Recent Advances in Graphene Oxide: Biomedical Applications, Electrochemical Energy Storage and Emerging Perspectives: A short Review

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Abstract:
Graphene oxide (GO) has emerged as an important two-dimensional nanomaterial because of its large specific surface area, abundant oxygen-containing functional groups, hydrophilicity, tunable surface chemistry, mechanical strength, optical properties and facile functionalization. In biomedical research, GO has attracted considerable attention for drug delivery, gene delivery, biosensing, bioimaging, cancer therapy, antimicrobial treatment, tissue engineering, wound healing and regenerative medicine. In battery electrodes, GO has been investigated as an electrochemically active material and as a functional component of composite electrodes for lithium-ion, sodium-ion and lithium–sulfur batteries. GO also presents important challenges, including relatively low electrical conductivity, irreversible electrochemical reactions, aggregation, structural heterogeneity, batch-to-batch variation and concentration-, size- and surface-chemistry-dependent biological toxicity. In biomedical applications, long-term biocompatibility, biodegradation and immune responses require systematic evaluation. In battery applications, control over oxidation degree, functional-group distribution, electrode architecture and mass loading remains essential for obtaining reproducible electrochemical performance. This review comprehensively discusses the synthesis, structural characteristics, physicochemical properties, functionalization strategies, biomedical applications and battery-electrode applications of GO. Particular emphasis is placed on structure–property relationships, mechanisms of action, recent advances, limitations and future research directions. The review highlights the importance of precise control over GO chemistry and morphology for developing safe, efficient and application-specific GO-based technologies.

Keywords: Graphene oxide; two-dimensional nanomaterial; surface functionalization; biosensors; batteries; electrode materials; electrochemical energy storage.

1. Introduction

The development of advanced nanomaterials has created new opportunities in biomedical engineering, energy storage, sensing and environmental technologies. Among various two-dimensional nanomaterials, graphene oxide has received substantial scientific attention because its carbon framework combines a large surface area with abundant oxygen-containing functional groups. These characteristics distinguish GO from many conventional carbon materials and provide a versatile platform for chemical modification and interaction with biological and electrochemical systems. GO originates from the chemical oxidation and exfoliation of graphite. Oxidation introduces oxygen-containing groups such as hydroxyl, epoxy, carbonyl and carboxyl groups into the carbon framework. These functional groups modify the electronic structure, interlayer spacing,

hydrophilicity, surface charge and chemical reactivity of the material. Dreyer et al. (2010) described GO as a chemically modified carbon material whose properties depend strongly on its oxygen functionality, structural defects and oxidation state. The high surface area and functional-group density of GO facilitate interaction with proteins, nucleic acids, drugs, enzymes and cellular components. Consequently, GO has become attractive for drug and gene delivery, biosensing, bioimaging, tissue engineering, antimicrobial systems and cancer-related applications. Mehta et al. (2024) reported that GO possesses significant potential in drug delivery, biosensing, tissue engineering, imaging and gene delivery because of its surface chemistry and physicochemical properties. GO also possesses important electrochemical characteristics. Oxygen-containing groups and structural defects provide chemically active sites for interaction with lithium and sodium ions. The expanded interlayer environment produced during oxidation provides additional space for ion interaction compared with highly ordered graphite. Xie et al. (2015) demonstrated that the electrochemical behavior of GO depends strongly on its oxygen-containing functional groups; carbonyl and carboxyl groups contribute to reversible lithium-storage capacity, whereas unstable oxygen functionalities such as epoxy groups increase irreversible capacity and reduce initial Coulombic efficiency. Recent research has therefore moved beyond viewing GO simply as a chemically modified carbon material. GO is increasingly investigated as a functional platform whose surface chemistry is deliberately engineered for a specific application. In biomedical systems, this involves controlling size, surface charge, functional groups and molecular interactions. In battery electrodes, it involves controlling oxidation degree, interlayer spacing, oxygen functionality, defect density, electrode thickness and electrolyte interaction. The objective of this review is to provide a comprehensive and critical assessment of GO alone for biomedical and battery-electrode applications. The review discusses GO synthesis, structural characteristics, physicochemical properties, functionalization, biomedical applications, electrochemical mechanisms, battery-electrode applications, challenges and future perspectives.

2. Physicochemical Properties of Graphene Oxide

Table 1 summarizes the major physicochemical properties of graphene oxide and their significance in biomedical and battery-electrode applications.

Table 1. Physicochemical properties of graphene oxide and their significance

Physicochemical property	Origin/characteristic	Significance in GO applications
Two-dimensional structure	Thin, sheet-like carbon framework with large accessible surface	Provides a high interface for molecular adsorption, biomolecule interaction and electrochemical reactions.
Large specific surface area	Extended two-dimensional sheet morphology	Enhances drug loading, biomolecule immobilization, ion interaction and electrode–electrolyte contact.
Oxygen-containing functional groups	Hydroxyl, epoxy, carbonyl and carboxyl groups introduced during oxidation	Provides chemically active sites for functionalization, molecular interaction, ion adsorption and surface redox reactions.
Hydrophilicity	Mainly associated with polar oxygen-containing groups	Promotes dispersion in aqueous media and supports biomedical processing and electrolyte interaction.

Surface charge	Ionization of surface functional groups, particularly carboxyl groups	Influences colloidal stability, cellular interaction, biomolecule adsorption and ionic interactions.
Interlayer spacing	Expanded relative to graphite because of oxidation and intercalated water/molecules	Facilitates exfoliation and provides accessible pathways for ion and molecule interaction.
Structural defects	Vacancies, disrupted carbon bonds, oxidized regions and edge defects	Creates additional active sites for molecular adsorption, functionalization and electrochemical reactions.
sp^2/sp^3 carbon domains	Partial disruption of the graphitic sp^2 network by oxidation	Controls electronic, optical and chemical properties of GO.
Chemical reactivity	Abundant surface functional groups and defect sites	Enables covalent and non-covalent modification with polymers, drugs, proteins and other materials.
Optical properties	Electronic structure containing oxidized and relatively graphitic domains	Supports optical sensing, imaging and photoresponsive biomedical applications.
Mechanical strength	Strong in-plane carbon framework	Supports the development of films, membranes, hydrogels, scaffolds and composite electrodes.
Electrochemical activity	Oxygen functionalities, defects and accessible surface	Provides active sites for Li^+/Na^+ interaction, surface redox reactions and charge storage.
Thermal behavior	Decomposition and rearrangement of oxygen-containing groups with heating	Important for processing, thermal treatment and stability of GO-based materials.

GO possesses a two-dimensional sheet-like structure and large accessible surface area, which provide extensive interfaces for molecular adsorption, biomolecule immobilization and electrochemical reactions. The presence of abundant oxygen-containing functional groups, including hydroxyl, epoxy, carbonyl and carboxyl groups, represents one of the most important characteristics of GO. These functional groups increase surface reactivity and provide active sites for interaction with drugs, proteins, nucleic acids, polymers and ions. The oxygen functionalities also enhance the hydrophilicity of GO, allowing relatively stable dispersion in aqueous media, which is particularly advantageous for biomedical applications. The surface charge of GO, mainly influenced by ionizable oxygen-containing groups, affects colloidal stability, biomolecular interactions and cellular uptake. The expanded interlayer spacing of GO originates from oxidation and the incorporation of water or other molecules between adjacent layers. This structural feature facilitates exfoliation and provides

accessible regions for molecular and ionic interactions (Xie et al., 2015). Structural defects, including vacancies, disrupted carbon bonds and oxidized edge sites, further increase the chemical reactivity and provide additional active sites for adsorption, functionalization and electrochemical reactions. The coexistence of sp^2 and sp^3 carbon domains produces distinctive electrical, optical and chemical properties because oxidation partially disrupts the continuous graphitic π-electron network. GO also exhibits useful optical properties, supporting applications in optical sensing and biomedical imaging, while its mechanical strength contributes to the development of films, membranes, hydrogels, scaffolds and composite electrode structures. Furthermore, the oxygen functionalities and defect sites provide electrochemical activity, enabling interactions with Li^+ and Na^+ ions and contributing to surface redox reactions and charge storage. The thermal behavior of GO is associated mainly with the decomposition and rearrangement of oxygen-containing groups and is important during thermal processing and material stabilization. The combination of large surface area, oxygen-rich surface chemistry, hydrophilicity, structural defects, expanded interlayer spacing, mechanical strength and electrochemical activity makes GO a versatile material for both biomedical and battery-electrode applications. The final properties of GO depend strongly on the graphite precursor, oxidation conditions, purification process, exfoliation method and resulting functional-group distribution (Dreyer et al., 2010; Xie et al., 2015).

3. Structural Characteristics of Graphene Oxide

Graphene oxide is a two-dimensional carbon-based nanomaterial produced through the oxidation and exfoliation of graphite. Its structure consists of a carbonaceous sheet containing a combination of sp^2- and sp^3-hybridized carbon atoms. During the oxidation process, the extended sp^2-hybridized carbon network of graphite undergoes partial disruption, accompanied by the incorporation of abundant oxygen-containing functional groups. These functional groups include hydroxyl (–OH) and epoxy (C–O–C) groups mainly distributed across the basal plane, while carbonyl (C=O) and carboxyl (–COOH) groups are predominantly associated with the edges and defect sites of the GO sheets. The heterogeneous distribution of these functional groups produces a chemically active and structurally disordered surface. Figure 1 illustrates the structural characteristics of graphene oxide, showing a two-dimensional carbon framework containing both sp^2 and sp^3 hybridized carbon regions. The GO sheet contains various oxygen-containing functional groups, including hydroxyl (–OH), epoxy (C–O–C), carbonyl (C=O), and carboxyl (–COOH) groups. These functional groups are mainly distributed over the basal plane, edges and defect sites of the carbon sheet. Oxidation also introduces structural defects and increases the interlayer spacing between adjacent GO sheets. The presence of oxygen functionalities and defects enhances the hydrophilicity, surface reactivity, molecular interaction and functionalization ability of GO. The expanded interlayer spacing facilitates the interaction of ions and molecules with the GO structure.

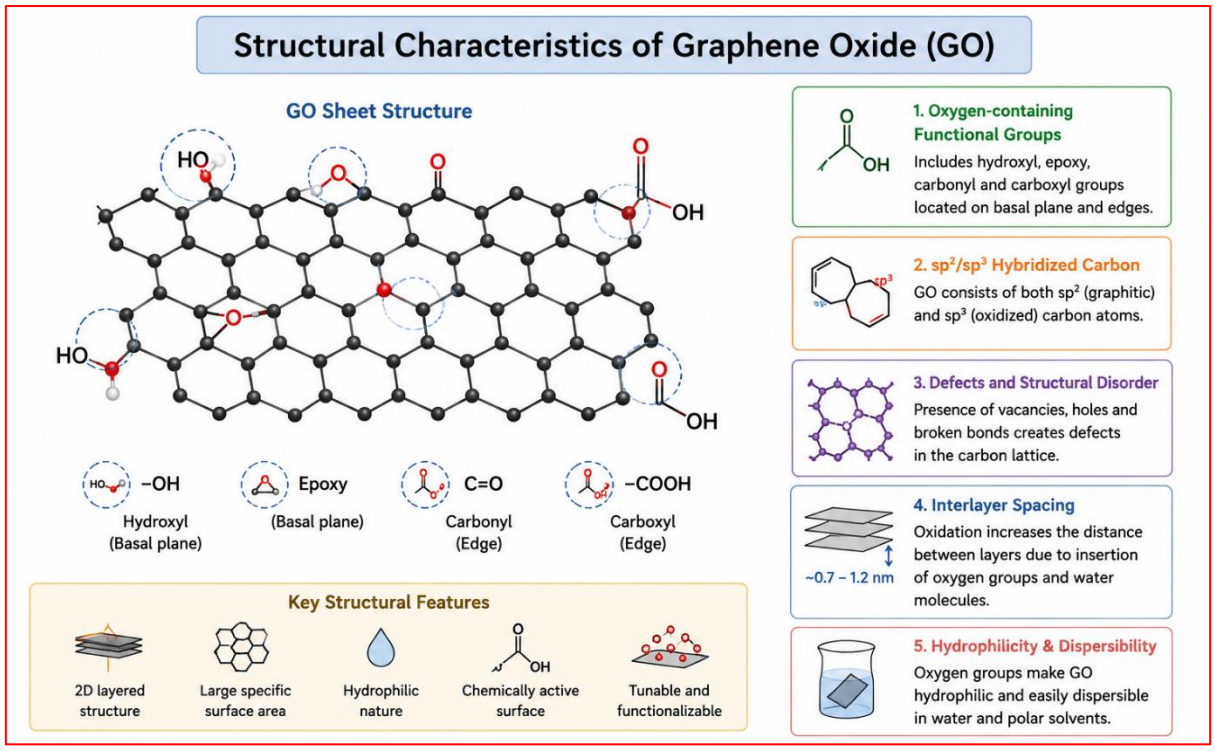

Figure 1: Structural characteristics of graphene oxide

The oxidation process also increases the interlayer distance compared with graphite because of the introduction of oxygen functionalities and the incorporation of water molecules between the layers. This expanded interlayer spacing facilitates exfoliation and provides accessible sites for interactions with ions, molecules and biomolecules. The structural characteristics of GO depend strongly on the graphite precursor, oxidation conditions, reaction time, oxidizing-agent concentration and purification procedure (Dreyer et al., 2010). The GO structure contains both relatively intact graphitic sp^2 domains and highly oxidized sp^3-rich regions. The coexistence of these domains produces distinctive electrical, optical and chemical properties. The disruption of the conjugated π-electron network substantially decreases electrical conductivity compared with graphite, while the introduction of oxygen-containing groups significantly increases hydrophilicity, chemical reactivity and dispersibility in aqueous media. The oxygen functionalities also provide active sites for covalent and non-covalent surface modification, allowing GO to interact with polymers, proteins, nucleic acids, drugs and inorganic materials. In electrochemical applications, these functional groups and structural defects provide sites for ion adsorption and surface redox reactions, whereas the expanded interlayer structure facilitates electrolyte penetration and ion interaction. In biomedical applications, the same structural features promote adsorption and immobilization of therapeutic molecules and biomolecules. Therefore, the heterogeneous distribution of sp^2/sp^3 carbon domains, oxygen-containing functional groups, structural defects and expanded interlayer spacing determines the physicochemical behavior of GO and establishes the fundamental relationship between its structure and performance in biomedical and battery-electrode applications (Dreyer et al., 2010; Xie et al., 2015).

3.1 Molecular Structure of GO

At the molecular level, GO does not possess a perfectly uniform crystalline structure. Instead, it contains a heterogeneous arrangement of graphitic domains, oxidized regions and structural defects. Hydroxyl and epoxy groups are primarily present on the basal plane, whereas carbonyl and carboxyl groups are frequently located at sheet edges and defect regions. The relative concentration and distribution of these functional groups vary with the oxidation process and strongly influence the surface charge, hydrophilicity, chemical reactivity and

electrochemical behavior of GO. The presence of oxygen functionalities also generates polar regions within the carbon framework, producing strong interactions with water and other polar molecules. This molecular heterogeneity represents a major characteristic of GO and distinguishes it from highly ordered graphitic materials (Dreyer et al., 2010).

3.2 Oxygen-Containing Functional Groups

The oxygen-containing functional groups represent the most important chemical feature of GO. Hydroxyl, epoxy, carbonyl and carboxyl groups provide chemically active sites for interaction with surrounding molecules and ions. Hydroxyl and carboxyl groups contribute substantially to the hydrophilic nature of GO and promote stable dispersion in aqueous environments. Carboxyl groups also provide reactive sites for coupling reactions with amines, peptides, proteins and other biomolecules, which is particularly important for biomedical applications. Epoxy groups participate in nucleophilic reactions and provide additional opportunities for surface functionalization. Carbonyl groups contribute to the chemical reactivity and electrochemical activity of GO. Xie et al. (2015) demonstrated that different oxygen-containing functional groups produce different effects on lithium-ion storage; carbonyl and carboxyl groups contribute to reversible lithium storage, whereas labile epoxy groups contribute to irreversible capacity and reduced initial Coulombic efficiency. Thus, the type, concentration and distribution of oxygen-containing groups are critical parameters controlling the performance of GO in both biomedical and battery-electrode applications.

3.3 Defects and Structural Disorder

Oxidation introduces various structural defects into the carbon framework of GO. These defects include vacancies, disrupted carbon–carbon bonds, oxidized edge sites and regions with different degrees of oxidation. Structural disorder is commonly evaluated using Raman spectroscopy through the intensity ratio of the D and G bands. The D band is associated primarily with structural defects and disorder, whereas the G band originates from the in-plane vibration of sp^2 carbon atoms. The \(I_D/I_G\) ratio therefore provides useful information regarding the degree of structural disorder. Defect sites are important because they increase the chemical reactivity and provide additional sites for molecular adsorption and ion interaction. However, excessive structural disorder also disrupts electronic transport through the carbon framework. Consequently, an appropriate balance between functionalization and structural integrity is important for obtaining application-specific GO performance.

3.4 Interlayer Spacing

The interlayer spacing of GO is substantially larger than that of graphite because oxidation introduces oxygen-containing groups and promotes the incorporation of water and other molecules between adjacent sheets. This increased spacing facilitates the exfoliation of graphite oxide into individual or few-layer GO sheets. The expanded interlayer structure also provides additional pathways for molecular and ionic interaction. In battery electrodes, interlayer spacing directly influences electrolyte penetration and ion transport. In biomedical applications, the accessible interlayer and surface regions provide sites for molecular adsorption and functionalization. Therefore, interlayer spacing represents an important structural parameter linking the oxidation state of GO with its functional performance.

4. Synthesis of Graphene Oxide

Figure 2 presents the general synthesis methods used for the preparation of graphene oxide, beginning with graphite as the primary carbon precursor. The synthesis mainly involves oxidation of graphite after that exfoliation and purification. In the conventional chemical approach, graphite is treated with strong oxidizing agents in an acidic medium, which introduces oxygen-containing functional groups into the graphitic layers

and increases the interlayer spacing. The oxidation step disrupts the strong interactions between adjacent graphite layers and facilitates subsequent exfoliation into individual or few-layer GO sheets. The oxidized material is then subjected to repeated washing, centrifugation, filtration and dialysis to remove residual acids, salts and oxidizing species, followed by drying or dispersion in a suitable solvent.

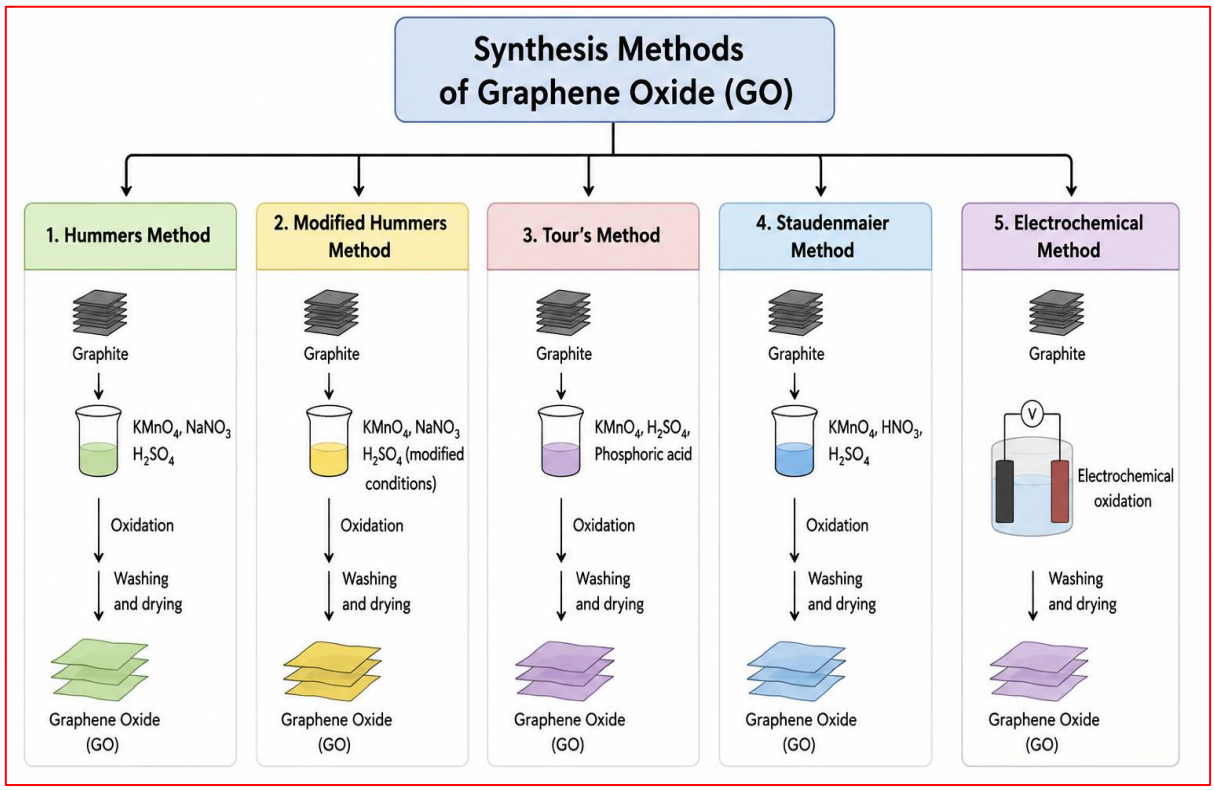

Figure 2: Synthesis methods of graphene oxide

Among the conventional chemical routes, the Brodie, Staudenmaier and Hummers methods are widely recognized. Brodie introduced an early oxidation route using potassium chlorate and nitric acid, while the Staudenmaier method improved the oxidation process by using additional chlorate under strongly acidic conditions. The Hummers method, introduced by Hummers and Offeman (1958), uses graphite, concentrated sulfuric acid, sodium nitrate and potassium permanganate and became one of the most widely adopted approaches for GO preparation. Modified Hummers methods subsequently replaced or eliminated sodium nitrate and optimized the oxidant concentration and reaction conditions to improve oxidation efficiency and reduce hazardous gas formation. Marcano et al. (2010) developed an improved oxidation method using a sulfuric acid/phosphoric acid mixture and potassium permanganate, providing efficient graphite oxidation with improved safety characteristics. In addition to conventional chemical oxidation, electrochemical, microwave-assisted, hydrothermal and green synthesis approaches have received increasing attention. Electrochemical synthesis uses an applied potential to oxidize graphite directly, reducing dependence on strong chemical oxidants and providing better control over oxidation conditions. Microwave-assisted methods accelerate oxidation through rapid and uniform heating, thereby reducing reaction time. Hydrothermal and related assisted methods provide alternative routes for controlled structural modification of graphite-derived materials. Green synthesis approaches focus on reducing hazardous chemicals, energy consumption and waste generation by employing environmentally compatible oxidizing agents and processing conditions. Regardless of the synthesis route, the final properties of GO depend strongly on the oxidation degree, oxidizing-agent concentration, reaction temperature, reaction time, graphite precursor, exfoliation conditions and purification

procedure. These parameters control the oxygen-functional-group distribution, defect density, interlayer spacing, lateral sheet size and surface chemistry of GO.

5. Applications of Graphene Oxide

Figure 3 illustrates the broad range of applications of graphene oxide, which arise from its two-dimensional structure, large surface area, abundant oxygen-containing functional groups, hydrophilicity, surface charge, optical properties and electrochemical activity.

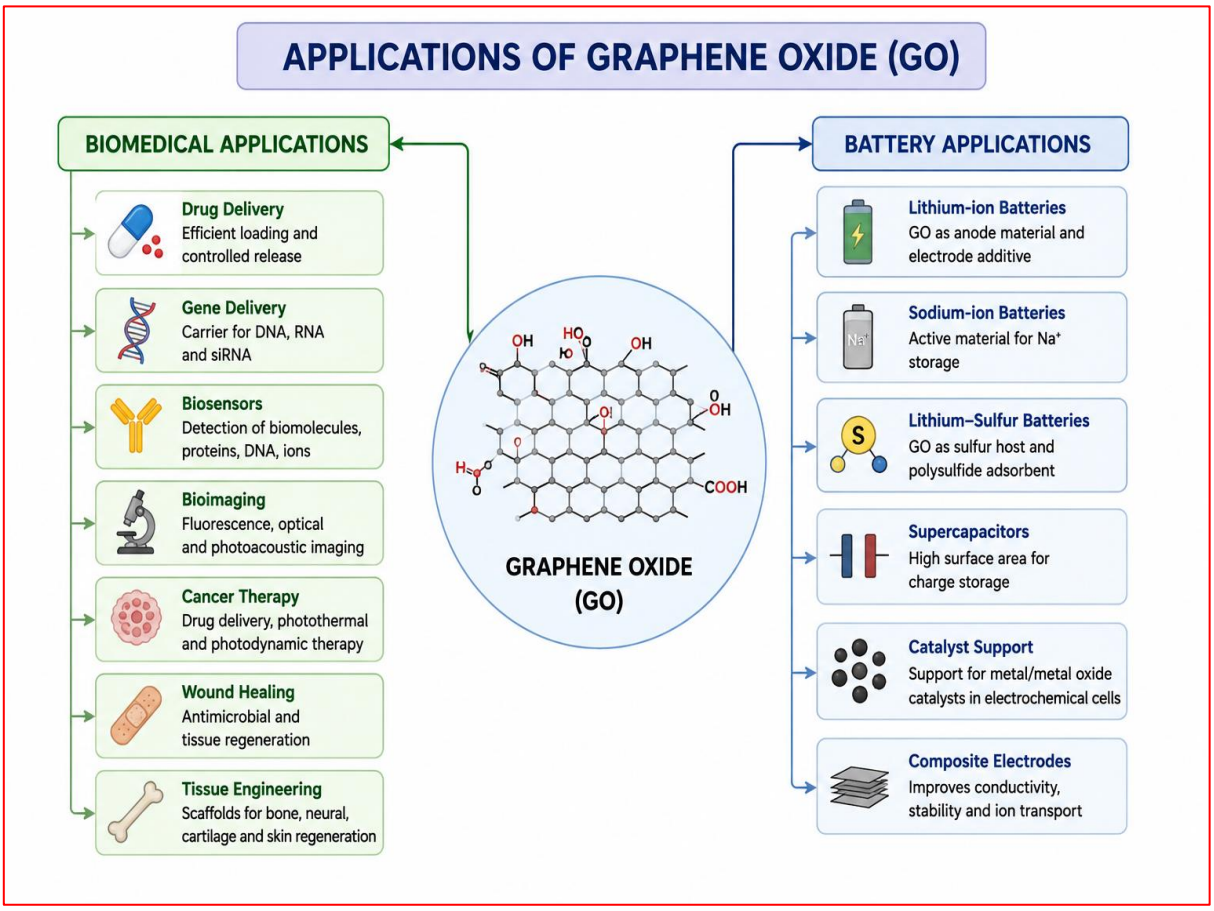

Figure 3: Applications of graphene oxide

In biomedical applications, GO is widely investigated for drug delivery, gene delivery, biosensing, bioimaging, cancer therapy, antimicrobial treatment, tissue engineering and wound healing. Its large surface area provides effective sites for loading therapeutic molecules, while hydroxyl, epoxy, carbonyl and carboxyl groups facilitate functionalization with drugs, proteins, peptides and nucleic acids. The optical and surface properties of GO also support sensitive biosensing and imaging applications. In energy-storage applications, GO is investigated as an electrode material and functional component in lithium-ion batteries, sodium-ion batteries and lithium–sulfur batteries. Its oxygen-containing groups, structural defects and expanded interlayer spacing provide active sites for ion interaction and electrochemical reactions. GO is also studied in membranes, coatings, environmental treatment, separation and sensing technologies because of its tunable surface chemistry and high adsorption capacity. Thus, the multifunctional nature of GO enables its application across biomedical, electrochemical, environmental and sensing fields.

Table 2 compares the significance of the major physicochemical properties of GO in biomedical and battery-electrode applications. The large surface area of GO provides extensive sites for drug loading, biomolecule immobilization and cellular interaction in biomedical systems, while the same surface provides electrolyte-

accessible active sites for ion adsorption and electrochemical reactions in batteries. The oxygen-containing functional groups are particularly important because they enable covalent and non-covalent attachment of drugs, proteins, peptides and nucleic acids in biomedical applications, whereas they participate in Li^+ and Na^+ interactions and surface redox reactions in battery electrodes. The hydrophilic nature of GO promotes dispersion in aqueous biological environments and supports the fabrication of hydrogels, membranes and tissue-engineering scaffolds; in battery systems, it facilitates electrolyte wetting and interfacial interaction. Surface charge influences protein adsorption, cellular uptake and membrane interaction in biomedical systems, while it also affects ion adsorption and electrode–electrolyte interactions. The two-dimensional structure and expanded interlayer spacing provide accessible regions for molecular interaction in biomedical applications and facilitate electrolyte penetration and ion transport in battery electrodes. Structural defects provide reactive sites for biomolecule functionalization and additional electrochemical active sites for ion storage. The optical properties of GO support biosensing and bioimaging, whereas its electrochemical properties contribute directly to charge-storage and surface redox processes. Table 2 demonstrates that the same fundamental physicochemical characteristics of GO generate different functional roles depending on the application environment, establishing a direct relationship between GO structure, surface chemistry and application performance.

Table 2. Comparison of biomedical and battery applications of graphene oxide.

GO property	Biomedical significance	Battery-electrode significance
Large surface area	Provides extensive sites for drug loading, biomolecule immobilization, biosensing and cellular interaction.	Increases electrolyte-accessible surface and provides sites for ion adsorption and electrochemical reactions.
Oxygen-containing functional groups	Enable covalent and non-covalent functionalization with drugs, proteins, peptides, nucleic acids and polymers.	Provide active sites for Li^+/Na^+ interaction and surface redox reactions; their type and concentration influence reversible and irreversible capacity.
Hydrophilicity	Promotes dispersion in aqueous biological media and supports preparation of hydrogels, scaffolds and nanocarriers.	Improves interaction with liquid electrolytes and facilitates electrolyte wetting of the electrode surface.
Surface charge	Controls colloidal stability, protein adsorption, cellular uptake and interactions with biological membranes.	Influences ion adsorption, interfacial interactions and electrode–electrolyte behavior.

Two-dimensional structure	Supports nanocarrier formation, thin films, membranes and tissue-engineering scaffolds.	Provides a large interfacial area and flexible framework for electrode architectures and active-material integration.
Expanded interlayer spacing	Provides accessible regions for molecular loading and interaction with biomolecules.	Facilitates electrolyte penetration and ion interaction within the layered structure.
Structural defects	Provide reactive sites for biomolecule attachment and surface functionalization.	Provide additional electrochemically active sites for ion adsorption and charge-storage reactions.
Optical properties	Support fluorescence-based sensing, bioimaging and photoresponsive therapeutic systems.	Assist optical characterization and provide information about structural/electronic changes during material processing.
Mechanical strength	Supports mechanically stable films, membranes, hydrogels and tissue-engineering scaffolds.	Contributes to structural integrity and mechanical stability of GO-containing electrode architectures.
Chemical reactivity	Enables selective surface modification and attachment of therapeutic or recognition molecules.	Controls surface reactions with electrolyte species and active ions.
Electrochemical activity	Supports electrochemical biosensing and detection of biologically relevant analytes.	Contributes directly to Li^+/Na^+ storage, surface redox reactions and charge-transfer processes.

6. Future Perspectives

Future research on graphene oxide is focus on precise control of its structural, chemical, biological and electrochemical characteristics to improve its reliability for biomedical and battery-electrode applications. Although GO possesses a combination of large surface area, abundant oxygen-containing functional groups, hydrophilicity, structural defects and tunable surface chemistry, variations in synthesis procedures often produce significant differences in oxidation degree, lateral sheet size, defect density, functional-group distribution and surface charge. Therefore, the development of standardized and reproducible synthesis protocols represents an important priority. Advanced characterization techniques should be systematically combined to establish quantitative relationships between GO structure, oxygen functionality and application performance. Particular attention should be given to controlling hydroxyl, epoxy, carbonyl and carboxyl groups because these functionalities determine molecular interactions, surface reactivity and electrochemical behavior (Dreyer et al., 2010; Xie et al., 2015). In biomedical applications, future studies should emphasize

precise control of GO sheet dimensions, surface charge, oxidation degree and functionalization to improve therapeutic efficiency and biological compatibility. Research on GO-based drug and gene delivery systems should focus on controlled loading, targeted cellular uptake and predictable release behavior. Long-term investigations of cytotoxicity, inflammatory responses, biodistribution, biodegradation and clearance are also essential for establishing the safety profile of GO. Standardized biological testing protocols involving appropriate concentrations, exposure periods and cell models would improve comparison among different studies. Surface functionalization with biomolecules, polymers and targeting ligands represents an important direction for developing application-specific GO nanocarriers. GO-based biosensors also require improvements in selectivity, sensitivity, reproducibility and stability for practical diagnostic applications. Recent biomedical reviews emphasize that controlling GO physicochemical characteristics is essential for translating laboratory-scale investigations into reliable biomedical technologies (Mehta et al., 2024). For battery-electrode applications, future research should concentrate on understanding the individual contribution of GO's oxygen-containing functional groups, structural defects and interlayer spacing to ion storage and charge-transfer processes. In lithium-ion batteries, particular attention should be given to reducing irreversible reactions associated with unstable oxygen functionalities while maintaining sufficient electrochemical active sites. Xie et al. (2015) demonstrated that carbonyl and carboxyl functionalities contribute differently to lithium storage, highlighting the importance of functional-group-specific engineering. Similar structure–property investigations are required for sodium-ion batteries, where the larger Na^+ ion places greater importance on accessible interlayer spacing and suitable surface chemistry. In lithium–sulfur batteries, GO surface functional groups require optimization for effective interaction with sulfur species and polysulfides. Future electrochemical studies should also emphasize realistic electrode conditions, including high active-material loading, practical electrode thickness, appropriate electrolyte-to-active-material ratios and long-term cycling stability rather than relying only on low-loading laboratory configurations. Another important research direction involves the development of green and sustainable GO technologies. Conventional oxidation processes involve strong acids and oxidizing agents and generate chemical waste, creating environmental and safety concerns during large-scale production. Future synthesis strategies should therefore reduce hazardous reagents, water consumption and energy requirements while maintaining reproducible GO quality. Sustainable processing, solvent recovery, waste minimization and environmentally responsible disposal should receive greater attention. In parallel, scalable production methods should provide consistent control over GO oxidation degree, sheet dimensions and functional-group distribution. Such improvements are essential for transferring GO technologies from laboratory research to industrial and biomedical applications. Future GO research should also increasingly employ computational modeling, artificial intelligence and data-driven materials design to predict relationships between synthesis conditions, structural characteristics and application performance. Combining experimental characterization with molecular simulations and machine-learning approaches would provide deeper understanding of interactions between GO and biological molecules, ions and electrolyte species. Ultimately, the development of application-specific GO with controlled oxidation degree, functional-group distribution, lateral dimensions, defect density, surface charge and interlayer spacing represents the most promising direction. Establishing standardized material specifications and reliable structure–property–performance relationships will strengthen the scientific reproducibility of GO research and accelerate the development of safe biomedical systems and high-performance battery electrodes.

Conclusion

Graphene oxide has emerged as a versatile two-dimensional carbon-based nanomaterial with remarkable potential in biomedical and battery-electrode applications. Its unique structural characteristics, including a large surface area, two-dimensional morphology, expanded interlayer spacing, structural defects and abundant

oxygen-containing functional groups such as hydroxyl, epoxy, carbonyl and carboxyl groups, provide diverse physicochemical properties. These characteristics promote strong molecular interactions, surface functionalization, hydrophilicity and electrochemical activity. In biomedical applications, GO shows significant potential for drug delivery, gene delivery, biosensing, bioimaging, cancer therapy, antimicrobial applications, tissue engineering and wound healing. In battery technologies, its surface functionalities, defect sites and expanded interlayer regions support ion adsorption, charge storage and electrochemical reactions, making GO an important material for advanced electrode systems. The performance of GO in both fields is strongly dependent on its oxidation degree, functional-group distribution, sheet dimensions, defect density, surface charge and interlayer spacing. Therefore, controlled synthesis and precise structural engineering are essential for achieving reproducible and application-specific performance. GO provides an effective multifunctional platform that connects advanced nanomaterial chemistry with biomedical technology and electrochemical energy storage, and continued optimization of its structural and surface properties will strengthen its practical applicability in these rapidly developing fields.

Declaration of competing interest

The authors declare that they have no known competing financial interest.

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