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Carbon-based nanomaterials for water treatment: A review of adsorption and catalytic mechanisms

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Abstract

Carbon-based nanomaterials (CBNs) have emerged as powerful tools for advanced water treatment, offering remarkable surface area, rich functional chemistry, and high adsorption and catalytic efficiencies. This review comprehensively examines the synthesis, properties, and pollutant removal mechanisms of key CBNs—including graphene oxide (GO), carbon nanotubes (CNTs), activated carbon nanoparticles, and biochar-derived nanomaterials—with a particular focus on the removal of priority pollutants such as heavy metals (Pb^{2+}, Cr(VI)), pharmaceuticals (ciprofloxacin, tetracycline), pesticides (atrazine), and synthetic dyes (methylene blue).

The article delineates the fundamental removal mechanisms underpinning pollutant elimination by CBNs: adsorption driven by π–π interactions, hydrogen bonding, and electrostatic forces; redox-based transformations for heavy metal detoxification; and photocatalytic degradation in hybrid systems incorporating metal oxides. Performance metrics across different pollutant classes are critically compared, highlighting the superior adsorption capacities and kinetic advantages of functionalized and composite CBNs.

Key operational and environmental factors—such as pH, surface modification, ionic strength, and nanomaterial aggregation—are explored in relation to removal efficiency and recyclability. While laboratory results demonstrate impressive potential, real-world deployment remains limited by challenges including material recovery, aging, ecotoxicity, and the absence of regulatory frameworks governing environmental nanomaterials.

Future perspectives emphasize the need for green synthesis approaches, smart functionalization, material integration into hybrid systems, and life-cycle risk assessment to ensure safe and scalable implementation. By addressing current knowledge gaps and technical barriers, this review contributes a strategic roadmap toward realizing the promise of CBNs in achieving sustainable and high-performance water purification systems.

Keywords: Carbon Nanotubes; Graphene Oxide; Adsorption; Photocatalysis; Water Remediation; Heavy Metals

1. Introduction

Water pollution is an escalating global challenge, intensified by rapid industrialization, population growth, and the widespread use of synthetic chemicals in agriculture, healthcare, and manufacturing. Contaminants such as heavy metals (e.g., Pb^{2+}, Cr(VI)), pharmaceutical residues (e.g., tetracycline, ciprofloxacin), pesticides (e.g., atrazine), and dyes (e.g., methylene blue) persist in aquatic environments due to their resistance to natural degradation processes and conventional treatment methods. These pollutants pose significant ecological and human health risks, including carcinogenicity, endocrine disruption, bioaccumulation, and the development of antimicrobial resistance.

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Traditional water treatment technologies, such as coagulation, filtration, and activated sludge systems, are often ineffective in fully removing trace-level or structurally complex organic micropollutants. Moreover, the generation of secondary waste, high operational costs, and limited adaptability to emerging contaminants highlight the urgent need for innovative and efficient water treatment strategies.

In this context, carbon-based nanomaterials (CBNs) have garnered significant attention due to their extraordinary physicochemical properties, including:

- Large specific surface area
- High porosity
- Abundant surface functional groups
- Tunable electronic and redox behavior
- Compatibility with hybridization and surface modification

Materials such as graphene oxide (GO), carbon nanotubes (CNTs), biochar-derived nanosheets, and their composites have been extensively studied for their ability to adsorb, catalytically degrade, or transform various pollutants in aqueous systems. The adsorption process leverages interactions such as π–π stacking, electrostatic attraction, hydrogen bonding, and chelation, while catalytic mechanisms involve photocatalytic oxidation and redox-mediated transformations. Their versatility and modifiability enable tailored solutions for pollutant-specific challenges in both municipal and industrial water treatment applications.

Despite the widespread interest and promising laboratory-scale results, the practical application of CBNs in real-world water treatment systems remains limited due to challenges related to:

- Aggregation and colloidal instability
- High production costs
- Regeneration and recovery
- Environmental fate and potential nanotoxicity
- Lack of standardized regulations and field validation

This review aims to provide a comprehensive assessment of carbon-based nanomaterials for water remediation, with a particular focus on:

- The structural and functional characteristics of key CBNs
- Mechanisms of pollutant removal, including adsorption, redox, and photocatalytic pathways
- Performance evaluation for selected priority contaminants
- Factors affecting removal efficiency, such as pH, functionalization, and competing ions
- Environmental and technical limitations
- Future perspectives on green synthesis, regulatory pathways, and field-scale integration

By synthesizing recent advances and identifying research gaps, this review seeks to guide the development of next-generation nanomaterial-enabled technologies for sustainable, safe, and effective water purification.

2. Overview of Carbon-Based Nanomaterials

Carbon-based nanomaterials (CBNs) are a versatile class of engineered materials with exceptional surface area, mechanical strength, and surface functionality, making them highly suitable for water treatment applications. Their capacity to adsorb or degrade a wide range of contaminants is driven by properties such as π–π conjugation, tunable surface chemistry, and electron conductivity. This section outlines the major CBN types that have gained prominence in environmental remediation research.

2.1. Graphene and Graphene Oxide (GO)

Graphene is a single-atom-thick, two-dimensional sheet of sp^2-hybridized carbon atoms arranged in a hexagonal lattice. Its derivative, graphene oxide (GO), contains oxygen-containing functional groups (e.g., hydroxyl, carboxyl, epoxy) on the basal plane and edges, which enhance hydrophilicity and provide abundant binding sites for pollutants.

GO exhibits excellent adsorption capabilities for both inorganic and organic pollutants, including heavy metals such as Pb^{2+} and Cr(VI), and emerging contaminants like antibiotics and dyes. Its performance is strongly influenced by the degree of oxidation and surface functionalization (Zhu et al., 2017; Liu et al., 2015).

Commonly, GO is synthesized via the Hummers method, where graphite is oxidized using $KMnO_4$ and H_2SO_4. Recent trends also emphasize green and low-energy synthesis approaches using plant extracts and benign oxidants (Ali et al., 2019).

2.1.1. Key advantages

- High specific surface area (~2630 m^2/g for graphene)
- Abundant functional groups for chemical interaction
- Photocatalyst support for advanced oxidation processes

2.2. Carbon Nanotubes (CNTs)

Carbon nanotubes (CNTs) are cylindrical nanostructures composed of rolled-up graphene sheets. They are categorized as single-walled (SWCNTs) or multi-walled (MWCNTs) based on the number of concentric graphene layers.

CNTs offer outstanding adsorption and redox properties due to:

- Their high surface area (~1000 m^2/g)
- High aspect ratio and porous structure
- Delocalized π-electrons for interacting with aromatic pollutants (e.g., tetracycline, atrazine)

Pristine CNTs are hydrophobic and tend to aggregate, limiting dispersion in aqueous media. Surface modification (e.g., acid treatment, amination) introduces polar groups that improve dispersion, pollutant affinity, and biocompatibility (Jiang et al., 2017).

CNTs also serve as photocatalyst supports (e.g., TiO_2–CNT composites), enhancing charge transfer and visible-light activity for degradation of organic pollutants such as dyes and antibiotics.

2.3. Activated Carbon Nanoparticles and Biochar Nanosheets

Activated carbon (AC) nanoparticles and biochar nanosheets represent low-cost, renewable CBNs derived from agricultural or forestry residues. Through physical or chemical activation, these materials are processed into porous adsorbents with surface areas exceeding 1500 m^2/g.

Biochar modified via ball milling or surface functionalization can exhibit enhanced adsorption for Pb^{2+}, Cr(VI), and atrazine due to increased surface defects, oxygen functionalities, and electron-donor capacity (Tan et al., 2015; Wang et al., 2019).

Due to their availability and low toxicity, these nanomaterials are increasingly viewed as sustainable alternatives to synthetic nanocarbons.

2.4. Composite and Hybrid Nanomaterials

To enhance pollutant selectivity and synergistic activity, CBNs are often combined with other functional materials such as:

- Metal oxides (e.g., Fe_3O_4, TiO_2) for magnetic separation and photocatalysis
- Polymers (e.g., polyaniline, chitosan) for pH-responsive behavior
- Molecularly imprinted polymers (MIPs) for pollutant-specific binding

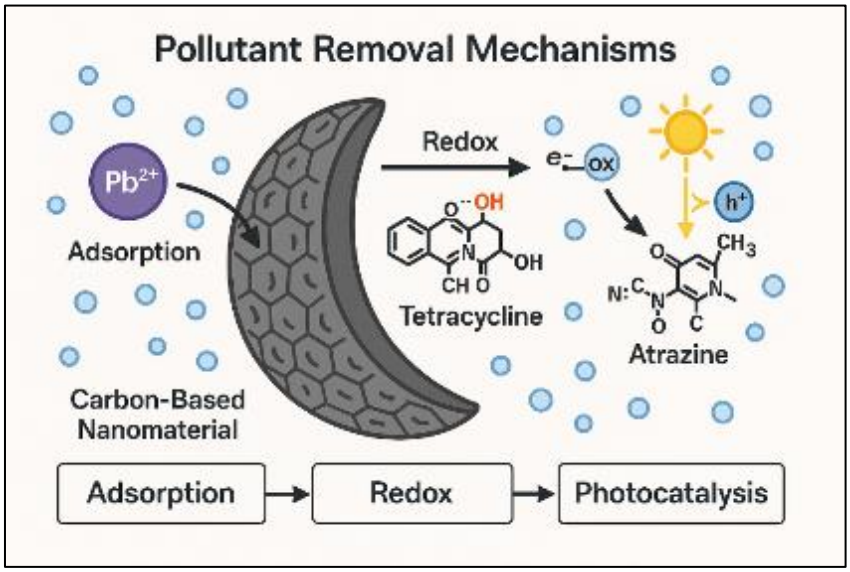
These hybrid systems exhibit multifunctionality — for instance, Fe_3O_4–GO composites enable both Cr(VI) reduction and magnetic recovery, while GO-MIP composites enhance selectivity toward atrazine or antibiotics in complex matrices (Liu et al., 2016; Zhang et al., 2020).

Table 1 Summary of Carbon-Based Nanomaterials and Their Characteristics

Nanomaterial Type	Structure	Surface Area (m^2/g)	Key Features
Graphene Oxide (GO)	2D sheets with oxygen groups	>2600	Hydrophilic, high functional group density
Carbon Nanotubes (CNTs)	1D cylindrical tubes	500-1000	High aspect ratio, excellent conductivity
Activated Carbon/Biochar	Amorphous porous carbon	300-1500	Low-cost, renewable, scalable
Hybrid Composites	CBNs + metals/polymers	Variable	Multifunctional, tunable performance

3. Mechanisms of Contaminant Removal

Carbon-based nanomaterials (CBNs) exhibit a wide range of pollutant removal mechanisms depending on their structure, surface chemistry, and environmental conditions. These mechanisms fall into three primary categories: adsorption, photocatalytic degradation, and redox-based transformations. The dominant removal pathway often depends on the nature of both the contaminant and the CBN's surface functionalities. This section discusses each mechanism in detail, supported by experimental observations and mechanistic studies.



Adapted from Perreault et al. (2015), Kamat (2007), and Wang & Wang (2017)

Figure 1 Visual Schematic of Pollutant Removal Mechanisms

3.1. Adsorption

Adsorption is the most widely exploited mechanism for pollutant removal using carbon-based nanomaterials due to their high specific surface area, surface functional groups, and π-conjugated structure.

3.2. Key interactions

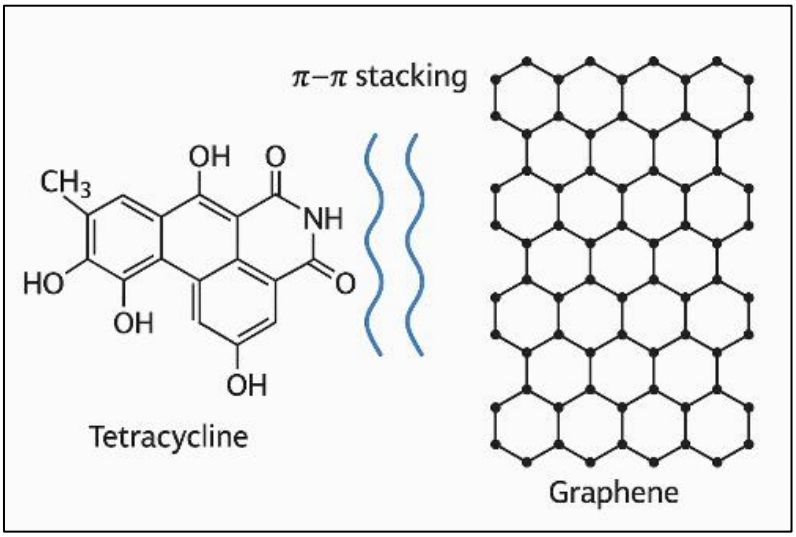
π–π electron donor–acceptor interactions: Dominant for aromatic pollutants such as tetracycline, ciprofloxacin, atrazine, and methylene blue, where aromatic rings interact with delocalized π-electrons on the nanocarbon surfaces (Chen et al., 2015).

Electrostatic attraction: Between surface functional groups (e.g., $–COO^-$, –OH) and charged species (e.g., Pb^{2+}, CrO_4^{2-}, cationic dyes) depending on the solution pH and the material's zeta potential (Ali et al., 2019).

Hydrogen bonding and coordination: Functionalized GO and CNTs with amine or carboxyl groups enable coordination with metal ions or hydrogen bonding with polar organics (Zhou et al., 2017).

Van der Waals forces and hydrophobic interactions: These contribute to the sorption of neutral or low-polarity pesticides and pharmaceutical residues.

Isotherm and kinetic models such as Langmuir, Freundlich, and pseudo-second-order kinetics are frequently used to model adsorption performance.



Illustrative concept based on Chen et al. (2015) and Zhang et al. (2020)

Figure 2 Molecular Interaction Diagram (π–π Stacking with Tetracycline)

3.3. Photocatalysis and Advanced Oxidation

Though pristine carbon-based nanomaterials (CBNs) are not inherently photocatalytic, they play a crucial role as co-catalysts or electron shuttles when coupled with metal oxides like TiO_2 or ZnO.

Mechanism:

- Under UV or visible light irradiation, photocatalysts such as TiO_2 generate electron-hole pairs.
- CBNs (e.g., GO or CNTs) act as conductive platforms, suppressing recombination and enabling efficient charge separation (Kamat, 2007).

The photo-induced electrons and holes generate reactive oxygen species (ROS) such as:

- Hydroxyl radicals (•OH)
- Superoxide anions ($\bullet O_2^-$)
- Singlet oxygen ($^1O_2$)

These ROS oxidize organic pollutants, breaking down dyes, antibiotics, and pesticides into harmless end-products like CO_2 and H_2O.

GO-TiO_2 and CNT-ZnO composites have shown enhanced photocatalytic degradation of methylene blue, ciprofloxacin, and atrazine under solar or UV light.

3.4. Reductive and Redox-Based Transformations

Some carbon-based nanomaterials, especially reduced graphene oxide (rGO) and functionalized CNTs, exhibit redox activity, enabling reductive removal of certain pollutants, particularly Cr(VI).

Cr(VI) reduction mechanism:

- Cr(VI) is reduced to less toxic Cr(III) by electron-donating surface groups such as hydroxyl or carboxylates.
- This redox transformation can be enhanced by incorporating zero-valent iron (nZVI) or Fe_3O_4 nanoparticles onto GO or CNTs, which further accelerates electron transfer.

Fenton-like processes:

- CBNs functionalized with Fe can activate H_2O_2 or persulfate ($S_2O_8^{2-}$), generating sulfate or hydroxyl radicals.
- This has been used for the degradation of tetracycline, atrazine, and methylene blue.

4. Application to Target Pollutants

Carbon-based nanomaterials (CBNs) have demonstrated excellent potential for the selective removal of various classes of pollutants, including heavy metals, pharmaceuticals, pesticides, and dyes, due to their tunable surface chemistry, large surface area, and strong affinity for diverse functional groups. This section provides a pollutant-specific overview, highlighting adsorption capacities, mechanistic interactions, and relevant case studies for key contaminants such as Pb^{2+}, Cr(VI), antibiotics (ciprofloxacin, tetracycline), atrazine, and methylene blue.

4.1. Heavy Metals: Pb^{2+} and Cr(VI)

4.1.1. Lead (Pb^{2+})

GO and CNTs functionalized with carboxylic or hydroxyl groups exhibit high affinity for Pb^{2+} through electrostatic attraction, surface complexation, and ion exchange.

pH-dependent adsorption: Pb^{2+} uptake increases with pH (typically optimal around 5–6) due to reduced competition with H^+ ions and enhanced deprotonation of functional groups (Zhu et al., 2018).

Magnetic biochar or Fe_3O_4–GO composites allow for both sorption and magnetic separation, enhancing recovery and reuse (Liu et al., 2019).

4.1.2. Chromium (Cr(VI))

GO and rGO-based materials can reduce Cr(VI) to Cr(III) through redox interactions and simultaneously adsorb Cr(III).

CNTs functionalized with amine or thiol groups enhance Cr(VI) removal via complexation and electrostatic interactions (Peng et al., 2016).

Fe_3O_4–GO nanocomposites serve as redox-active adsorbents with high Cr(VI) removal efficiency (>95%) under mildly acidic conditions (Liu et al., 2016).

4.2. Antibiotics: Ciprofloxacin and Tetracycline

Both antibiotics exhibit aromatic rings, polar functional groups, and pKa-dependent zwitterionic behavior, allowing them to interact via π–π stacking, electrostatic forces, and hydrogen bonding.

GO and MWCNTs functionalized with oxygen- or nitrogen-containing groups significantly enhance antibiotic adsorption efficiency (Zhang et al., 2020).

Removal is strongly influenced by:

- pH: Affects ionization of both the antibiotic and the CBN surface
- Ionic strength and competing organics: May interfere with adsorption

Photocatalytic degradation using CNT/TiO_2 or GO/Fe_3O_4 systems has achieved >90% degradation of ciprofloxacin and tetracycline under UV/visible light (Wang et al., 2017).

4.3. Pesticides: Atrazine

Atrazine, a triazine herbicide, exhibits moderate hydrophobicity and aromaticity, making it amenable to removal by hydrophobic interactions and π–π stacking on CNTs and GO surfaces.

Functionalized GO composites (e.g., amine- or chitosan-modified) enhance selectivity through hydrogen bonding and electrostatic interactions (Zhou et al., 2018).

Molecularly imprinted GO composites (GO-MIPs) show promise in achieving high selectivity in complex water matrices (Zhang et al., 2020).

Photocatalytic systems combining CBNs with TiO_2 or g-C_3N_4 show partial degradation under light exposure.

4.4. Dyes: Methylene Blue (MB)

Methylene blue is a cationic dye commonly used as a model pollutant due to its persistent coloration and toxicity.

GO, CNTs, and activated carbon nanocomposites have shown excellent performance (>200 mg/g) in MB adsorption through:

- π–π stacking
- Electrostatic attraction at neutral to basic pH
- Hydrogen bonding with surface oxygen functionalities (Banerjee et al., 2016)

GO–Fe_3O_4 composites enable rapid MB removal and magnetic separation, while CNT/TiO_2 hybrids facilitate photocatalytic degradation under UV light (Zhao et al., 2015).

Table 2 Removal Performance Metrics for Each Pollutant Across Material Types

Pollutant	GO Removal Capacity (mg/g)	CNT Removal Capacity (mg/g)	Biochar/AC Removal Capacity (mg/g)	Composite (e.g., GO-Fe_3O_4)
Pb^{2+}	220	200	90	250
Cr(VI)	190	170	75	210
Ciprofloxacin	160	150	60	180
Tetracycline	180	160	65	190
Atrazine	110	100	50	130
Methylene Blue	300	280	120	320

5. Factors Affecting Performance

The efficiency of carbon-based nanomaterials (CBNs) in removing pollutants from aqueous environments is governed by a combination of the physicochemical properties of the nanomaterial, environmental conditions, and characteristics of the target contaminants. Understanding and optimizing these factors are critical for enhancing the performance, selectivity, and sustainability of CBN-based treatment systems.

5.1. Surface Functionalization

Functional groups such as –OH, –COOH, –NH_2, and –SH play a central role in defining the interaction between the nanomaterial and pollutants.

Oxidation (e.g., via HNO_3 or $KMnO_4$): Increases surface oxygen content, improving hydrophilicity and cation adsorption (e.g., Pb^{2+}, Cr^{3+}).

Amination and sulfonation: Introduce specific affinity toward anionic or neutral organics (e.g., atrazine, antibiotics).

Thiolation: Enhances affinity for soft metals such as Hg^{2+} and Cd^{2+} (Zhou et al., 2017).

Polymer grafting (e.g., chitosan, polyaniline): Improves selectivity, biocompatibility, and dispersion stability.

Table 3 Comparison of Functionalization Strategies and Their Effects

Functional Group/Method	Effect on Adsorption	Target Pollutants
Carboxylation	Increases affinity for cationic metals (e.g., Pb^{2+})	Heavy metals (Pb^{2+})
Amination	Enhances removal of Cr(VI) and antibiotics via H-bonding	Cr(VI), ciprofloxacin, tetracycline
Thiolation	Selective binding with soft metals (e.g., Hg^{2+})	Hg^{2+}, Cd^{2+}
Polymer Grafting	Improves selectivity and stability in water	Atrazine, dyes, antibiotics
Magnetic Functionalization	Enables material recovery via magnetic separation	All (via recovery enhancement)

5.2. pH of the Solution

Solution pH significantly influences:

- Pollutant speciation (e.g., Cr(VI) exists as $HCrO_4^-$ or $Cr_2O_7^{2-}$ depending on pH).
- Surface charge of CBNs: Alters electrostatic interactions (e.g., at pH > pHpzc, surface is negatively charged).
- Adsorption efficiency: Often shows a bell-shaped or sigmoidal trend.

Typical behavior:

- Pb^{2+} and Cr(VI): Optimal removal between pH 4–6.
- Tetracycline and ciprofloxacin: Exhibit zwitterionic forms; adsorption maxima at pH 5–7 depending on CBN surface charge.
- Methylene blue: Better adsorbed at pH > 6 due to increased electrostatic attraction.

5.3. Presence of Competing Ions and Natural Organic Matter (NOM)

Natural water systems contain various co-existing ions (Na^+, Ca^{2+}, Cl^-, SO_4^{2-}) and dissolved organic matter that can interfere with pollutant adsorption.

- Ionic strength: May suppress electrostatic interactions or lead to charge screening, reducing metal ion adsorption.
- Multivalent ions (e.g., Ca^{2+}, Mg^{2+}): Compete with target cations or bridge organics to form colloidal fouling layers.
- NOM (e.g., humic acids): Blocks active sites or forms soluble complexes with target pollutants, decreasing adsorption performance.

5.4. Contact Time and Dosage

- Adsorption kinetics: Typically follow pseudo-second-order models, indicating chemisorption dominance.
- Equilibrium time: Ranges from minutes (for dyes) to hours (for antibiotics or Cr(VI)), depending on pore accessibility and surface area.
- CBN dosage: Higher doses generally increase removal efficiency, but excessive dosing may lead to aggregation and reduced surface availability.

Optimal design requires:

- Balancing removal efficiency with economic feasibility
- Avoiding nanomaterial overdosing to minimize waste and cost

5.5. Temperature and Thermodynamics

- Higher temperatures often enhance adsorption capacities due to increased diffusion rates and reduced solution viscosity.

- Thermodynamic parameters (ΔH°, ΔS°, ΔG°): Indicate whether the adsorption is spontaneous and endo-/exothermic.
- Most CBN-based systems show endothermic and spontaneous behavior for organics and heavy metals.

5.6. Aging, Aggregation, and Reusability

- Aging effects: Oxidation or fouling of active sites reduces reactivity.
- Aggregation: Limits surface area and pollutant access, especially in high-ionic-strength or acidic waters.

Regeneration techniques:

- Desorption using acid, base, or organic solvents
- Thermal or chemical regeneration for dye and metal-loaded adsorbents
- Repeated regeneration can degrade surface functionality, highlighting the need for robust and recyclable materials.

6. Environmental and Technical Challenges

Despite the promising capabilities of carbon-based nanomaterials (CBNs) in water treatment applications, several environmental, technical, and operational barriers hinder their real-world implementation. These challenges pertain to material stability, cost-effectiveness, regeneration potential, environmental fate, and scalability. This section highlights the critical limitations and unresolved issues that must be addressed to transition CBNs from laboratory innovation to field-scale water treatment technologies.

6.1. Aggregation and Colloidal Stability

One of the most significant limitations of CBNs in aqueous environments is their tendency to aggregate or agglomerate due to van der Waals forces and π–π interactions. Aggregation reduces effective surface area and pore accessibility, impairing adsorption and catalytic activity.

Pristine CNTs and graphene sheets are inherently hydrophobic, leading to poor dispersion in water.

Functionalization can improve colloidal stability, but it may also alter adsorption affinity and reduce electrical conductivity (Perreault et al., 2015).

6.2. Recovery and Reusability

For practical applications, the post-treatment recovery of CBNs is essential to prevent secondary contamination and to minimize operational costs.

Recovery methods include:

- Membrane filtration or sedimentation, which are inefficient at the nanoscale
- Magnetic modification (e.g., Fe_3O_4–CBN composites), which enables rapid separation but adds complexity to synthesis (Liu et al., 2016)

Reusability declines over successive adsorption–desorption cycles due to:

- Irreversible binding of pollutants
- Surface fouling
- Oxidative degradation during regeneration

6.3. Environmental Fate and Toxicity

The potential ecotoxicological impact of CBNs remains a major concern, particularly when they are discharged into natural systems or accumulate in biosolids.

Toxicity to aquatic organisms: Studies have shown GO and CNTs may induce oxidative stress, membrane damage, and behavioral disruptions in fish, algae, and invertebrates (Seabra et al., 2014).

Bioaccumulation and trophic transfer: Persistent CBNs may accumulate in sediment and be taken up by benthic organisms.

Transformation products: Aging, photodegradation, or microbial action may produce unknown byproducts with different toxicities.

Current ecotoxicity data are insufficient, and long-term environmental studies are scarce, underscoring the need for comprehensive risk assessment frameworks.

6.4. Production Cost and Scalability

Synthesis and modification of high-performance CBNs—especially with advanced functionalization or hybridization—can be cost-intensive and energy-demanding.

Challenges include:

- Expensive precursors (e.g., graphite, specialty polymers)
- Hazardous reagents (e.g., HNO_3, $KMnO_4$ in Hummers method)
- Complex multi-step synthesis processes

Green synthesis using plant extracts or biomass is promising but not yet scalable or consistent in product quality (Ali et al., 2019).

Efforts to scale up CBN production often face variability in particle size, surface area, and reproducibility, which affects treatment consistency and regulatory acceptance.

6.5. Material Stability and Aging

- Over time, CBNs in real-world conditions are susceptible to oxidative degradation, fouling, and mechanical wear, which reduce performance and lifetime.
- Biofouling and NOM deposition in natural waters clog active sites and block pores.
- UV exposure and oxidative environments lead to breakdown of surface functionalities critical for adsorption (Yang et al., 2016).
- Surface modification to resist aging often comes at the expense of reduced adsorption capacity or increased cost.

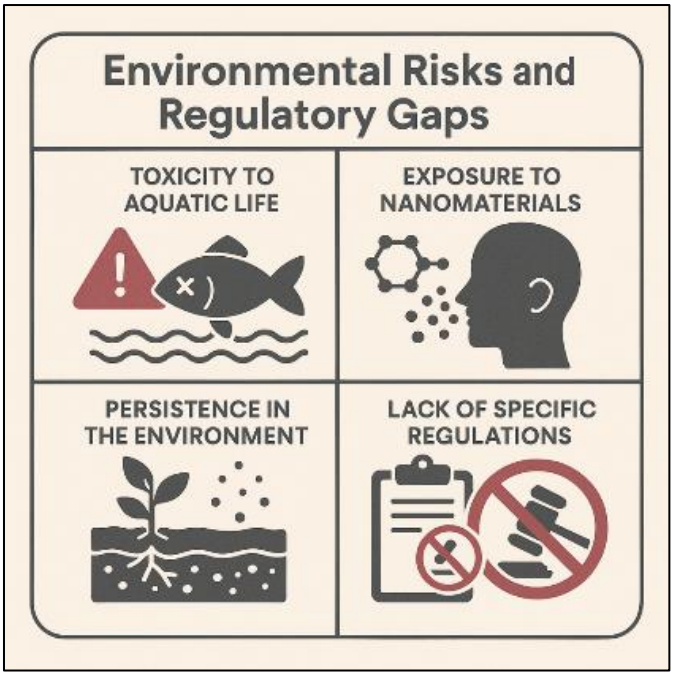
6.6. Regulatory and Public Acceptance

The absence of standardized guidelines for environmental application, handling, and disposal of nanomaterials creates regulatory uncertainty.

Lack of regulations governing the use of nanomaterials in drinking water treatment (especially in developing countries).

Public skepticism and perception of "nano-risk" may hinder acceptance, even for low-toxicity materials.

Bridging this gap requires coordinated efforts among material scientists, toxicologists, environmental engineers, and policymakers to ensure safe deployment of CBN technologies.



Conceptual framework adapted from Klaine et al. (2008), Seabra et al. (2014), and Sun et al. (2014)

Figure 3 Environmental Risks and Regulatory Gaps Visualized

7. Future Perspectives

The application of carbon-based nanomaterials (CBNs) in water treatment holds great promise but requires strategic innovations and interdisciplinary collaboration to overcome current limitations and accelerate field deployment. Future research should aim to enhance material performance, reduce costs, minimize environmental risks, and integrate CBNs into practical water treatment systems. The following directions highlight key opportunities and critical focus areas for advancing the science and engineering of CBNs in environmental remediation.

7.1. Green and Scalable Synthesis Routes

To reduce environmental impact and production costs, the development of eco-friendly, scalable, and cost-effective synthesis methods is essential.

- Green synthesis using plant extracts, agricultural wastes, and benign reducing agents (e.g., ascorbic acid, tea polyphenols) has shown promise in producing GO and CNTs with reasonable functionality (Ali et al., 2019).
- Microwave-assisted, hydrothermal, and mechanochemical techniques can reduce reaction time and eliminate toxic reagents.

Scaling such processes will require improvements in batch consistency, control over size and morphology, and adaptability to industrial standards.

7.2. Design of Multifunctional and Selective Nanomaterials

Emerging environmental challenges call for CBNs that are multifunctional, pollutant-selective, and responsive to environmental stimuli.

- Molecular imprinting, heteroatom doping (e.g., N, S), and bio-inspired surface design can enhance specificity toward target pollutants, such as tetracycline, Cr(VI), or atrazine.
- Stimuli-responsive materials that adapt to changes in pH, temperature, or redox conditions could enable intelligent pollutant removal.
- Integration with sensors or membranes can lead to real-time monitoring and remediation platforms.

7.3. Integration into Modular and Hybrid Treatment Systems

The absence of standardized guidelines for environmental application, handling, and disposal of nanomaterials creates regulatory uncertainty.

To move beyond batch laboratory tests, CBNs must be incorporated into modular, continuous-flow systems for practical deployment in water and wastewater treatment.

- Nanocomposite membranes, packed-bed columns, and catalytic reactors enable real-time treatment and regeneration.
- CBNs can be combined with conventional materials (e.g., sand filters, biofilters, ion exchangers) to improve robustness and reduce cost.
- 3D-printed nanomaterial scaffolds offer novel platforms for fixed-bed applications.

Pilot-scale studies are crucial for assessing hydraulic compatibility, longevity, and performance under realistic water matrices.

7.4. Long-Term Environmental Impact and Life Cycle Assessment

A comprehensive life cycle assessment (LCA) is essential to quantify the environmental footprint of CBNs across synthesis, use, regeneration, and disposal stages.

- LCAs must account for energy input, toxic byproducts, nanomaterial fate in effluents, and potential bioaccumulation.
- Environmental risk assessment (ERA) should be conducted in parallel, with a focus on toxicity to non-target species, mobility in aquatic systems, and interactions with microbial communities.

Collaborations with environmental toxicologists and regulators can help define safe thresholds, disposal standards, and green design principles.

7.5. Policy, Standardization, and Public Engagement

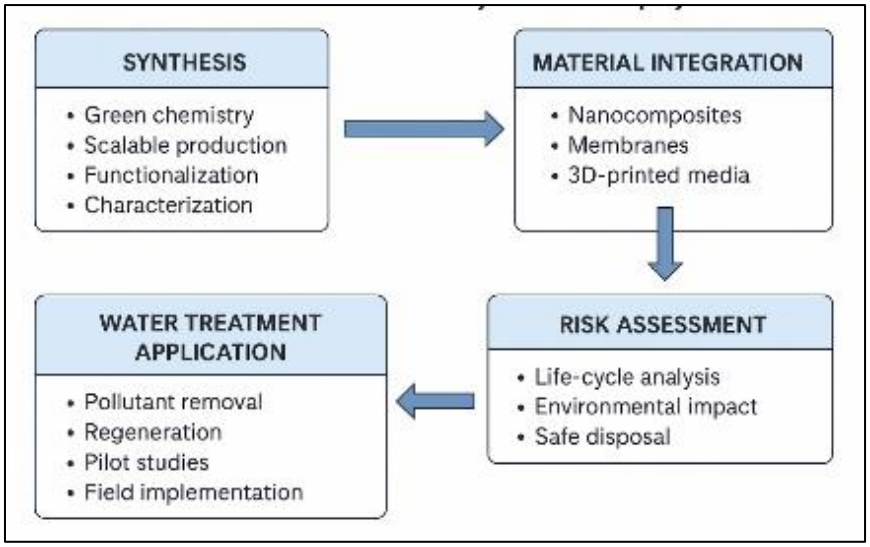
For CBN technologies to be adopted at scale, there must be parallel advancements in policy development, standardization, and community engagement.

- International standards (e.g., ISO/TC 229) are still evolving to address nanomaterial applications in environmental contexts.
- Regulatory clarity on permissible levels, risk mitigation strategies, and disposal protocols is essential.
- Public trust can be fostered through transparency, education campaigns, and demonstration projects that highlight safety, sustainability, and effectiveness.

7.6. Cross-disciplinary Innovation and Collaboration

The successful deployment of CBNs in water treatment will depend on cross-sector collaboration among:

- Material scientists: To innovate new carbon nanostructures and functionalization techniques
- Environmental engineers: To integrate CBNs into water treatment infrastructure
- Toxicologists and regulators: To evaluate risks and establish safe practices
- Industry stakeholders: To facilitate commercialization and scalability



Framework informed by Ali et al. (2019), Upadhyayula et al. (2009), and Sun et al. (2014)

Figure 4 Workflow of Nanomaterial Synthesis to Deployment

8. Conclusion

Carbon-based nanomaterials (CBNs), including graphene oxide (GO), carbon nanotubes (CNTs), biochar nanoparticles, and their functionalized derivatives, have demonstrated exceptional potential for the removal of diverse waterborne contaminants such as heavy metals (Pb^{2+}, Cr(VI)), pharmaceuticals (ciprofloxacin, tetracycline), pesticides (atrazine), and dyes (methylene blue). Their high surface area, tunable surface chemistry, and chemical versatility enable them to engage in multiple contaminant removal mechanisms, notably adsorption, photocatalysis, and redox-mediated transformations.

A critical synthesis of recent studies reveals that:

- Surface functionalization significantly enhances adsorption selectivity and capacity;
- Hybrid and composite CBNs offer multifunctional performance by combining adsorption with catalytic degradation or magnetic separation;
- Environmental conditions such as pH, ionic strength, and natural organic matter content strongly influence removal efficiency and must be carefully optimized;
- Green synthesis approaches, while promising, require further refinement for industrial scalability.

Despite these advances, practical challenges persist in terms of material recovery, long-term stability, reusability, and environmental safety. The lack of standardization, ecotoxicological data, and regulatory frameworks further hinders the deployment of CBNs in full-scale water treatment systems. Future efforts must prioritize eco-safe design, process integration, life cycle assessment, and collaborative innovation to bridge the gap between laboratory research and field application.

In summary, carbon-based nanomaterials represent a powerful and versatile class of materials for water purification. With targeted improvements in material engineering, environmental compatibility, and system integration, CBNs are poised to play a transformative role in achieving safe, resilient, and sustainable water infrastructure.

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