar, S.; Hidouri, S.; Azeez, M.A. Trends in green reduction of graphene oxides, issues and challenges: a review. *Mater. Res. Bull.* **2014**, *59*, 323–8, <https://doi.org/10.1016/j.materresbull.2014.07.051>.
49. Vinoth Kumar, S.H.B.; Muydinov, R.; Szyszka, B. Plasma Assisted Reduction of Graphene Oxide Films. *Nanomaterials* **2021**, *11*, 382, <https://doi.org/10.3390/nano11020382>.

50. Bellier, N.; Baipaywad, P.; Ryu, N.; Lee, J.Y.; Park, H. Recent biomedical advancements in graphene oxide- and reduced graphene oxide-based nanocomposite nanocarriers. *Biomater. Res.* **2022**, *26*, 65, <https://doi.org/10.1186/s40824-022-00313-2>.
51. Lu, X.; Yu, M.; Huang, H.; Ruoff, R.S. Tailoring graphite with the goal of achieving single sheets. *Nanotechnology* **1999**, *10*, 269, <https://doi.org/10.1088/0957-4484/10/3/308>.
52. Zhang, Y.; Small, J.P.; Pontius, W.V.; Kim, P. Fabrication and electric-field-dependent transport measurements of mesoscopic graphite devices. *Appl. Phys. Lett.* **2005**, *86*, 073104, <https://doi.org/10.1063/1.1862334>.
53. Shi, S.; Chen, F.; Ehlerding, E.B.; Cai, W. Surface engineering of graphene-based nanomaterials for biomedical applications. *Bioconjug Chem.* **2014**, *25*, 1609–1619, <https://doi.org/10.1021/bc500332c>.
54. Wu, S.Y.; An, S.S.; Hulme, J. Current applications of graphene oxide in nanomedicine. *Int. J. Nanomed.* **2015**, *10*, 9–24, <https://doi.org/10.2147/IJN.S88285>.
55. Kim, H.; Namgung, R.; Singha, K.; Oh, I.K.; Kim, W.J. Graphene oxide-polyethylenimine nanoconstruct as a gene delivery vector and bioimaging tool. *Bioconjug Chem.* **2011**, *22*, 2558–2567, <https://doi.org/10.1021/bc200397j>.
56. Zhang, L.; Lu, Z.; Zhao, Q.; Huang, J.; She., Zhang, Z. Enhanced chemotherapy efficacy by sequential delivery of siRNA and anticancer drugs using PEI-grafted graphene oxide. *Small* **2011**, *7*, 460–464, <https://doi.org/10.1002/sml.201001522>.
57. Bao, H.; Pan, Y.; Ping, Y.; Sahoo, N.G.; Wu, T.; Li, L.; Li, J.; Gan, L.H. Chitosan-functionalized graphene oxide as a nanocarrier for drug and gene delivery. *Small* **2011**, *7*, 1569–1578, <https://doi.org/10.1002/sml.201100191>.
58. Zainal-Abidin, M.H.; Hayyan, M.; Ngoh, G.C.; Wong, W.F. Doxorubicin Loading on Functional Graphene as a Promising Nanocarrier Using Ternary Deep Eutectic Solvent Systems. *ACS omega* **2020**, *5*, 1656–1668, <https://doi.org/10.1021/acsomega.9b03709>.
59. Zhang, L.; Xia, J.; Zhao, Q.; Liu, L.; Zhang, Z. Functional graphene oxide as a nanocarrier for controlled loading and targeted delivery of mixed anticancer drugs. *Small* **2010**, *6*, 537–544, <https://doi.org/10.1002/sml.200901680>.
60. Khan, M.U.A.; Yaqoob, Z.; Ansari, M.N.M.; Razak, S.I.A.; Raza, M.A.; Sajjad, A.; Haider, S.; Busra, F.M. Chitosan/Poly Vinyl Alcohol/Graphene Oxide Based pH-Responsive Composite Hydrogel Films: Drug Release, Anti-Microbial and Cell Viability Studies. *Polymers* **2021**, *13*, 3124, <https://doi.org/10.3390/polym13183124>.
61. Liu, Z.; Robinson, J.T.; Sun, X.; Dai, H. PEGylated nanographene oxide for delivery of water-insoluble cancer drugs. *J. Am. Chem. Soc.* **2008**, *130*, 10876–10877, <https://doi.org/10.1021/ja803688x>.
62. Sun, X.; Liu, Z.; Welsher, K.; Robinson, J.T.; Goodwin, A.; Zaric, S.; Dai, H. Nanographene Oxide for Cellular Imaging and Drug Delivery. *Nano Res.* **2008**, *1*, 203–212, <https://doi.org/10.1007/s12274-008-8021-8>.
63. Yang, K.; Zhang, S.; Zhang, G.; Sun, X.; Lee, S.T.; Liu, Z. Graphene in mice: ultrahigh in vivo tumor uptake and efficient photothermal therapy. *Nano Lett.* **2010**, *10*, 3318–3323, <https://doi.org/10.1021/nl100996u>.
64. Markovic, Z.M.; Harhaji-Trajkovic, L.M.; Todorovic-Markovic, B.M.; Kepić, D.P.; Arsin, K.M., Jovanović, S.P.; Pantovic, A.C.; Dramićanin, M.D.; Trajkovic, V.S. In vitro comparison of the photothermal anticancer activity of graphene nanoparticles and carbon nanotubes. *Biomaterials* **2011**, *32*, 1121–1129, <https://doi.org/10.1016/j.biomaterials.2010.10.030>.
65. Zhang, W.; Guo, Z.; Huang, D.; Liu, Z.; Guo, X.; Zhong, H. Synergistic effect of chemo-photothermal therapy using PEGylated graphene oxide. *Biomaterials* **2011**, *32*, 8555–8561, <https://doi.org/10.1016/j.biomaterials.2011.07.071>.
66. Huang, P.; Xu, C.; Lin, J.; Wang, C.; Wang, X.; Zhang, C.; Zhou, X.; Guo, S.; Cui, D. Folic Acid-conjugated Graphene Oxide loaded with Photosensitizers for Targeting Photodynamic Therapy. *Theranostics* **2011**, *1*, 240–250, <https://doi.org/10.7150/thno/v01p0240>.
67. Vallejo, W.; Rueda, A.; Díaz-Urbe, C.; Grande, C.; Quintana, P. Photocatalytic activity of graphene oxide-TiO₂ thin films sensitized by natural dyes extracted from *Bactris guineensis*. *R. Soc. Open Sci.* **2019**, *6*, 181824, <https://doi.org/10.1098/rsos.181824>.
68. Liu, S.; Zeng, T.H.; Hofmann, M.; Burcombe, E.; Wei, J.; Jiang, R.; Kong, J.; Chen, Y. Antibacterial activity of graphite, graphite oxide, graphene oxide, and reduced graphene oxide: membrane and oxidative stress. *ACS Nano* **2011**, *5*, 6971–6980, <https://doi.org/10.1021/nn202451x>.

69. Ruiz, O.N.; Fernando, K.A.; Wang, B.; Brown, N.A.; Luo, P.G.; McNamara, N.D.; Vangsness, M.; Sun, Y.P.; Bunker, C.E. Graphene oxide: a nonspecific enhancer of cellular growth. *ACS Nano* **2011**, *5*, 8100–8107, <https://doi.org/10.1021/nn202699t>.
70. Ryoo, S.R.; Kim, Y.K.; Kim, M.H.; Min, D.H. Behaviors of NIH-3T3 fibroblasts on graphene/carbon nanotubes: proliferation, focal adhesion, and gene transfection studies. *ACS Nano* **2010**, *4*, 6587–6598. <https://doi.org/10.1021/nn1018279>.
71. Fan, H.; Wang, L.; Zhao, K.; Li, N.; Shi, Z.; Ge, Z.; Jin, Z. Fabrication, mechanical properties, and biocompatibility of graphene-reinforced chitosan composites. *Biomacromolecules* **2010**, *11*, 2345–2351, <https://doi.org/10.1021/bm100470q>.
72. Li, N.; Zhang, X.; Song, Q.; Su, R.; Zhang, Q.; Kong, T.; Liu, L.; Jin, G.; Tang, M.; Cheng, G. The promotion of neurite sprouting and outgrowth of mouse hippocampal cells in culture by graphene substrates. *Biomaterials* **2011**, *32*, 9374–9382, <https://doi.org/10.1016/j.biomaterials.2011.08.065>.
73. Priyadarsini, S.; Mohanty, S.; Mukherjee, S.; Basu, S.; Mishra, M. Graphene and graphene oxide as nanomaterials for medicine and biology application. *J. Nanostruct. Chem.* **2018**, *8*, 123-37, <https://doi.org/10.1007/s40097-018-0265-6>.
74. Magne, T.M.; de Oliveira Vieira, T.; Alencar, L.M.R.; Junior, F.F.M.; Gemini-Piperni, S.; Carneiro, S.V.; Fechine, L.M.U.D.; Freire, R.M.; Golokhvast, K.; Metrangolo, P.; Fechine, P.B.A.; Santos-Oliveira, R. Graphene and its derivatives: understanding the main chemical and medicinal chemistry roles for biomedical applications. *J. Nanostructure Chem.* **2022**, *12*, 693–727, <https://doi.org/10.1007/s40097-021-00444-3>.
75. Chakraborty, M.; Hashmi, M.S.J. Graphene as a Material – An Overview of Its Properties and Characteristics and Development Potential for Practical Applications. In Reference Module in Materials Science and Materials Engineering; Elsevier: **2018**; <https://doi.org/10.1016/B978-0-12-803581-8.10319-4>.
76. Mikhlin, Y.; Likhatski, M.; Borisov, R.; Karpov, D.; Vorobyev, S. Metal Chalcogenide-Hydroxide Hybrids as an Emerging Family of Two-Dimensional Heterolayered Materials: An Early Review. *Materials* **2023**, *16*, 6381, <https://doi.org/10.3390/ma16196381>.
77. Lim, S.; Park, H.; Yamamoto, G.; Lee, C.; Suk, J.W. Measurements of the Electrical Conductivity of Monolayer Graphene Flakes Using Conductive Atomic Force Microscopy. *Nanomaterials* **2021**, *11*, 2575, <https://doi.org/10.3390/nano11102575>.
78. Fang, C.; Zhang, J.; Chen, X.; Weng, G.J. Calculating the Electrical Conductivity of Graphene Nanoplatelet Polymer Composites by a Monte Carlo Method. *Nanomaterials* **2020**, *10*, 1129, <https://doi.org/10.3390/nano10061129>.
79. López-Polín, G.; Gómez-Navarro, C.; Parente, V.; Guinea, F.; Katsnelson, M.I.; Perez-Murano, F.; Gómez-Herrero, J. Increasing the elastic modulus of graphene by controlled defect creation. *Nature Phys.* **2015**, *11*, 26-31, <https://doi.org/10.1038/nphys3183>.
80. Shao, T.; Wen, B.; Melnik, R.; Yao, S.; Kawazoe, Y.; Tian, Y. Temperature dependent elastic constants and ultimate strength of graphene and graphyne. *J. Chem. Phys.* **2012**, *137*, 194901, <https://doi.org/10.1063/1.4766203>.
81. Szczeńniak, B.; Choma, J.; Jaroniec, M. Gas adsorption properties of graphene-based materials. *Adv. Colloid Interface Sci.* **2017**, *243*, 46–59, <https://doi.org/10.1016/j.cis.2017.03.007>.
82. Cao, Y.; Li, X. Adsorption of graphene for the removal of inorganic pollutants in water purification: a review. *Adsorption* **2014**, *20*, 713-27, <https://doi.org/10.1007/s10450-014-9615-y>.
83. Wang, X.; Liu, B.; Lu, Q.; Qu, Q. Graphene-based materials: fabrication and application for adsorption in analytical chemistry. *J. Chromatography. A* **2014**, *1362*, 1–15, <https://doi.org/10.1016/j.chroma.2014.08.023>.
84. Ersan, G.; Apul, O.G.; Perreault, F.; Karanfil, T. Adsorption of organic contaminants by graphene nanosheets: A review. *Water Res.* **2017**, *126*, 385–398, <https://doi.org/10.1016/j.watres.2017.08.010>.
85. Jiang, T.; Sun, W.; Zhu, Q.; Burns, N. A.; Khan, S.A.; Mo, R.; Gu, Z. Furin-mediated sequential delivery of anticancer cytokine and small-molecule drug shuttled by graphene. *Adv. Mater.* **2015**, *27*, 1021–1028, <https://doi.org/10.1002/adma.201404498>.
86. Li, W.; Zhang, G.; Wei, X. Lidocaine-loaded reduced graphene oxide hydrogel for prolongation of effects of local anesthesia: *In vitro* and *in vivo* analyses. *J. Biomater. Appl.* **2021**, *35*, 1034–1042, <https://doi.org/10.1177/0885328220988462>.
87. Dubey, N.K.; Mishra, S.B.; Mukerjee, A.; Singh, A.K. Graphene conjugated usnic acid nano-formulation for the treatment of topical fungal infection. *Int. J. Pharm. Pharm. Sci.* **2020**, *12*, 47-53, <https://doi.org/10.22159/ijpps.2020v12i5.34724>.

88. Chhabra, P.; Chauhan, G.; Kumar, A. Augmented healing of full thickness chronic excision wound by rosmarinic acid loaded chitosan encapsulated graphene nanopockets. *Drug Dev. Ind. Pharm.* **2020**, *46*, 878–888, <https://doi.org/10.1080/03639045.2020.1762200>.
89. Qiao, W.; Wang, L.; Ye, B.; Li, G.; Li, J. Electrochemical behavior of palmatine and its sensitive determination based on an electrochemically reduced L-methionine functionalized graphene oxide modified electrode. *Analyst* **2015**, *140*, 7974–7983, <https://doi.org/10.1039/c5an01770j>.
90. Yousuf, S.; Arjmand, F.; Siddique, H.R.; Ali, M.S.; Al-Lohedan, H.A.; Tabassum, S. Biophysical binding profile with ct-DNA and cytotoxic studies of a modulated nanoconjugate of umbelliferone cobalt oxide loaded on graphene oxide (GO) as drug carrier. *J. Biomol. Struct. Dyn.* **2022**, *40*, 4558–4569, <https://doi.org/10.1080/07391102.2020.1860821>.
91. Gollavelli, G.; Ghule, A.V.; & Ling, Y.C. Multimodal Imaging and Phototherapy of Cancer and Bacterial Infection by Graphene and Related Nanocomposites. *Molecules* **2022**, *27*, 5588, <https://doi.org/10.3390/molecules27175588>.
92. Qin, X.C.; Guo, Z.Y.; Liu, Z.M.; Zhang, W.; Wan, M.M.; Yang, B.W. Folic acid-conjugated graphene oxide for cancer targeted chemo-photothermal therapy. *J. Photochem. Photobiol. B* **2013**, *120*, 156–162, <https://doi.org/10.1016/j.jphotobiol.2012.12.005>.
93. Hu, Z.; Huang, Y.; Sun, S.; Guan, W.; Yao, Y.; Tang, P.; Li, C. Visible light driven photodynamic anticancer activity of graphene oxide/TiO₂ hybrid. *Carbon* **2012**, *50*, 994–1004, <https://doi.org/10.1016/j.carbon.2011.10.002>.
94. Khadair, A.; Gerard, B.; Handa, H.; Mao, G.; Shekhar, M.P.; Panyam, J. Surfactant-polymer nanoparticles enhance the effectiveness of anticancer photodynamic therapy. *Mol. Pharm.* **2008**, *5*, 795–807, <https://doi.org/10.1021/mp800026t>.
95. Lu, Y.J.; Yang, H.W.; Hung, S.C.; Huang, C.Y.; Li, S.M.; Ma, C.C.; Chen, P.Y.; Tsai, H.C.; Wei, K.C.; Chen, J.P. Improving thermal stability and efficacy of BCNU in treating glioma cells using PAA-functionalized graphene oxide. *Int. J. Nanomed.* **2012**, *7*, 1737–1747, <https://doi.org/10.2147/IJN.S29376>.
96. Kavitha, T.; Abdi, S.I.; Park, S.Y. pH-sensitive nanocargo based on smart polymer functionalized graphene oxide for site-specific drug delivery. *Phys. Chem. Chem. Phys.* **2013**, *15*, 5176–85, <https://doi.org/10.1039/C3CP00008G>.
97. Liu, G.; Shen, H.; Mao, J.; Zhang, L.; Jiang, Z.; Sun, T.; Lan, Q.; Zhang, Z. Transferrin modified graphene oxide for glioma-targeted drug delivery: in vitro and in vivo evaluations. *ACS Appl. Mater. Interface* **2013**, *5*, 6909–6914, <https://doi.org/10.1021/am402128s>.
98. Yang, H.W.; Hua, M.Y.; Hwang, T.L.; Lin, K.J.; Huang, C.Y.; Tsai, R.Y.; Ma, C.C.; Hsu, P.H.; Wey, S.P.; Hsu, P.W.; Chen, P.Y. Non-invasive synergistic treatment of brain tumors by targeted chemotherapeutic delivery and amplified focused ultrasound-hyperthermia using magnetic nanographene oxide. *Adv. Mater.* **2013**, *25*, 3605–11, <https://doi.org/10.1002/adma.201301046>.
99. Sahoo, N.G.; Bao, H.; Pan, Y.; Pal, M.; Kakran, M.; Cheng, H.K.; Li, L.; Tan, L.P. Functionalized carbon nanomaterials as nanocarriers for loading and delivery of a poorly water-soluble anticancer drug: a comparative study. *Chem. Commun.* **2011**, *47*, 5235–7, <https://doi.org/10.1039/C1CC00075F>.
100. Hu, H.; Yu, J.; Li, Y.; Zhao, J.; Dong, H. Engineering of a novel pluronic F127/graphene nanohybrid for pH responsive drug delivery. *J. Biomed. Mater. Res. A* **2012**, *100*, 141–148, <https://doi.org/10.1002/jbm.a.33252>.
101. Hong, H.; Yang, K.; Zhang, Y.; Engle, J.W.; Feng, L.; Yang, Y.; Nayak, T.R.; Goel, S.; Bean, J.; Theuer, C.P.; Barnhart, T.E.; Liu, Z.; Cai, W. In vivo targeting and imaging of tumor vasculature with radiolabeled, antibody-conjugated nanographene. *ACS Nano* **2012**, *6*, 2361–2370, <https://doi.org/10.1021/nn204625e>.
102. Wate, P.S.; Banerjee, S.S.; Jalota-Badhwar, A.; Mascarenhas, R.R.; Zope, K.R.; Khandare, J.; Misra, R.D. Cellular imaging using biocompatible dendrimer-functionalized graphene oxide-based fluorescent probe anchored with magnetic nanoparticles. *Nanotechnology* **2012**, *23*, 415101, <https://doi.org/10.1088/0957-4484/23/41/415101>.
103. Sheng, Z.; Song, L.; Zheng, J.; Hu, D.; He, M.; Zheng, M.; Gao, G.; Gong, P.; Zhang, P.; Ma, Y.; Cai, L. Protein-assisted fabrication of nano-reduced graphene oxide for combined in vivo photoacoustic imaging and photothermal therapy. *Biomaterials* **2013**, *34*, 5236–5243, <https://doi.org/10.1016/j.biomaterials.2013.03.090>.
104. Adetunji, C.O.; Ogundolie, F.A.; Mathew, J.T.; Inobeme, A.; Titilayo, O.; Olaniyan, O.T.; Ijobadeniyi, O.A.; Ajiboye, M.D.; Ajayi, O.O.; Dauda, W.; Ghazanfar, S.; Adetunji, J.B. Chapter 12 - Graphene-based nanomaterials for targeted drug delivery and tissue engineering. In *Novel Platforms for Drug Delivery*

- Applications, Das, S., Thomas, S., Das, P.P., Eds.; Woodhead Publishing: **2023**; pp. 277-288, <https://doi.org/10.1016/B978-0-323-91376-8.00014-8>.
105. Tian, B.; Wang, C.; Zhang, S.; Feng, L.; Liu, Z. Photothermally enhanced photodynamic therapy delivered by nanographene oxide. *ACS Nano* **2011**, *5*, 7000–7009, <https://doi.org/10.1021/nn201560b>.
106. Jin, Y.; Wang, J.; Ke, H.; Wang, S.; Dai, Z. Graphene oxide modified PLA microcapsules containing gold nanoparticles for ultrasonic/CT bimodal imaging guided photothermal tumor therapy. *Biomaterials* **2013**, *34*, 4794–4802, <https://doi.org/10.1016/j.biomaterials.2013.03.027>.
107. Miao, W.; Shim, G.; Kang, C.M.; Lee, S.; Choe, Y.S., Choi, H.G., Oh, Y.K. Cholesteryl hyaluronic acid-coated, reduced graphene oxide nanosheets for anti-cancer drug delivery. *Biomaterials* **2013**, *34*, 9638–9647, <https://doi.org/10.1016/j.biomaterials.2013.08.058>.
108. Chen, M.L.; He, Y.J.; Chen, X.W.; Wang, J.H. Quantum-dot-conjugated graphene as a probe for simultaneous cancer-targeted fluorescent imaging, tracking, and monitoring drug delivery. *Bioconjug Chem.* **2013**, *24*, 387–397, <https://doi.org/10.1021/bc3004809>.
109. Han, F.; Wang, J.; Ding, L.; Hu, Y.; Li, W.; Yuan, Z.; Guo, Q.; Zhu, C.; Yu, L.; Wang, H.; Zhao, Z.; Jia, L.; Li, J.; Yu, Y.; Zhang, W.; Chu, G.; Chen, S.; Li, B. Tissue Engineering and Regenerative Medicine: Achievements, Future, and Sustainability in Asia. *Front. Bioeng. Biotechnol.* **2020**, *8*, 83, <https://doi.org/10.3389/fbioe.2020.00083>.
110. Chen, H.; Wang, Z.; Zong, S.; Wu, L.; Chen, P.; Zhu, D.; Wang, C.; Xu, S.; Cui, Y. SERS-fluorescence monitored drug release of a redox-responsive nanocarrier based on graphene oxide in tumor cells. *ACS Appl. Mater. Interfaces* **2014**, *6*, 17526–17533, <https://doi.org/10.1021/am505160v>.
111. Bai, J.; Liu, Y.; Jiang, X. Multifunctional PEG-GO/CuS nanocomposites for near-infrared chemophotothermal therapy. *Biomaterials* **2014**, *35*, 5805–5813, <https://doi.org/10.1016/j.biomaterials.2014.04.008>.
112. Gollavelli, G.; Ling, Y.C. Magnetic and fluorescent graphene for dual modal imaging and single light induced photothermal and photodynamic therapy of cancer cells. *Biomaterials* **2014**, *35*, 4499–4507, <https://doi.org/10.1016/j.biomaterials.2014.02.011>.
113. Arya, N.; Arora, A.; Vasu, K.S.; Sood, A.K.; Katti, D.S. Combination of single walled carbon nanotubes/graphene oxide with paclitaxel: a reactive oxygen species mediated synergism for treatment of lung cancer. *Nanoscale* **2013**, *5*, 2818-29, <https://doi.org/10.1039/C3NR33190C>.
114. Yin, D.; Li, Y.; Lin, H.; Guo, B.; Du, Y.; Li, X.; Jia, H.; Zhao, X.; Tang, J.; Zhang, L. Functional graphene oxide as a plasmid-based Stat3 siRNA carrier inhibits mouse malignant melanoma growth in vivo. *Nanotechnology* **2013**, *24*, 105102, <https://doi.org/10.1088/0957-4484/24/10/105102>.
115. Depan, D.; Shah, J.; Misra, R.D. Controlled release of drug from folate-decorated and graphene mediated drug delivery system: Synthesis, loading efficiency, and drug release response. *Mater. Sci. Eng. C* **2011**, *31*, 1305-12, <https://doi.org/10.1016/j.msec.2011.04.010>.
116. Murakami, T.; Tsuchida, K. Recent advances in inorganic nanoparticle-based drug delivery systems. *Mini-Rev. Med. Chem.* **2008**, *8*, 175–183, <https://doi.org/10.2174/138955708783498078>.
117. Mauri, E.; Salvati, A.; Cataldo, A.; Mozetic, P.; Basoli, F.; Abbruzzese, F.; Trombetta, M.; Bellucci, S.; Rainer, A. Graphene-laden hydrogels: A strategy for thermally triggered drug delivery. *Mater. Sci. Eng. C Mater. Biol. Appl.* **2021**, *118*, 111353, <https://doi.org/10.1016/j.msec.2020.111353>.
118. Ezzati, N.; Mahjoub, A.R.; Shokrollahi, S.; Amiri, A.; Abolhosseini Shahrnoy, A. Novel Biocompatible Amino Acids-Functionalized Three-dimensional Graphene Foams: As the Attractive and Promising Cisplatin Carriers for Sustained Release Goals. *Int. J. Pharm.* **2020**, *589*, 119857, <https://doi.org/10.1016/j.ijpharm.2020.119857>.
119. Tiwari, G.; Tiwari, R.; Sriwastawa, B.; Bhati, L.; Pandey, S.; Pandey, P.; Bannerjee, S.K. Drug delivery systems: An updated review. *Int. J. Pharm. Invest.* **2012**, *2*, 2–11, <https://doi.org/10.4103/2230-973X.96920>.
120. Gong, P.; Zhou, Y.; Li, H.; Zhang, J.; Wu, Y.; Zheng, P.; Jiang, Y. Theoretical Study on the Aggregation and Adsorption Behaviors of Anticancer Drug Molecules on Graphene/Graphene Oxide Surface. *Molecules* **2022**, *27*, 6742, <https://doi.org/10.3390/molecules27196742>.
121. Li, H.; Jia, Y.; Liu, C. RETRACTED: Pluronic® F127 stabilized reduced graphene oxide hydrogel for transdermal delivery of ondansetron: Ex vivo and animal studies. *Colloids Surf. B Biointerfaces* **2020**, *195*, 111259, <https://doi.org/10.1016/j.colsurfb.2020.111259>.
122. Shahabi, M.; Raissi, H. Payload delivery of anticancer drug Tegafur with the assistance of graphene oxide nanosheet during biomembrane penetration: Molecular dynamics simulation survey. *Appl. Surf. Sci.* **2020**, *517*, 146186, <https://doi.org/10.1016/j.apsusc.2020.146186>.

123. Castillo-Henríquez, L.; Castro-Alpízar, J.; Lopretti-Correa, M.; Vega-Baudrit, J. Exploration of Bioengineered Scaffolds Composed of Thermo-Responsive Polymers for Drug Delivery in Wound Healing. *Int. J. Mol. Sci.* **2021**, *22*, 1408, <https://doi.org/10.3390/ijms22031408>.
124. Wang, Y.; Wang, C. Self-assembly of graphene sheets actuated by surface topological defects: Toward the fabrication of novel nanostructures and drug delivery devices. *Appl. Surf. Sci.* **2020**, *505*, 144008, <https://doi.org/10.1016/j.apsusc.2019.144008>.
125. Mohammed, M.H.; Hanoon, F.H. Theoretical prediction of delivery and adsorption of various anticancer drugs into pristine and metal-doped graphene nanosheet. *Chinese J. Phys.* **2020**, *68*, 578-95, <https://doi.org/10.1016/j.cjph.2020.09.030>.
126. Mondal, A.; Nayak, A.K.; Chakraborty, P.; Banerjee, S.; Nandy, B.C. Natural Polymeric Nanobiocomposites for Anti-Cancer Drug Delivery Therapeutics: A Recent Update. *Pharmaceutics* **2023**, *15*, 2064, <https://doi.org/10.3390/pharmaceutics15082064>.
127. Trusek, A.; Kijak, E.; Granicka, L. Graphene oxide as a potential drug carrier - Chemical carrier activation, drug attachment and its enzymatic controlled release. *Mater. Sci. Eng. C Mater. Biol. Appl.* **2020**, *116*, 111240, <https://doi.org/10.1016/j.msec.2020.111240>.
128. Omidi, S.; Pirhayati, M.; Kakanejadifard, A. Co-delivery of doxorubicin and curcumin by a pH-sensitive, injectable, and in situ hydrogel composed of chitosan, graphene, and cellulose nanowhisker. *Carbohydr. Polym.* **2020**, *231*, 115745, <https://doi.org/10.1016/j.carbpol.2019.115745>.
129. Anirudhan, T.S.; Chithra Sekhar, V.; Athira, V.S. Graphene oxide based functionalized chitosan polyelectrolyte nanocomposite for targeted and pH responsive drug delivery. *Int. J. Biol. Macromol.* **2020**, *150*, 468–479, <https://doi.org/10.1016/j.ijbiomac.2020.02.053>.
130. Feng, L.; Liu, Z. Graphene in biomedicine: opportunities and challenges. *Nanomedicine* **2011**, *6*, 317–324, <https://doi.org/10.2217/nmm.10.158>.
131. Loh, Q.L.; Choong, C. Three-dimensional scaffolds for tissue engineering applications: role of porosity and pore size. *Tissue Eng. Part B Rev.* **2013**, *19*, 485–502, <https://doi.org/10.1089/ten.TEB.2012.0437>.
132. Jamjoum, H.A.A.; Umar, K.; Adnan, R.; Razali, M.R.; Mohamad Ibrahim, M.N. Synthesis, Characterization, and Photocatalytic Activities of Graphene Oxide/metal Oxides Nanocomposites: A Review. *Front. Chem.* **2021**, *9*, 752276, <https://doi.org/10.3389/fchem.2021.752276>.
133. Storm, M.M.; Overgaard, M.; Younesi, R.; Reeler, N.E.A.; Vosch, T.; Nielsen, U.G.; Edström, K.; Norby, P. Reduced graphene oxide for Li-air batteries: the effect of oxidation time and reduction conditions for graphene oxide. *Carbon* **2015**, *85*, 233-244, <https://doi.org/10.1016/j.carbon.2014.12.104>.
134. Duan, S.; Yang, X.; Mei, F.; Tang, Y.; Li, X.; Shi, Y.; Mao, J.; Zhang, H.; Cai, Q. Enhanced osteogenic differentiation of mesenchymal stem cells on poly(L-lactide) nanofibrous scaffolds containing carbon nanomaterials. *J. Biomed. Mater. Res. A* **2015**, *103*, 1424–1435, <https://doi.org/10.1002/jbm.a.35283>.
135. Sadak, O. One-pot scalable synthesis of rGO/AuNPs nanocomposite and its application in enzymatic glucose biosensor. *Nanocomposites*, **2021**, *7*, 44–52. <https://doi.org/10.1080/20550324.2021.1917837>.
136. Pattara, V.P.; Nandibewoor, S.T. Electroanalytical method for the determination of 5-fluorouracil using a reduced graphene oxide/chitosan modified sensor. *RSC Adv.*, **2015**, *5*, 34292-34301.
137. Măghinici, A.R.; Bounegru, A.V.; Apetrei, C. Electrochemical Detection of Diclofenac Using a Screen-Printed Electrode Modified with Graphene Oxide and Phenanthroline. *Chemosensors* **2025**, *13*, 55. <https://doi.org/10.3390/chemosensors13020055>.
138. Giusto, E.; Žárská, L.; Beirne, D.F.; Rossi, A.; Bassi, G.; Ruffini, A.; Montesi, M.; Montagner, D.; Ranc, V.; Panseri, S. Graphene Oxide Nanoplatfoms to Enhance Cisplatin-Based Drug Delivery in Anticancer Therapy. *Nanomaterials* **2022**, *12*, 2372. <https://doi.org/10.3390/nano12142372>.
139. Balcioglu, M.; Rana, M.; Yigit, M.V. Doxorubicin loading on graphene oxide, iron oxide and gold nanoparticle hybrid. *J. Mater. Chem.* **2013**, *1*, 6187.
140. Chauhan, G.; Chopra, V.; Tyagi, A.; Rath, G.; Sharma, R.K.; Goyal, A.K. Gold nanoparticles composite-folic acid conjugated graphene oxide nanohybrids” for targeted chemo-thermal cancer ablation: In vitro screening and in vivo studies, *Eur. J. Pharm. Sci.* **2017**, *96*, 351-361. <https://doi.org/10.1016/j.ejps.2016.10.011>.
141. Shin, S.R.; Li, Y.C.; Jang, H.L.; Khoshakhlagh, P.; Akbari, M.; Nasajpour, A.; Zhang, Y.S.; Tamayol, A.; Khademhosseini, A. Graphene-based materials for tissue engineering. *Adv. Drug Deliv. Rev.* **2016**, *105*, 255-274.

142. Pei, B.; Wang, W.; Dunne, N.; Li, X. Applications of Carbon Nanotubes in Bone Tissue Regeneration and Engineering: Superiority, Concerns, Current Advancements, and Prospects. *Nanomaterials (Basel)*. **2019**, *9*, 1501.
143. Kang, M.S.; Jeong, S.J.; Lee, S.H.; Kim, B.; Hong, S.W.; Lee, J.H.; Han, D.W. Reduced graphene oxide coating enhances osteogenic differentiation of human mesenchymal stem cells on Ti surfaces. *Biomater. Res.* **2021**, *25*, 4. <https://doi.org/10.1186/s40824-021-00205-x>.
144. Prasad, S.; Suresh, S.; Wong, R. Osteogenic Potential of Graphene in Bone Tissue Engineering Scaffolds. *Materials* **2018**, *11*, 1430. <https://doi.org/10.3390/ma11081430>.
145. Lee, J.; Shin, Y.; Lee, S.M.; Jin, O.S.; Kang, S.H.; Hong, S.W.; Jeong, C.M.; Huh, J.B.; Han, D.W. Enhanced Osteogenesis by Reduced Graphene Oxide/Hydroxyapatite Nanocomposites. *Sci Rep* **2015**, *5*, 18833. <https://doi.org/10.1038/srep18833>.
146. Lim, H.N.; Huang, N.M.; Lim, S.S.; Harrison, I.; Chia, C.H. Fabrication and characterization of graphene hydrogel via hydrothermal approach as a scaffold for preliminary study of cell growth. *Int. J. Nanomedicine* **2011**, *6*, 1817-23.

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