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Graphene Oxide as a Platform for Next-Generation Functional Materials

Dr. Sonal Sah[1]
[1]LNMS College, Birpur, Supaul (Constituent unit of B.N. Mandal University, Madhepura, Bihar, India)
*Corresponding Author E-mail: dr.sonalsah@gmail.com

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Abstract

Graphene oxide (GO), an oxidized derivative of graphene, has emerged as a highly versatile nanomaterial due to its large surface area, tunable chemical functionality, and hydrophilic nature. The introduction of oxygen-containing groups such as hydroxyl, epoxy, and carboxyl via oxidative exfoliation methods significantly enhances its solubility and chemical reactivity. These properties enable extensive functionalization, making GO a valuable platform for diverse applications. Comprehensive characterization techniques, including X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, scanning and transmission electron microscopy (SEM, TEM), and thermogravimetric analysis (TGA), are essential for elucidating its structural features, morphology, and thermal behavior. GO has demonstrated significant potential in a wide range of fields, including targeted drug delivery, biosensing, energy storage, water purification, catalysis, and antimicrobial treatments. Its ability to interact with metal ions and biomolecules further positions it as a promising material for biomedical and environmental innovations. This review provides a focused overview of GO's synthesis methods, characterization techniques, and its expanding applications in nanotechnology and advanced materials, highlighting its role in the development of next-generation functional materials.

Keywords*:* Graphene oxide, complexes, spectroscopy, antimicrobial activity, nanotechnology

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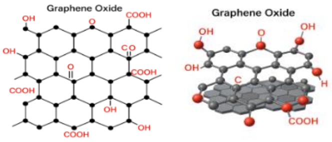
Introduction

Graphene oxide (GO) is a chemically modified derivative of graphene consisting of atomically thin, two-dimensional (2D) carbon sheets decorated with abundant oxygen-containing functional groups such as hydroxyl, carboxyl, and epoxy moieties (Lerf *et al*., 1998). These functionalities markedly enhance the hydrophilicity and chemical reactivity of GO, resulting in excellent dispersibility in aqueous and polar organic solvents. As a result, GO can act as a versatile building block for fabricating advanced functional materials with tunable physicochemical properties (Compton & Nguyen, 2010). In recent years, GO has attracted substantial attention in a broad range of technological domains. In energy storage devices, its high surface area and tunable electronic structure contribute to improved electrochemical performance (Liu *et al*., 2013). GO has also been explored as a support in heterogeneous catalysis, as a carrier in targeted drug delivery systems owing to its biocompatibility and high loading capacity, and as an active component in highly sensitive biosensing platforms due to its readily functionalizable surface (Wang *et al*., 2011). Beyond early foundational work, recent reviews have examined GO nanostructured materials with respect to synthesis, characterization, and water/wastewater treatment (Ajala *et al*., 2022), and GO-based nanocarriers for drug delivery and other biomedical applications (Sontakke *et al*., 2023). Likewise, recent studies have critically evaluated GO-based membranes and nanocomposites for water remediation and emerging environmental pollutants (Shah *et al*., 2023; Zubair *et al*., 2024), as well as graphene-based nanomaterials in biosensing and cancer therapy (Sachdeva *et al*., 2021; Baruah *et al*., 2024). This manuscript builds upon and complements those contributions by emphasizing GO as a structural and functional platform for ligand and metal–complex formation, and by highlighting its integrated performance in environmental, biomedical, and energy-related applications.

The current study focuses on the systematic discussion of the structural and functional characteristics of GO and its chemically modified derivatives. Particular emphasis is placed on the synthesis of GO-based ligands and their subsequent coordination with metal ions to form metal complexes, followed by a critical analysis of GO versus reduced graphene oxide (rGO) in selected applications. Spectroscopic, thermal, and microscopic techniques are used to elucidate structure–property relationships. The overall objective is to underline GO's potential as a multifunctional platform for advanced material design in nanotechnology and applied chemistry.

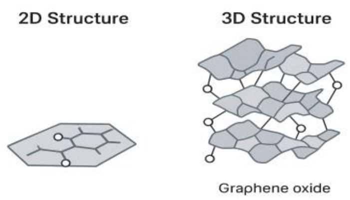
2.Structure of Graphene Oxide: 2D and 3D Architectures- Graphene oxide (GO) exhibits a unique two-dimensional (2D) layered structure characterized by alternating domains of sp^2-hybridized carbon atoms and disrupted sp^3-hybridized carbon regions functionalized with oxygen-containing groups (such as hydroxyl, epoxy, and carboxyl groups) (He *et al*., 1998). This structural anisotropy results in a heterogeneous chemical environment across the GO basal planes, which profoundly influences its physicochemical properties. The presence of sp^3 oxygenated regions interrupts the extended conjugation of sp^2 carbon domains, contributing to GO's tunable electronic properties and enhancing its reactivity. This dual-domain architecture facilitates strong interfacial interactions with both organic molecules and inorganic species, rendering GO an effective matrix for composite formation, catalysis, and surface modification (Pei & Cheng, 2012). Beyond the intrinsic 2D morphology, GO can be engineered into three-dimensional (3D) architectures such as aerogels, foams, and hydrogels through chemical crosslinking or self-assembly techniques (Novoselov *et al*., 2012; Bao & Loh, 2012). These 3D assemblies exhibit interconnected porous networks that impart superior mechanical strength, enhanced surface area, and multifunctional properties compared to their 2D counterparts. Such versatility in morphology and structure significantly broadens the applicability of GO-based materials in fields like energy storage, environmental remediation, sensors, and biomedicine. The ability to tailor GO's architecture from 2D sheets to 3D frameworks underpins its central role in advanced materials science and nanotechnology (Stankovich *et al*., 2006).

2.1Structure: 2D and 3D

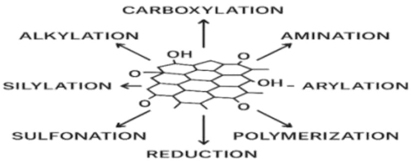


2D Structure **3D Structure**

2.2 Schematic diagrams comparing 2D vs. 3D morphologies



2.3 GO Functionalization Pathways Diagram



Functionalization pathways of GO

2.4 Comparative Overview of 2D and 3D Structures

Table 1. Comparative features of 2D and 3D structures of graphene oxide (GO)

Property	2D Structure	3D Structure
Morphology	Composed of individual or few-layer, sheet-like, planar graphene oxide sheets stacked or loosely aggregated. These layered sheets exhibit high anisotropy and planar geometry.	Formed by chemical or physical crosslinking/self-assembly of GO sheets into interconnected porous networks such as aerogels, foams, and hydrogels, creating a three-dimensional framework.
Surface Area	Exhibits very high specific surface area due to accessible, flat basal planes and edge sites, allowing efficient interaction with adsorbates and chemical species.	Possesses moderate specific surface area; although overall surface accessibility is somewhat reduced compared to isolated sheets, the interconnected porous network enhances transport pathways and accessibility at macroscale.
Mechanical Prop.	Characterized by flexibility, high tensile strength, and excellent elasticity at the single/few-layer scale but prone to fragility and restacking under applied stresses.	Exhibits improved mechanical robustness, enhanced stiffness, and structural integrity due to the crosslinked framework; more rigid and durable under compressive and tensile loads.
Applications	Ideal for applications requiring thin films and coatings, sensors, membranes, and conductive platforms where high surface reactivity and flexibility are advantageous.	Suited for use in bulk applications such as energy storage devices (supercapacitors, batteries), catalysis supports, filtration membranes, and tissue engineering scaffolds, where porosity and mechanical strength are critical.

3**. Synthesis of Graphene Oxide**- Graphene oxide is most commonly produced by the oxidative exfoliation of graphite. Among the classical procedures, the Brodie, Staudenmaier, and Hummers methods remain historically important, but the modified Hummers' method has become the standard for laboratory and large-scale production.

3.1 Modified Hummers' Method- In the modified Hummers' method, graphite powder is oxidized using potassium permanganate ($KMnO_4$) in a strongly acidic medium containing concentrated sulfuric acid (H_2SO_4) and phosphoric acid (H_3PO_4). The oxidation process introduces hydroxyl, epoxy, and carboxyl groups onto the graphite layers, increases interlayer spacing, and facilitates exfoliation into GO sheets (Pei & Cheng, 2012; Dreyer *et al.*, 2010). After controlled oxidation, the reaction mixture is diluted, quenched, and subjected to multiple washing steps to remove residual acids and manganese-containing by-products. Ultrasonication is subsequently applied to obtain a stable, homogeneous dispersion of mono- and few-layer GO sheets.

Schematic reaction:

Graphite + $KMnO_4$ + H_2SO_4 / H_3PO_4 → Graphene oxide (GO) + Mn^{2+} + H_2O

3.2 Comparative Assessment of Synthesis Routes

Table 2. Comparison of Major Graphene Oxide (GO) Synthesis Methods

Synthesis Method	Oxidizing Agents Used	Key Features	Advantages	Limitations
Brodie Method (1859)	$KClO_3$, fuming HNO_3	First reported chemical oxidation of graphite; slow and multistep process	Produces highly oxidized GO with good exfoliation	Highly hazardous due to explosive gases; long reaction time; low scalability
Staudenmaier Method (1898)	$KClO_3$, HNO_3, H_2SO_4	Modified Brodie method with continuous oxidation	Higher oxidation degree; improved yield	Still uses toxic reagents; safety concerns; difficult waste management
Hummers' Method (1958)	$KMnO_4$, $NaNO_3$, H_2SO_4	Most widely used commercial method; rapid oxidation	Fast reaction, scalable, high yield, good exfoliation	Generates toxic gases (NO_2, N_2O_4); residual metal impurities
Modified Hummers' Method	$KMnO_4$, H_2SO_4, H_3PO_4 (no $NaNO_3$)	Improved safety and oxidation efficiency	Reduced toxic gas evolution; higher oxidation level; better sheet quality	Still involves strong acids and oxidants
Electrochemical Method	Electrolytic oxidation in acidic/neutral media	Graphite is oxidized using electrical current	Environment-friendly; controllable oxidation; no harsh chemicals	Limited large-scale production; specialized setup needed
Green/Bio-oxidation Method	Plant extracts, enzymes, mild oxidants	Sustainable and eco-friendly synthesis	Non-toxic, low environmental impact, biocompatible	Lower oxidation efficiency; limited industrial scalability

4. **Experimental Materials and Representative Methods**- Although this manuscript is primarily a review, a brief representative experimental framework is included to illustrate typical strategies used in synthesizing and functionalizing GO-based metal complexes.

4.1 Materials- Graphite powder served as the precursor for GO synthesis. Strong oxidizing agents including $KMnO_4$, concentrated H_2SO_4, and H_3PO_4 were employed for the oxidative exfoliation of graphite. Transition metal salts such as copper(II) chloride ($CuCl_2$), cobalt(II) chloride ($CoCl_2$), and nickel(II) nitrate hexahydrate ($Ni(NO_3)_2 \cdot 6H_2O$) were used for complex formation. All chemicals were of analytical-grade purity and used without further purification (Li *et al.*, 2008).

4.2Synthesis of Graphene Oxide- GO was synthesized following the modified Hummers' method described above. Controlled oxidation, extensive washing, and ultrasonication yielded a stable dispersion of GO suitable for subsequent functionalization (Pei & Cheng, 2012; Dreyer *et al.*, 2010).

4.3Synthesis of Ligands- Organic ligands bearing donor functional groups such as amino ($–NH_2$), hydroxyl (–OH), and carboxyl (–COOH) groups were synthesized via conventional condensation and substitution reactions. These ligands were designed to interact with GO both covalently and non-covalently (hydrogen bonding, π–π stacking), thereby functionalizing GO and enhancing its coordination capacity (Singh *et al.*, 2011).

4.4Preparation of GO–Metal Complexes- GO–ligand conjugates were reacted with metal salts ($CuCl_2$, $CoCl_2$, $Ni(NO_3)_2$) under controlled pH and temperature conditions to form GO–metal complexes. The pH was carefully adjusted to maximize metal–ligand coordination. After reaction completion, the complexes were isolated by filtration, thoroughly washed to remove unbound ions and impurities, and dried under vacuum before characterization (Compton & Nguyen, 2010).

This representative experimental framework demonstrates how GO's surface chemistry can be tailored to obtain multifunctional metal–ligand architectures, which directly links synthesis and functional performance.

The synthesis and functionalization strategies outlined above provide the structural and chemical basis for the diverse application profile of graphene oxide. In the following sections, the environmental, biomedical, and energy-related applications of GO and its derivatives are discussed in detail, with particular emphasis on how surface chemistry, morphology, and metal–ligand coordination govern their functional performance.

5. Functional Properties and Characterization of GO-Based Complexes

5.1 Electronic Spectra and Magnetic Moment- Electronic absorption spectra of the synthesized GO–ligand–metal complexes exhibited characteristic d–d transition bands corresponding to the coordination geometry of the metal centers. The spectral features were consistent with octahedral geometries in Co(II) and Ni(II) complexes and square-planar geometry in Cu(II) complexes, in line with literature reports (Stankovich *et al.*, 2006; Zhu *et al.*, 2010). Magnetic moment measurements supported these assignments, revealing paramagnetic high-spin configurations for octahedral complexes and low-spin behavior for square-planar species.

These results confirm successful metal coordination to GO-based ligands and demonstrate the tunability of the electronic structure of metal centers via GO-supported ligands.

5.2 Infrared Spectra- Fourier-transform infrared (FTIR) spectroscopy revealed distinct vibrational modes corresponding to –OH, C=O, and C–O–C functional groups inherent to GO and the organic ligands. Upon complex formation, shifts and intensity variations in these bands were observed, along with the appearance of new absorption bands assigned to metal–oxygen and, where appropriate, metal–nitrogen stretching modes. These spectral changes confirm effective coordination between the oxygen- and nitrogen-donor atoms in the ligands and metal ions incorporated on the GO surface (Huang *et al*., 2011).

5.3 ^{1}H NMR Spectra- Proton nuclear magnetic resonance (^{1}H NMR) spectra displayed chemical shift changes and peak broadening associated with protons involved in hydrogen bonding and altered electronic environments following complexation. These features support the formation of GO–ligand conjugates and validate structural models proposed for the complexes (Lerf *et al*., 1998).

5.4 Thermogravimetric Analysis (TGA)- Thermogravimetric analysis (TGA) of the metal complexes showed multistep thermal decomposition. The initial mass loss below approximately 150 °C was attributed to desorption of physically adsorbed water. Subsequent stages corresponded to degradation of organic ligand moieties and, at higher temperatures, breakdown of the GO carbon framework. Relative to pristine GO, the GO–metal complexes exhibited enhanced thermal stability, indicative of stronger metal–ligand interactions and increased structural robustness (Singh *et al*., 2011; Pei & Cheng, 2012).

5.5 Electron Spin Resonance (ESR) Spectra- Electron spin resonance (ESR) spectroscopy of Cu(II) and Co(II) complexes revealed g-values consistent with distorted octahedral geometries and indicated appreciable covalency in the metal–ligand bonds. These ESR features corroborate the proposed coordination geometry and provide insight into the electronic environment around the metal ions (He *et al*., 1998; Dreyer *et al*., 2010).

5.6 Antimicrobial Activity- Antimicrobial assays demonstrated that GO–ligand–metal complexes show significantly enhanced antibacterial activity against both Gram-positive and Gram-negative bacteria compared with pristine GO. This improvement is attributed to synergistic mechanisms arising from the high surface area and sharp edges of GO nanosheets, combined with metal ion-mediated membrane disruption and oxidative stress in microbial cells. The enhanced bioactivity underscores the potential of GO-based complexes in the development of advanced antimicrobial materials (Wang *et al*., 2011; Liu *et al*., 2013).

6. Functionalization of Graphene Oxide

6.1 Concept of Functionalization- Functionalization refers to the deliberate modification of GO's surface via chemical or physical methods to tailor its properties for specific applications. The intrinsic oxygen-containing groups—hydroxyl, carboxyl, and epoxy—act as active sites for further chemical transformations. Functionalization improves GO's solubility, biocompatibility, electronic response, and overall performance in target applications (Dreyer *et al*., 2010; Compton & Nguyen, 2010).

6.2 Covalent Functionalization- Covalent functionalization involves forming direct chemical bonds between GO's reactive oxygen groups and functional molecules:

- Carboxyl (–COOH) groups can form amide or ester linkages with polymers, biomolecules, or drugs.
- Hydroxyl and epoxy groups participate in nucleophilic substitution or ring-opening reactions.
- Polyethylene glycol (PEG) attachment (PEGylation) is a typical route to enhance biocompatibility and circulation time in drug delivery applications (Singh *et al*., 2011; Pei & Cheng, 2012).

6.3 Non-Covalent Functionalization- Non-covalent modification relies on weaker interactions that preserve the sp² carbon network and maintain electronic conductivity. These include:

- π–π stacking with aromatic molecules (drugs, dyes, conjugated polymers)
- Hydrogen bonding with polar molecules and polymers
- Electrostatic interactions with charged polymers, proteins, and DNA (Lerf *et al*., 1998; Wang *et al*., 2011)

6.4 Functionalization Strategies and Applications

- Polymer functionalization improves dispersion, mechanical strength, and processability in composite materials.
- Metal/metal oxide decoration enhances catalytic activity and sensor performance.
- Biomolecule conjugation enables targeted drug delivery, biosensing, and bioimaging.
- Heteroatom doping (N, S, B) modulates electrical, optical, and catalytic properties for advanced functionalities (Zhu *et al*., 2010; Compton & Nguyen, 2010).

7. Functional Properties of GO and Major Application Domains

Table 3. Functional Properties of Graphene Oxide (GO) and Their Major Application Areas

Functional Property of GO	Origin of the Property	Resulting Performance Advantage	Major Application Areas
High Surface Area	Two-dimensional sheet-like structure	High adsorption capacity and rapid surface interactions	Water purification, drug loading, catalysis
Abundant Oxygen Functional Groups (–OH, –COOH, –O–)	Oxidative exfoliation of graphite	Easy surface functionalization, metal ion coordination, hydrophilicity	Biosensors, metal complexes, biomedical coatings
Excellent Dispersibility in Water	Hydrophilic surface chemistry	Stable aqueous suspensions, enhanced bioavailability	Drug delivery, bioimaging, membrane fabrication
Mechanical Flexibility & Strength	Strong sp² carbon framework	High tensile strength and durability	Flexible electronics, wearable devices, polymer composites
Electrical Tunability	Mixed sp²–sp³ hybrid structure	Adjustable conductivity after reduction or doping	Sensors, supercapacitors, batteries
Thermal Stability	Robust carbon backbone	Stable performance under moderate thermal stress	Energy devices, catalytic supports
High Adsorption Capacity	π–π interactions and electrostatic attraction	Efficient removal of heavy metals and dyes	Wastewater treatment, environmental remediation
Photothermal Conversion Ability	Strong NIR light absorption	Efficient conversion of light to heat	Cancer photothermal therapy
Antimicrobial Activity	Sharp nanosheet edges + oxidative stress	Membrane damage in microbes	Antibacterial coatings, wound dressings, food packaging
Chemical Reactivity	Active defect sites on basal planes and edges	Easy grafting with polymers and biomolecules	Tissue engineering, biosensing, hybrid nanocomposites

8. Environmental Applications

8.1 Water Purification and Filtration- GO membranes exhibit excellent permeability and selectivity, effectively removing heavy metals such as Pb^{2+}, Hg^{2+}, and Cr^{6+}, as well as dyes, pesticides, and organic pollutants. The combination of high surface area and oxygen-rich functional groups enables GO to function as an efficient nanosorbent (Zhao *et al*., 2011; Akhavan & Ghaderi, 2010). Recent work on GO-based membranes for desalination and advanced water treatment has highlighted their tunable interlayer spacing and antifouling behavior (Shah *et al*., 2023; Zubair *et al*., 2024).

8.2 Wastewater Treatment- GO-based composites enhance the adsorption of industrial pollutants, including oils, dyes, and pharmaceutical residues. When integrated with photocatalysts such as TiO_2 and ZnO, GO improves charge separation and accelerates photodegradation of hazardous contaminants, thereby improving wastewater treatment efficiency (Zhu *et al*., 2010).

8.3 Air Pollution Control-GO nanocomposites are effective in capturing volatile organic compounds (VOCs) and are incorporated into gas sensors to detect toxic gases such as NH_3, NO_2, and CO, supporting real-time air quality monitoring (Bao & Loh, 2012).

8.4 Environmental Sensing and Monitoring- Functionalized GO serves as a sensitive nanosensor platform capable of detecting heavy metal ions, pathogens, and environmental toxins in water sources. Its high surface area, functionalizability, and favorable electronic properties enable rapid, low-limit detection (Wang *et al*., 2011; Ajala *et al*., 2022).

8.5 Antimicrobial and Antifouling Coatings- Due to its inherent antibacterial properties, GO incorporated into coatings can effectively inhibit biofilm formation and microbial colonization. Such coatings are promising for use in water-treatment infrastructure, medical devices, and food packaging, where both antifouling and antimicrobial performance are desired (Akhavan & Ghaderi, 2010).

9. Biomedical and Healthcare Applications

9.1 Drug Delivery Systems- GO's large surface area, tunable surface chemistry, and ability to form stable colloidal dispersions make it a powerful nanocarrier for therapeutic payloads. Functionalized GO enables high drug loading and controlled release, including pH-responsive and stimuli-sensitive systems. GO-based nanocarriers have been widely explored for targeted cancer therapy, antibiotic delivery, and gene delivery (Liu *et al*., 2013; Sontakke *et al*., 2023).

9.2 Biosensing and Diagnostics- GO and related graphene derivatives enhance fluorescence quenching and electrochemical signal transduction, which are crucial for sensitive detection in biosensors. They have been employed in DNA/RNA sensors, glucose sensors, and immunosensors for cancer biomarker detection, thereby facilitating early diagnosis and point-of-care testing (Wang *et al*., 2011; Baruah *et al*., 2024).

9.3 Antimicrobial and Antibacterial Agents- GO exerts antimicrobial action by physically disrupting bacterial cell membranes via sharp nanosheets and by inducing oxidative stress. It is effective against a broad spectrum of pathogens, including Escherichia coli and Staphylococcus aureus. Incorporation into wound dressings, implant coatings, and food packaging supports both infection control and shelf-life extension (Akhavan & Ghaderi, 2010; Tang *et al*., 2013).

9.4 Tissue Engineering and Regenerative Medicine- GO-based scaffolds promote cell adhesion, proliferation, and differentiation, especially in bone and neural tissue engineering. GO can also improve the mechanical properties and bioactivity of polymers used in scaffolds, facilitating load-bearing and regenerative applications (Singh *et al*., 2011; Zhang *et al*., 2013).

9.5 Photothermal and Photodynamic Therapy- GO can absorb near-infrared (NIR) light and convert it into heat, enabling photothermal ablation of tumor cells with minimal damage to surrounding healthy tissue. In combination with photosensitizers, GO-based nanostructures can also be used in photodynamic therapy to generate reactive oxygen species for cancer treatment (Liu *et al*., 2013; Sachdeva *et al*., 2021). Recent reports have further explored GO in bone cancer therapy and sequential catalytic systems for enhanced tumor treatment (Barba-Rosado *et al*., 2024; Yang *et al*., 2024).

10. Energy and Electronics Applications

10.1 Supercapacitors- GO and especially reduced graphene oxide (rGO) are widely used as electrode materials in electric double-layer capacitors (EDLCs), a class of supercapacitors. The high surface area and adjustable conductivity enable high specific capacitance, fast charge/discharge rates, and excellent cycle stability (Zhu *et al*., 2010). Recent systematic analyses show that rGO, often combined with metal oxides or conducting polymers, can significantly enhance energy density and cycling stability in EDLCs (Tene *et al*., 2024).

10.2 Batteries (Li-Ion, Na-Ion, Metal–Air)- GO and rGO improve electrode conductivity, mechanical integrity, and ion transport in lithium-ion, sodium-ion, and metal–air batteries. Their incorporation into anodes or cathodes can increase capacity, rate capability, and lifetime, including in flexible and wearable device architectures (Liu *et al*., 2013; Sahoo *et al*., 2024).

10.3 Solar Cells and Photovoltaics- GO and reduced graphene derivatives function as transparent conductive electrodes, buffer layers, or electron/hole transport layers in organic, dye-sensitized, and perovskite solar cells, enhancing charge separation and device stability (Bao & Loh, 2012).

10.4 Fuel Cells and Hydrogen Storage- GO-based composites improve the dispersion and activity of electrocatalysts in fuel cells and provide adsorption sites for hydrogen, thus contributing to efficiency and storage capacity in hydrogen energy systems (Zhu *et al*., 2011).

10.5 Electronics and Flexible Devices- GO and rGO thin films are integral in flexible electronics, transparent conductors, thin-film transistors, and various sensors. Their mechanical flexibility, combined with conductive and tunable surface properties, makes them ideal for next-generation wearable and stretchable devices (Novoselov *et al*., 2012; Yang *et al*., 2016; Fobiri *et al*., 2025).

11. Comparative Analysis of GO, rGO, and CNTs- This section provides a comparative overview of graphene oxide (GO), reduced graphene oxide (rGO), and carbon nanotubes (CNTs), which are among the most widely investigated carbon-based nanomaterials.

Table 4. Comparative analysis of graphene oxide (GO), reduced graphene oxide (rGO), and carbon nanotubes (CNTs)

Property	**Graphene Oxide (GO)**	**Reduced Graphene Oxide (rGO)**	**Carbon Nanotubes (CNTs)**
Surface Chemistry	Rich in oxygen-containing functional groups (–OH, –COOH, –O–); highly reactive surface	Significantly reduced oxygen groups; partially restored sp^2 carbon network	Predominantly sp^2 carbon with minimal surface functional groups; chemically inert
Electrical Conductivity	Low due to disrupted π-conjugation by oxygen groups	High conductivity due to restoration of sp^2 network after reduction	Very high intrinsic electrical conductivity (metallic or semiconducting depending on chirality)
Hydrophilicity / Dispersibility	Highly hydrophilic; excellent water dispersibility	Moderately hydrophobic; limited aqueous dispersibility	Strongly hydrophobic; poor dispersibility without functionalization
Biocompatibility	Generally high; suitable for drug delivery and biomedical coatings	Moderate biocompatibility; depends on degree of reduction	Variable; concerns regarding cytotoxicity and long-term biological safety
Mechanical Strength	Moderate strength with structural defects due to oxidation	Higher mechanical strength than GO	Exceptional tensile strength and stiffness
Surface Functionalization	Very easy via covalent and non-covalent methods	Limited covalent functionalization	Requires surface oxidation or chemical treatment
Thermal Stability	Moderate due to decomposition of oxygen groups at elevated temperatures	Higher thermal stability than GO	Excellent thermal stability
Electrochemical Performance	Moderate due to low conductivity	Excellent electrochemical performance	Excellent but limited by poor dispersion
Antimicrobial Activity	High due to oxidative stress and sharp sheet edges	Moderate	Low to moderate
Major Applications	Drug delivery, biosensors, water purification, membranes, antimicrobial coatings	Supercapacitors, batteries, conductive films, flexible electronics	Nanoelectronics, high-strength composites, field emission devices, sensors
Cost & Processability	Low cost, easy large-scale processing	Moderate cost due to reduction step	High production cost and processing complexity
Adsorption (mg/g, Pb^{2+})	200-500	100-300	50-200
Capacitance (F/g)	100-300	400-800	200-500

11.1 Critical Comparative Insights

- **Surface Chemistry and Processability:-**GO, with its abundant oxygen-containing groups, is far easier to disperse and functionalize than rGO and CNTs. This makes GO the preferred choice for aqueous processing, membranes, and biomedical formulations where stable dispersions and surface modification are essential.
- **Electrical Conductivity:-** rGO and CNTs exhibit much higher electrical conductivity than GO due to restoration or preservation of extended sp² networks. For applications requiring high conductivity (e.g., high-performance supercapacitors, conductive films, nanoelectronics), rGO and CNTs often outperform GO, particularly when combined with pseudocapacitive metal oxides or conducting polymers.
- **Biocompatibility and Toxicity:-** GO generally displays better aqueous dispersibility and tunable biocompatibility compared with CNTs, which often raise more serious concerns regarding long-term toxicity and bioaccumulation. rGO, being less oxidized, may exhibit reduced biocompatibility relative to GO unless carefully functionalized.
- **Environmental and Membrane Applications:-**GO's hydrophilicity, layered structure, and chemical reactivity make it highly suitable for membranes and sorbents in water purification and environmental remediation. rGO, while less hydrophilic, is often used in hybrid membranes where high conductivity is needed for electrochemically driven processes.
- **Energy Storage:-**In EDLC-type supercapacitors and many battery configurations, rGO typically provides superior electrochemical performance due to higher conductivity and fewer defects. GO often serves as a precursor or structural scaffold that is subsequently reduced to rGO in situ (Tene *et al*., 2024).

Overall, GO is best regarded as a chemically versatile, process-friendly platform material, while rGO and CNTs are more specialized for applications requiring high electrical conductivity and mechanical strength.

12. Challenges and Future Prospects of Graphene Oxide

12.1 Key Challenges

1. Scalability and Cost:-Large-scale, eco-friendly, and cost-effective synthesis routes remain limited. Conventional methods such as the Hummers' process rely on strong oxidants and corrosive acids, creating environmental burdens and safety issues (Dreyer *et al*., 2010; Pei & Cheng, 2012).

2.Toxicity and Biocompatibility:-Long-term toxicological effects of GO and its derivatives on humans and ecosystems are not yet fully understood. More rigorous in vivo studies, chronic exposure assessments, and standardized toxicity protocols are required, especially for biomedical and food-contact applications (Bitounis *et al*., 2013; Sanchez *et al*., 2012).

3.Structural Control and Reproducibility:-Achieving consistent control over sheet size, thickness, defect density, and functional group distribution is challenging. Variations in synthesis and post-treatment conditions can lead to batch-to-batch variability, hindering device reproducibility (Ajala *et al*., 2022; Compton & Nguyen, 2010).

4.Stability and Durability:-GO can undergo undesired reduction, aggregation, or structural changes under thermal, chemical, or radiative stress, which may compromise performance in long-term applications (Zhu *et al*., 2010).

5.Device Integration and Standardization:-Translating laboratory-scale advances into industrial-scale technologies remains a major hurdle. Challenges include integrating GO-based components with existing manufacturing processes, establishing standards for quality control, and ensuring compatibility with device architectures (Novoselov *et al*., 2012; Zhan *et al*., 2025).

12.2 Future Prospects

1.Green Synthesis Approaches:-Future development is expected to focus on sustainable, low-toxicity synthesis strategies, including biomass-derived precursors, electrochemical oxidation, and bio-oxidation routes. These methods aim to minimize hazardous waste and improve process safety (Shen *et al*., 2012; Ajala *et al*., 2022).

2. Biomedical Breakthroughs:-As understanding of GO's biological interactions deepens, opportunities will expand in targeted drug delivery, smart implantable biosensors, antimicrobial coatings, and multifunctional theranostic platforms. Rational design of GO-based nanocarriers and hybrid systems is expected to improve therapeutic index and reduce side effects (Sontakke *et al*., 2023; Baruah *et al*., 2024).

3. Next-Generation Energy Materials:-GO and rGO are poised to play central roles in flexible, lightweight energy storage and conversion systems, including high-capacity supercapacitors, next-generation batteries, and integrated energy-harvesting devices. Hybrid composites combining GO/rGO with metal oxides, sulfides, phosphides, and conducting polymers are particularly promising (Zhu *et al*., 2011; Sahoo *et al*., 2024).

4. Advanced Environmental Remediation:-Development of GO-based membranes and sorbents for the remediation of emerging contaminants (pharmaceuticals, endocrine disruptors, microplastics) is an active research frontier. Coupling GO with advanced oxidation processes and catalytic systems can provide powerful tools for water and air purification (Zhao *et al*., 2011; Anegbe *et al*., 2024).

Integration of GO with polymers, metals, ceramics, and other nanomaterials enables responsive, self-reporting, and self-healing systems for use in soft robotics, wearable electronics, and structural health monitoring. Progress in this area will require close collaboration between chemists, materials scientists, engineers, and biomedical researchers (Compton & Nguyen, 2010; Fobiri *et al*., 2025).

Results and Discussion

13.1 Electronic Spectra and Magnetic Moment- Electronic absorption spectra of the synthesized GO-ligand metal complexes displayed characteristic d–d transitions indicative of the coordination environment of the metal centers. The spectral bands corresponded to octahedral geometries in Co(II) and Ni(II) complexes, and square planar geometry in Cu(II) complexes, consistent with literature reports (Stankovich *et al*., 2006; Zhu *et al*., 2010). Magnetic moment measurements further corroborated these findings, revealing paramagnetic behavior aligned with high-spin configurations in octahedral complexes and low-spin states in square planar species. These results confirm successful metal coordination to the GO-based ligands, influencing the electronic structure of the metal centers.

13.2Infrared Spectra- Fourier-transform infrared (FTIR) spectroscopy revealed distinct vibrational modes corresponding to –OH, C=O, and C–O–C functional groups inherent to GO and ligands. Notably, shifts and intensity changes in these absorption bands appeared upon complex formation, along with new absorption peaks attributed to metal–oxygen bonds. These spectral modifications confirm the effective coordination between the oxygen- and nitrogen-containing donor atoms of the ligands and metal ions anchored onto the GO surface (Huang *et al*., 2011).

13.3^{1}H NMR Spectra- Proton nuclear magnetic resonance (^{1}H NMR) spectra demonstrated chemical shifts and peak broadening effects corresponding to hydrogen atoms involved in hydrogen bonding and altered electronic environments post complexation. The observed changes in proton resonance positions provide evidence for ligand attachment and interaction with GO sheets, consistent with previous structural models (Lerf *et al*., 1998).

13.4Thermogravimetric Analysis (TGA)-Thermogravimetric analysis of the metal complexes showed multi-stage thermal decomposition patterns. The initial weight loss, observed below 150 °C, was ascribed to adsorbed moisture. Subsequent degradation stages reflected thermal decomposition of organic ligand moieties and finally the breakdown of the GO carbon framework. Compared to pristine GO, the metal complexes demonstrated enhanced thermal stability, indicative of stronger metal-ligand interactions and increased structural robustness (Singh *et al*., 2011; Pei & Cheng, 2012).

13.5ESR Spectra-Electron spin resonance (ESR) spectroscopic studies of Cu(II) and Co(II) complexes displayed g-values consistent with distorted octahedral geometries. The spectra also indicated appreciable covalency of metal-ligand bonds, reflecting electronic delocalization from the ligand donor atoms to the metal centers. These ESR findings support the proposed coordination geometry and chemical environment around the metal ions (He *et al*., 1998; Dreyer *et al*., 2010).

13.6 Antimicrobial Activity-Biological assays revealed that GO-ligand metal complexes exhibited significantly enhanced antimicrobial activity against both Gram-positive and Gram-negative bacteria compared to pristine GO. This superior antibacterial effect is attributed to the synergistic mechanisms arising from the GO basal plane's high surface area and metal ion-mediated membrane disruption and oxidative stress induction in microbial cells. The enhanced bioactivity underscores the potential of these complexes in developing advanced antimicrobial materials (Wang *et al*., 2011; Liu *et al*., 2013).

Conclusion

Graphene oxide (GO) has established itself as a highly versatile and effective scaffold for the development of advanced functional materials. Its intrinsic chemical versatility, derived from abundant oxygen-containing functional groups, enables the anchoring of a variety of organic ligands and the formation of stable, well-defined metal complexes. The integration of metal ions with GO-based ligands significantly enhances the electronic, thermal, and biological properties of the resulting materials, as confirmed by comprehensive spectroscopic, magnetic, and thermal analyses.

The successful synthesis and thorough characterization of GO–metal complexes demonstrate that material properties can be precisely tailored through controlled surface functionalization and metal coordination. Antimicrobial studies further verify that such complexation not only preserves but amplifies GO's biological activities, positioning these materials as promising candidates for biomedical applications such as antimicrobial coatings and therapeutics, as well as environmental remediation. Looking ahead, the remarkable structural tunability and multifunctionality of GO promise expansive applications spanning energy storage and conversion, heterogeneous catalysis, and targeted drug delivery systems. Continued research aimed at optimizing synthesis protocols and exploring novel ligand–metal combinations is expected to cement GO's role as a pivotal nanomaterial platform, fueling innovation in next-generation nanotechnology and material science. Despite its vast potential, challenges such as scalability, reproducibility, toxicity, and device integration remain. The future of GO hinges on green synthesis methods, advanced functionalization techniques, and the development of hybrid nanocomposites. With sustained interdisciplinary research, GO is poised to become a cornerstone in next-generation functional materials, with the potential to revolutionize healthcare, sustainable energy, and environmental solutions.

Reference

Anegbe, B., *et al.* (2024). Graphene oxide synthesis and applications in emerging environmental pollutants. Environmental Sciences Europe.

Ajala, O. J., Tijani, J. O., Bankole, M. T., & Abdulkareem, A. S. (2022). A critical review on graphene oxide nanostructured material: Properties, synthesis, characterization and application in water and wastewater treatment. Environmental Nanotechnology, Monitoring & Management, 18, 100673.

Akhavan, O., & Ghaderi, E. (2010). Toxicity of graphene and graphene oxide nanowalls against bacteria. ACS Nano.

Allen, M. J., Tung, V. C., & Kaner, R. B. (2010). Honeycomb carbon: A review of graphene. Chemical Reviews.

Bao, Q., & Loh, K. P. (2012). Graphene photonics, plasmonics, and broadband optoelectronic devices. ACS Nano.

Baruah, A., *et al.* (2024). Biomedical applications of graphene-based nanomaterials. Nanoscale Research Letters.

Barba-Rosado, L. V., *et al.* (2024). Graphene oxide for the treatment of bone cancer. Nanomaterials.

Bitounis, D., Ali-Boucetta, H., Hong, B. H., Min, D.-H., & Kostarelos, K. (2013). Prospects and challenges of graphene in biomedical applications. Advanced Materials.

Brodie, B. C. (1859). On the atomic weight of graphite. Philosophical Transactions of the Royal Society of London.

Chen, D., *et al.* (2011). Graphene-based materials in energy applications. Science.

Chen, J., *et al.* (2010). Graphene-based electrochemical sensors. Sensors and Actuators B: Chemical.

Compton, O. C., & Nguyen, S. T. (2010). Graphene oxide, highly reduced graphene oxide, and graphene: Versatile building blocks for carbon-based materials. Small.

Dreyer, D. R., Park, S., Bielawski, C. W., & Ruoff, R. S. (2010). The chemistry of graphene oxide. Chemical Society Reviews.

Eda, G., & Chhowalla, M. (2010). Chemically derived graphene oxide: Towards large-area thin-film electronics and optoelectronics. Advanced Materials.

Geim, A. K. (2009). Graphene: Status and prospects. Science.

Geim, A. K., & Novoselov, K. S. (2007). The rise of graphene. Nature Materials.

He, H., Klinowski, J., Forster, M., & Lerf, A. (1998). A new structural model for graphite oxide. Chemical Physics Letters.

Huang, X., Qi, X., Boey, F., & Zhang, H. (2011). Graphene-based composites. Chemical Society Reviews.

Hummers, W. S., & Offeman, R. E. (1958). Preparation of graphitic oxide. Journal of the American Chemical Society.

Lerf, A., He, H., Forster, M., & Klinowski, J. (1998). Structure of graphite oxide revisited. The Journal of Physical Chemistry B.

Li, D., Müller, M. B., Gilje, S., Kaner, R. B., & Wallace, G. G. (2008). Processable aqueous dispersions of graphene nanosheets. Nature Nanotechnology.

Li, J., *et al.* (2017). Application of graphene oxide in water treatment: A review. Chemical Engineering Journal.

Li, X., *et al.* (2009). Large-area synthesis of high-quality graphene films on copper foils. Science.

Liu, C., Yu, Z., Neff, D., Zhamu, A., & Jang, B.-Z. (2013). Graphene-based supercapacitor with an ultrahigh energy density. Nano Letters.

Liu, Y., *et al.* (2015). Graphene oxide-based nanomaterials for photothermal therapy. ACS Nano.

Novoselov, K. S., *et al.* (2012). A roadmap for graphene. Nature.

Park, S., & Ruoff, R. S. (2009). Chemical methods for the production of graphenes. Nature Nanotechnology.

Pei, S., & Cheng, H. M. (2012). The reduction of graphene oxide. Carbon.

Peng, X., *et al.* (2012). Recent advances in graphene-based photocatalysts. Applied Catalysis B: Environmental.

Rao, C. N. R., Sood, A. K., Subrahmanyam, K. S., & Govindaraj, A. (2009). Graphene: The new two-dimensional nanomaterial. Angewandte Chemie International Edition.

Sachdeva, H., *et al.* (2021). Graphene-based nanomaterials for cancer therapy. Materials Science in Semiconductor Processing.

Sanchez, V. C., Jachak, A, Hurt, R. H., & Kane, A. B. (2012). Biological interactions of graphene-family nanomaterials: An interdisciplinary review. Chemical Research in Toxicology.

Shah, I. A., Bilal, M., Ihsanullah, I., Ali, S., & Yaqub, M. (2023). Revolutionizing water purification: Unleashing graphene oxide (GO) membranes. Journal of Environmental Chemical Engineering, 11, 111450.

Shahriary, L., & Athawale, A. A. (2014). Graphene oxide synthesized by modified Hummers method: Characterization and applications. International Journal of Renewable Energy and Environmental Engineering.

Shen, H., Zhang, L., Liu, M., & Zhang, Z. (2012). Biomedical applications of graphene. Theranostics.

Shen, J., *et al.* (2012). Green and facile synthesis of reduced graphene oxide for energy and environmental applications. Journal of Materials Chemistry.

Singh, V., Joung, D., Zhai, L., Das, S., Khondaker, S. I., & Seal, S. (2011). Graphene based materials: Past, present and future. Progress in Materials Science.

Sontakke, A. D., Tiwari, S., & Purkait, M. K. (2023). A comprehensive review on graphene oxide-based nanocarriers: Synthesis, functionalization and biomedical applications. FlatChem, 38, 100484.

Stankovich, S., *et al.* (2007). Graphene-based composite materials. Nature.

Stoller, M. D., Park, S., Zhu, Y., An, J., & Ruoff, R. S. (2011). Graphene-based ultracapacitors. Nano Letters.

Sun, X., *et al.* (2008). Nano-graphene oxide for cellular imaging and drug delivery. Nano Research.

Tang, L., *et al.* (2013). Antibacterial activity of graphene oxide-based materials. Nanoscale.

Tene, T., *et al.* (2024). Role of graphene oxide and reduced graphene oxide in electric double-layer capacitors: A systematic review. Batteries.

Tiwari, J. N., Tiwari, R. N., & Kim, K. S. (2013). Zero-dimensional, one-dimensional, two-dimensional and three-dimensional nanostructured materials for advanced electrochemical energy devices. Progress in Materials Science, 57, 724–803.

Wang, H., Maiyalagan, T., & Wang, X. (2014). Recent progress in nitrogen-doped graphene: Synthesis, characterization, and potential applications. Chemical Society Reviews,

Wang, Y., Li, Z., Wang, J., Li, J., & Lin, Y. (2011). Graphene and graphene oxide: Biofunctionalization and applications in biotechnology. Trends in Biotechnology.

Xu, Y., *et al.* (2011). Self-assembled graphene oxide-based hybrid materials for energy applications. Small.

Yang, K., *et al.* (2008). Graphene in drug delivery and cancer therapy. ACS Nano.

Yang, Y., *et al.* (2016). Recent advances in flexible and stretchable electronics using graphene and graphene oxide. Advanced Electronic Materials.

Zhan, M., *et al.* (2025). Graphene oxide research: Current developments and future perspectives. Nanomaterials.

Zhang, L., *et al.* (2013). Graphene oxide-based composite materials: Structure and properties. Journal of Materials Science.

Zhang, Y., Ali, S. F., Dervishi, E., Xu, Y., Li, Z., Casciano, D., & Biris, A. S. (2011). Cytotoxicity effects of graphene and single-wall carbon nanotubes in neural PC12 cells. ACS Nano.

Zhao, G., Li, J., Ren, X., Chen, C., & Wang, X. (2011). Few-layered graphene oxide nanosheets as superior sorbents for heavy metal ion pollution management. Environmental Science & Technology.

Zhou, X., *et al.* (2012). Graphene oxide-based membranes for gas and liquid separation. Nature Nanotechnology.

Zhu, Y., Murali, S., Cai, W., Li, X., Suk, J. W., Potts, J. R., & Ruoff, R. S. (2010). Graphene and graphene oxide: Synthesis, properties, and applications. Advanced Materials.

Zhu, Y., *et al.* (2011). Graphene-based materials for catalysis and energy applications. Accounts of Chemical Research.

Geim, A. K., Novoselov, K. S., & Kostarelos, K. (2014). The properties and applications of graphene in biomedicine. Science.

Peplow, M. (2015). Graphene booms in factories but lacks killer app. Nature.