

Nitrogen-Doped Hybrid Nanomaterials for Environmental Monitoring, Water Treatment, and Green Industrial Technologies



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ABSTRACT

Rapid industrialization, urbanization, and increasing anthropogenic activities have significantly intensified environmental pollution, posing serious challenges to water quality, ecosystem sustainability, and human health. Conventional remediation technologies often suffer from limited efficiency, high operational costs, poor selectivity, and secondary pollution. Nitrogen-doped hybrid nanomaterials have recently emerged as an advanced class of multifunctional materials owing to their unique electronic structures, enhanced surface reactivity, high electrical conductivity, tunable physicochemical properties, and superior catalytic performance. Incorporation of nitrogen atoms into carbon-based and inorganic nanomaterials modifies their electronic configuration, increases defect density, improves active site availability, and enhances adsorption and catalytic efficiency. Furthermore, hybridization with metal nanoparticles, metal oxides, graphene, carbon nanotubes, biochar, metal-organic frameworks (MOFs), quantum dots, and conducting polymers has greatly expanded their environmental applications. These multifunctional nanomaterials have demonstrated remarkable performance in environmental monitoring, water purification, wastewater treatment, photocatalysis, electrocatalysis, gas sensing, pollutant degradation, antimicrobial activity, and sustainable industrial processes. This review summarizes recent advances in synthesis methods, structural engineering, physicochemical properties, functionalization strategies, environmental applications, industrial technologies, current challenges, and future prospects of nitrogen-doped hybrid nanomaterials for sustainable environmental management.

Keywords: Nitrogen-doped nanomaterials, Hybrid nanomaterials, Environmental monitoring, Water treatment, Green technology.

1. Introduction

Environmental pollution has become one of the most pressing global challenges due to rapid industrial development, population growth, urban expansion, intensive agriculture, and increasing consumption of synthetic chemicals. Large quantities of hazardous contaminants, including heavy metals, dyes, pesticides, pharmaceutical residues, endocrine-disrupting compounds, volatile organic compounds (VOCs), persistent organic pollutants, and greenhouse gases, are continuously released into aquatic and terrestrial ecosystems. These pollutants accumulate within the environment, threaten biodiversity, impair ecosystem services, and pose serious health risks through long-term exposure and bioaccumulation. Traditional environmental remediation technologies such as activated carbon adsorption, coagulation, membrane filtration, ion exchange, biological treatment, and chemical oxidation have

contributed substantially to pollution control [1]. However, many conventional approaches exhibit limitations including low adsorption capacity, poor selectivity, membrane fouling, high operational costs, sludge generation, and incomplete degradation of emerging contaminants. Consequently, there is growing interest in developing advanced multifunctional nanomaterials capable of efficient pollutant removal while supporting sustainable industrial development.

Nitrogen-doped hybrid nanomaterials have emerged as one of the most promising classes of advanced functional materials. Nitrogen incorporation into carbonaceous and inorganic nanostructures significantly modifies their electronic configuration by introducing electron-rich active sites, increasing defect density, improving electrical conductivity, and enhancing catalytic activity. Various nitrogen configurations, including pyridinic nitrogen, pyrrolic nitrogen, graphitic nitrogen, and oxidized nitrogen, contribute differently to adsorption behavior, electron transfer, catalytic reactions, and sensing performance. Hybridization further enhances material functionality by combining nitrogen-doped materials with graphene, reduced graphene oxide, carbon nanotubes, carbon dots, biochar, metal nanoparticles, semiconductor oxides, metal sulfides, metal-organic frameworks (MOFs), coordination polymers, and conducting polymers. These hybrid systems exhibit synergistic interactions that improve adsorption capacity, photocatalytic degradation, antimicrobial activity, electrochemical performance, and environmental stability [2]. Recent advances in green synthesis, computational materials design, artificial intelligence-assisted optimization, renewable biomass-derived precursors, and sustainable manufacturing have accelerated the development of environmentally friendly nitrogen-doped hybrid nanomaterials.

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Their applications now extend beyond pollution control to environmental monitoring, renewable energy production, industrial catalysis, carbon capture, hydrogen evolution, and smart sensing technologies.

2. Fundamentals and Structural Characteristics of Nitrogen-Doped Hybrid Nanomaterials

Nitrogen-doped hybrid nanomaterials are multifunctional materials in which nitrogen atoms are incorporated into carbonaceous or inorganic frameworks while simultaneously integrating additional functional components to improve physicochemical performance. Nitrogen doping alters the electronic distribution within the host material because nitrogen possesses a different electronegativity and atomic radius than carbon. Consequently, localized charge redistribution occurs, creating highly active catalytic and adsorption sites [3]. Nitrogen exists within carbon materials in several chemical configurations. Pyridinic nitrogen contributes one p-electron to the aromatic system while providing lone-pair electrons that strongly interact with metal ions and pollutant molecules. Pyrrolic nitrogen contributes two p-electrons within five-membered aromatic rings and enhances surface polarity. Graphitic or quaternary nitrogen substitutes directly into the graphene lattice, significantly improving electrical conductivity and electron transport. Oxidized nitrogen species further modify surface hydrophilicity and adsorption characteristics. Various host materials have been successfully nitrogen-doped, including graphene, graphene oxide, reduced graphene oxide, carbon nanotubes, activated carbon, porous carbon, biochar, carbon quantum dots, graphitic carbon nitride (g-C₃N₄), carbon aerogels, and mesoporous carbon. Hybridization with secondary functional materials such as titanium dioxide, zinc oxide, iron oxide, cobalt oxide, nickel oxide, molybdenum sulfide, silver nanoparticles, gold nanoparticles, metal-organic frameworks, and conductive polymers further enhances catalytic activity, adsorption efficiency, and environmental stability. The exceptionally high surface area of nitrogen-doped porous materials provides abundant adsorption sites for environmental contaminants. Simultaneously, nitrogen-induced structural defects facilitate electron transfer, accelerate redox reactions, and improve photocatalytic performance. These synergistic structural characteristics enable efficient removal of heavy metals, dyes, pharmaceuticals, pesticides, and atmospheric pollutants while supporting advanced catalytic and sensing applications.

Table 1: Common Nitrogen-Doped Hybrid Nanomaterials

Material	Hybrid Component	Major Environmental Application
N-doped graphene	Metal oxides	Water purification
N-doped graphene oxide	TiO ₂	Photocatalysis
N-doped carbon nanotubes	Fe ₃ O ₄	Heavy metal removal
N-doped biochar	Metal nanoparticles	Wastewater treatment
Graphitic carbon nitride	Graphene	Organic pollutant degradation
N-doped carbon dots	Polymers	Environmental sensing
N-doped porous carbon	MOFs	Carbon capture

3. Synthesis and Functionalization Strategies

The synthesis of nitrogen-doped hybrid nanomaterials has evolved considerably with advances in nanotechnology and green chemistry. The choice of synthesis method strongly influences nitrogen content, dopant configuration, pore architecture, surface chemistry, particle morphology, and overall environmental performance. Modern fabrication techniques emphasize precise control over structural properties while minimizing energy consumption and environmental impact.

Thermal annealing remains one of the most widely employed nitrogen-doping methods. Carbon precursors are heated in the presence of nitrogen-rich compounds such as urea, melamine, ammonia, thiourea, or dicyandiamide at elevated temperatures. During pyrolysis, nitrogen atoms become incorporated into the carbon lattice, generating various nitrogen functional groups that enhance electrical conductivity and catalytic activity. Hydrothermal and solvothermal synthesis techniques enable simultaneous nitrogen doping and hybrid nanocomposite formation under controlled temperature and pressure conditions. These approaches facilitate homogeneous incorporation of metal nanoparticles, semiconductor oxides, graphene derivatives, and polymeric components, producing multifunctional materials with excellent structural integrity and catalytic performance [3-5]. Chemical vapor deposition provides high-quality nitrogen-doped graphene and carbon nanotubes with controlled nitrogen concentration and crystallinity. Although this technique requires sophisticated instrumentation, it produces highly conductive materials suitable for advanced sensing and catalytic applications. Green synthesis has become increasingly important for sustainable nanomaterial production. Biomass-derived precursors including cellulose, lignin, chitosan, agricultural waste, fruit peels, algae, proteins, amino acids, and plant extracts serve as renewable carbon and nitrogen sources. These environmentally friendly approaches eliminate hazardous chemicals while reducing production costs and supporting circular economy principles. Surface functionalization further improves material performance by introducing amino, carboxyl, sulfonic acid, phosphonate, thiol, and polymeric groups that increase adsorption capacity, hydrophilicity, pollutant selectivity, and catalytic activity. Hybridization with metal nanoparticles, graphene derivatives, metal-organic frameworks, quantum dots, and conducting polymers creates multifunctional systems capable of simultaneous adsorption, catalysis, sensing, and antimicrobial activity.

Table 2: Major Synthesis Methods

Method	Nitrogen Source	Major Advantages
Thermal annealing	Urea, melamine	Simple and scalable
Hydrothermal synthesis	Ammonia, amino acids	Uniform nanostructures
Solvothermal synthesis	Organic amines	High crystallinity
Chemical vapor deposition	NH ₃ gas	High-quality graphene
Green synthesis	Biomass, proteins	Eco-friendly production
Microwave synthesis	Urea derivatives	Rapid fabrication

4. Applications in Environmental Monitoring

Nitrogen-doped hybrid nanomaterials have become highly effective materials for environmental monitoring because of their excellent electrical conductivity, high sensitivity, rapid electron transfer, and abundant active surface sites. They are widely used in electrochemical, fluorescent, and optical sensors for detecting heavy metals, pesticides, antibiotics, toxic gases, volatile organic compounds (VOCs), and other environmental pollutants [6]. Nitrogen doping enhances charge transport and signal amplification, resulting in lower detection limits, higher selectivity, and improved sensor stability. These materials enable rapid, real-time monitoring of environmental contaminants for water quality assessment and industrial pollution control.

Table 3: Environmental Monitoring Applications

Material	Target Pollutant	Application
N-doped graphene	Pb ²⁺ , Hg ²⁺	Heavy metal sensing
N-doped carbon dots	Pesticides	Fluorescent sensors
N-doped CNTs	NO ₂ , NH ₃	Gas sensors
g-C ₃ N ₄ hybrids	Organic pollutants	Photocatalytic sensing
N-doped graphene composites	Antibiotics	Water quality monitoring

5. Applications in Water Treatment

Nitrogen-doped hybrid nanomaterials exhibit excellent performance in water purification owing to their large surface area, enhanced adsorption capacity, and catalytic activity. These materials effectively remove heavy metals, synthetic dyes, pharmaceutical residues, pesticides, and pathogenic microorganisms through adsorption, photocatalysis, catalytic oxidation, and membrane filtration. Hybridization with metal oxides, graphene, and magnetic nanoparticles further improves removal efficiency and allows easy recovery and reuse of the materials [6]. Their excellent chemical stability makes them suitable for long-term wastewater treatment.

6. Green Industrial Technologies

Nitrogen-doped hybrid nanomaterials are increasingly utilized in sustainable industrial technologies because of their outstanding catalytic performance, durability, and energy efficiency. They serve as catalysts in green chemical synthesis, electrocatalysis, hydrogen production, carbon dioxide reduction, fuel cells, and energy storage devices [7-8]s. In environmental industries, these materials support wastewater treatment, gas purification, carbon capture, and pollution monitoring while reducing energy consumption and chemical waste. Their multifunctional properties contribute significantly to cleaner production processes and sustainable industrial development.

7. Conclusion

Nitrogen-doped hybrid nanomaterials have emerged as one of the most promising classes of advanced functional materials for environmental monitoring, water treatment, and sustainable industrial technologies. Nitrogen incorporation significantly modifies the electronic structure, surface chemistry, and catalytic properties of nanomaterials, resulting in enhanced adsorption capacity, improved electrical conductivity, greater catalytic efficiency, and superior chemical stability. Hybridization with graphene, carbon nanotubes, metal oxides, metal nanoparticles, graphitic carbon nitride, metal-organic frameworks (MOFs), and polymeric materials further enhances their multifunctional performance through synergistic interactions.

These advanced materials have demonstrated remarkable effectiveness in removing heavy metals, dyes, pharmaceutical residues, pesticides, volatile organic compounds, and other emerging pollutants through adsorption, photocatalysis, electrocatalysis, and advanced oxidation processes. Their excellent sensing capabilities also enable rapid and sensitive detection of environmental contaminants, supporting real-time monitoring and pollution management. Furthermore, their applications in green catalysis, renewable energy conversion, carbon capture, hydrogen production, and industrial wastewater treatment contribute significantly to sustainable industrial development and environmental protection.

References

- Geim, A. K., & Novoselov, K. S. (2007). The rise of graphene. *Nature Materials*, 6(3), 183–191. <https://doi.org/10.1038/nmat1849>
- Kumar, R., Raizada, P., Hosseini-Bandegharai, A., Singh, P., Nguyen, V. H., & Thakur, P. (2022). Graphene-based nanomaterials for environmental remediation: Recent advances and future perspectives. *Chemosphere*, 287, 132082.
- Liu, J., Wang, N., Yu, F., & Zhao, Q. (2021). Graphene-based composite materials for wastewater treatment: Recent advances and future opportunities. *Journal of Environmental Chemical Engineering*, 9(6), 106748.
- Palani, G., & Apsari, R. (2022). Metal-doped graphitic carbon nitride nanomaterials for photocatalytic environmental applications—A review. *Nanomaterials*, 12(10), 1754. <https://doi.org/10.3390/nano12101754>
- Pan, Y., Xu, K., & Wu, C. (2023). Graphene-based hybrid materials for photocatalytic degradation of environmental pollutants: Progress and prospects. *Journal of Hazardous Materials*, 452, 131308.
- Perreault, F., de Faria, A. F., & Elimelech, M. (2015). Environmental applications of graphene-based nanomaterials. *Chemical Society Reviews*, 44(16), 5861–5896.
- Wang, J., & Zhuang, S. (2022). Graphene-based materials for environmental remediation and energy applications: A review. *Environmental Research*, 212, 113370.
- Zhang, Y., Khan, A., Lee, J., & Chen, X. (2023). Recent advances in graphene-based nanocomposites for environmental remediation and sustainable catalysis. *Coordination Chemistry Reviews*, 486, 215134.
- Zhao, Y., Zhang, X., Li, H., & Wang, L. (2023). Recent advances on energy and environmental applications of graphitic carbon nitride (g-C₃N₄)-based photocatalysts: A review. *Journal of Environmental Chemical Engineering*, 11(3), 110164.