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Carbon Nanomaterials and Graphene: Synthesis, Properties, and Applications in Energy Storage and Environmental Remediation

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Abstract: *Among modern nanoscale materials, graphene and its derivatives stand out as an unusually versatile platform for materials science, thanks to a rare combination of high electrical conductivity, mechanical robustness, and large specific surface area. This review surveys the structure, synthesis, and functionalization of graphene and related carbon nanostructures — including graphene oxide (GO), reduced graphene oxide (rGO), and carbon nanotubes (CNTs) — with representative reaction schemes for the two dominant synthesis routes: chemical vapor deposition (CVD) for pristine graphene, and Hummers-based oxidation for graphene oxide. Comparative tables summarize how the synthesis route governs layer number, defect density, and yield. Two quantitative case studies follow: functionalized graphene oxide used to capture heavy-metal ions and organic dyes from water, comparing maximum adsorption capacities across several GO derivatives; and graphene/carbon-nanotube composite electrodes built for supercapacitor-based energy storage, comparing specific capacitance across representative hybrid architectures. The review then discusses persisting obstacles to scalable, defect-controlled, and environmentally benign production of carbon nanomaterials, and outlines emerging directions — green and solvent-reduced GO synthesis, three-dimensional graphene architectures, and hybrid carbon-metal oxide composites. Taken together, this synthesis aims to provide a quantitatively grounded reference linking the fundamental chemistry of carbon nanomaterials to their applied performance in energy and environmental technologies.*

Key Words: graphene, graphene oxide, carbon nanotubes, Hummers method, chemical vapor deposition, supercapacitors, environmental remediation.

I. INTRODUCTION

Since its isolation via mechanical exfoliation of graphite in 2004, graphene — a single atomic layer of sp^2-hybridized carbon arranged in a hexagonal lattice — has become the archetypal two-dimensional material, with a theoretical specific surface area of ~2630 m²/g, electron mobility exceeding 200,000 $cm^2\ V^{-1}\ s^{-1}$, a Young's modulus near 1 TPa, and thermal conductivity in the range of 4840–5300 W/mK [1,2]. Together with the wider carbon nanomaterial family — fullerenes, single- and multi-walled carbon nanotubes (CNTs), and graphene oxide (GO) — these properties have made carbon nanostructures a focal point of research spanning electronics, energy storage, structural composites, and environmental remediation [3].

One key practical divide in this family separates pristine, defect-free graphene — typically produced by chemical vapor deposition (CVD) or mechanical exfoliation — from oxidized derivatives such as graphene oxide and reduced graphene oxide (rGO), which form via wet-chemical oxidation of graphite. Rather than competing, the two routes complement each other: CVD yields high-quality, large-area films suited to electronics and sensors, whereas GO/rGO chemistry yields solution-processable, functionalizable, comparatively low-cost material well suited to composites, membranes, and adsorbents [4,5].

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This review first lays out the structure and principal synthesis routes for graphene and its oxidized derivatives, with representative reaction schemes, before examining two application domains in quantitative detail: (i) graphene oxide and its functionalized derivatives used to remove heavy metals and dyes in water treatment, directly relevant to environmental remediation chemistry, and (ii) graphene/CNT composite electrodes for supercapacitor-based energy storage. Throughout, comparative tables and figures link synthesis conditions and material structure to measurable performance outcomes.

II. STRUCTURE AND CLASSIFICATION OF CARBON NANOMATERIALS

Carbon nanomaterials are typically grouped by dimensionality: zero-dimensional fullerenes (e.g., C_{60}), one-dimensional carbon nanotubes (single-walled, SWCNTs, and multi-walled, MWCNTs), and two-dimensional graphene together with its derivatives [3]. Graphene oxide differs structurally from pristine graphene in that oxygen-containing functional groups — hydroxyl, epoxide, carbonyl, and carboxyl — decorate its basal plane and edges as a result of oxidative synthesis. These groups break up the sp^2 network, leaving GO electrically insulating yet strongly hydrophilic and readily dispersible in water — the property that makes it valuable both as a solution-processable precursor and as an adsorbent [6,7]. Removing a substantial share of these oxygen groups through thermal or chemical reduction partially restores conjugation and conductivity, yielding reduced graphene oxide (rGO), a material whose properties fall between GO and pristine graphene [8].

III. SYNTHESIS ROUTES

3.1 Chemical Vapor Deposition (CVD) of Pristine Graphene

In CVD growth, a catalytic metal substrate — most commonly copper foil — is exposed to a carbon-bearing precursor gas such as methane at elevated temperature; the precursor decomposes there, and carbon atoms nucleate and grow into a continuous monolayer film (Scheme 1) [4,9]. This route produces the highest-quality, large-area graphene with the fewest structural defects, which is why it remains the method of choice for electronic and sensor applications, although it demands high vacuum/temperature infrastructure and a subsequent transfer step to lift the film off the metal catalyst and onto a target substrate.

$$CH_4\ (g) \xrightarrow{\text{(Cu catalyst, ~1000 °C, low pressure)}} \text{Graphene (s, on Cu)} + 2\ H_2\ (g)$$

Scheme 1. Chemical vapor deposition (CVD) growth of monolayer graphene from methane on a copper catalyst substrate.

3.2 Modified Hummers Method for Graphene Oxide

Graphite is oxidatively exfoliated to obtain graphene oxide, almost always through the Hummers method or one of its modified variants: graphite is treated with a strong oxidant (potassium permanganate) in concentrated sulfuric acid, which intercalates and oxidizes the graphite layers before they are exfoliated into individual oxidized sheets (Scheme 2) [10,11]. Sodium-nitrate-free variants of the protocol were developed specifically to avoid the toxic NO*x* gases associated with the original Hummers procedure, improving the safety and environmental profile of the synthesis without sacrificing oxidation efficiency [11,12].

$$\text{Graphite (s)} \xrightarrow{\text{(KMnO4, H2SO4, H2O2 workup)}} \text{Graphite oxide (s)} \xrightarrow{\text{(exfoliation, sonication)}} \text{Graphene Oxide (GO)}$$

Scheme 2. Oxidative exfoliation of graphite to graphene oxide via the modified Hummers method.

GO obtained by modified Hummers routes is typically characterized by a carbon-to-oxygen (C:O) ratio near 1.8, an optical bandgap of roughly 2.5–3.6 eV, and a Raman disorder index (I_D/I_G) near 0.9 — figures that point to a high degree of oxidation and structural disorder relative to pristine graphite [13]. A later thermal or chemical reduction step (e.g., using hydrazine, ascorbic acid, or thermal annealing) converts GO into rGO, partially restoring the sp^2 network and thermal stability [14]. Table 1 summarizes the principal synthesis routes covered here.

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Table 1. Comparison of principal synthesis routes for graphene and its oxidized derivatives.

Method	Product	Typical conditions	Key advantage	Key limitation
Mechanical exfoliation	Pristine graphene (few-layer)	Ambient, adhesive-tape exfoliation	Highest crystalline quality	Not scalable
CVD	Monolayer/few-layer graphene	~1000 °C, Cu catalyst, CH4/H2	Large-area, high quality, transferable	High-energy cost; transfer step needed
Modified Hummers method	Graphene oxide (GO)	KMnO4/H2SO4 oxidation, no NaNO3	Scalable, water-dispersible, low equipment cost	Uses strong acids/oxidants; requires purification
Thermal/chemical reduction of GO	Reduced graphene oxide (rGO)	Hydrazine, ascorbic acid, or thermal annealing	Restores conductivity; solution-processable	Residual defects vs. pristine graphene

IV. CASE STUDIES: APPLICATIONS IN REMEDIATION AND ENERGY STORAGE

4.1 Case Study I — Graphene Oxide as an Adsorbent for Water Treatment

GO's basal plane and edges carry a large number of oxygen-containing functional groups, which offer multiple sites for electrostatic attraction, complexation, and hydrogen bonding with cationic dyes and metal ions — this is what makes GO and its functionalized derivatives such effective adsorbents for aqueous pollutants [15,16]. Functionalization approaches such as sulfonation, amination, or citrate grafting add further density and selectivity to these binding sites. Table 2 sets out the maximum adsorption capacities (Q_m) reported for GO and its functionalized derivatives against representative dyes and heavy-metal ions, shown graphically in Figure 1.

Table 2. Maximum adsorption capacity (Qm) of graphene oxide and its functionalized derivatives toward selected dyes and heavy-metal ions, based on Langmuir isotherm fits from the cited sources.

Adsorbent	Target pollutant	Qm (mg/g)	Ref.
Graphene oxide (GO)	Malachite green (dye)	384.6	[17]
Sulfonated GO (SGO)	Methylene blue (dye)	2530	[18]
Amino-functionalized GO (GO-NH2)	Ni(II)	714.3	[19]
Reduced GO (rGO) membrane	Cu2+	149.25	[20]
GO functionalized with citrate	Fe3+	535.0	[21]
Aminated corn-stover-derived rGO (ACS-RGO)	Malachite green (dye)	1088.3	[22]

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Figure 1. Maximum Adsorption Capacities of Graphene Oxide and Functionalized Derivatives for Dyes and Heavy Metal Ions

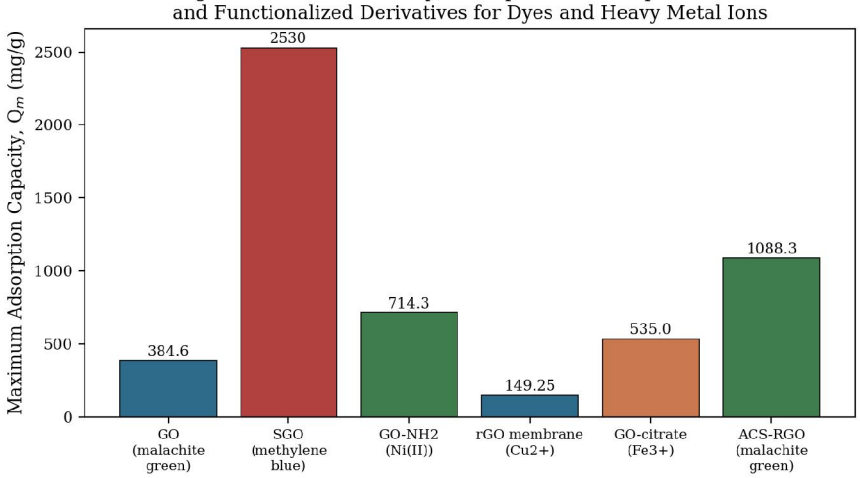


Figure 1. Maximum adsorption capacities of graphene oxide and its functionalized derivatives toward the dyes and heavy-metal ions in Table 2 (data compiled from refs. [17–22]).

Table 2 and Figure 1 point to two consistent patterns. First, functionalized GO consistently outperforms the unmodified material: sulfonation and amination add negatively or positively charged binding sites, which markedly strengthen electrostatic attraction to oppositely charged pollutants [18,19]. Second, cationic dyes tend to reach higher adsorption capacities than metal ions on a given adsorbent, which fits with the larger molecular footprint of aromatic dye molecules and the additional π–π stacking they can form on the graphitic basal plane, on top of electrostatic binding [17,22]. Taken together, these patterns indicate that rationally functionalized GO derivatives can complement the biosorbent- and MOF-based adsorbents described elsewhere in the green-chemistry remediation literature, especially in applications that call for high uptake capacity within a small material volume.

4.2 Case Study II — Graphene/CNT Composite Electrodes for Supercapacitors

Both graphene and CNTs are extensively studied as supercapacitor electrode materials because of their large surface area, electrical conductivity, and chemical stability, yet each has a structural weakness on its own: graphene sheets restack during electrode fabrication and lose accessible surface area, whereas CNTs alone give only a modest specific capacitance [23,24]. Combining the two into composite architectures — with CNTs acting as spacers that keep graphene sheets from restacking while adding their own conductive network — has been repeatedly shown to beat either component used individually. Table 3 and Figure 2 set out specific capacitance values reported for representative graphene/CNT-based electrode systems.

Table 3. Specific capacitance of representative graphene- and carbon-nanotube-based electrode materials for supercapacitors.

Electrode system	Electrolyte / conditions	Specific capacitance (F/g)	Ref.
CNT/reduced graphene oxide (rGO)	Symmetric cell, 25 °C	107.8	[25]
Graphene/single-walled CNT composite	Aqueous (1 M KCl)	290.6	[26]
CNT/graphene/FeCo nanocomposite	—	560.3	[25]
Graphene nanocomposite (GNC)	1 A/g current density	147.0	[24]
Graphene electrode	Ionic liquid electrolyte	244.0	[27]

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Electrode system	Electrolyte / conditions	Specific capacitance (F/g)	Ref.
	(EMIMTFSI)		

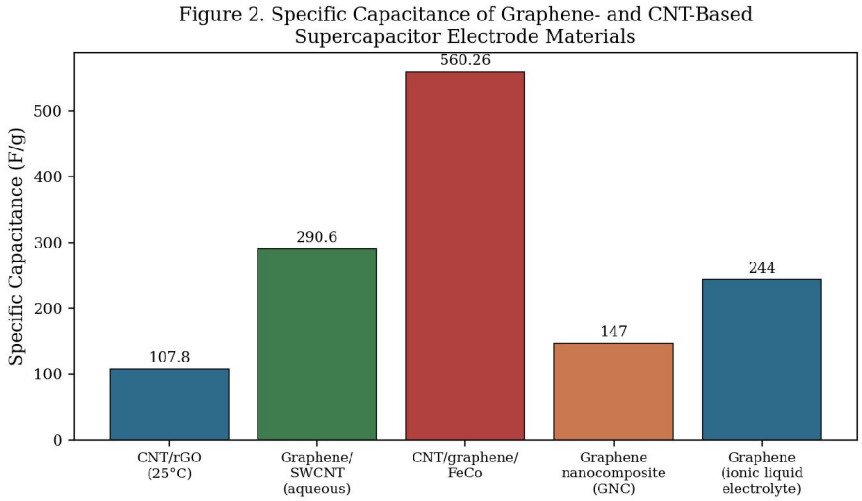


Figure 2. Specific capacitance of the graphene- and CNT-based electrode materials in Table 3, under the conditions cited there (data compiled from refs. [24–27]).

The values in Table 3 show that ternary or metal-doped composites (e.g., CNT/graphene/FeCo) reach the highest specific capacitance of the systems compared, in line with an added pseudocapacitive contribution from the metal component on top of the carbon framework's double-layer capacitance [25]. Even without a metal component, purely carbon-based graphene/CNT composites still clearly outperform graphene or CNTs on their own — evidence that hybridization's main benefit is structural, arising from suppressed restacking and preserved ion-accessible surface area, rather than purely compositional [23,26].

V. CHALLENGES AND FUTURE OUTLOOK

Scalability vs. quality trade-off: CVD gives the highest-quality graphene but at high-energy cost and with an extra transfer step; Hummers-based GO synthesis scales more easily but introduces structural defects and requires handling and purifying strong acids/oxidants.

Environmental footprint of GO synthesis: the conventional Hummers route uses large volumes of concentrated sulfuric acid and produces acidic, metal-containing waste streams; NaNO3-free modified protocols cut toxic gas evolution but still leave an acid-waste management burden.

Restacking and aggregation: both GO/rGO sheets and graphene films tend to restack or aggregate during processing, which erodes the accessible surface area that underlies most of their functional benefits.

Reproducibility: adsorption capacities and capacitance values reported for nominally similar GO or graphene/CNT materials vary considerably from study to study, reflecting sensitivity to precursor graphite quality, oxidation degree, and testing conditions — which makes direct comparison and standardized benchmarking difficult.

Promising directions going forward include greener, solvent-reduced GO synthesis routes that cut acid and oxidant use; three-dimensional graphene architectures (aerogels, foams) that resist restacking by design while keeping surface area high; and hybrid carbon–metal oxide or carbon–MOF composites that pair the conductivity and surface area of carbon nanomaterials with the tunable porosity of framework materials, for use in both energy storage and remediation [28,29].

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VI. CONCLUSION

Graphene and its derivatives — graphene oxide, reduced graphene oxide, and carbon nanotubes — form a family of carbon nanomaterials that is structurally varied yet chemically related, with properties that can be tuned through the choice of synthesis route and post-synthetic functionalization. CVD and modified Hummers chemistry remain the leading routes to pristine graphene and graphene oxide, respectively, each suited to a different set of downstream applications. The two case studies covered here — functionalized GO as a high-capacity adsorbent for dyes and heavy metals, and graphene/CNT composite electrodes for supercapacitors — show that rational functionalization and hybridization strategies can meaningfully lift performance above that of unmodified, single-component materials. Turning these laboratory-scale gains into practical environmental and energy technologies will depend on continued progress toward scalable, lower-impact synthesis and standardized performance benchmarking.

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