

Catalytic Applications of Carbon Nanodots

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Abstract

Carbon nanodots (CNDs) owing to their hydrophilicity and multifunctionality and with ultrasmall size exhibit metal-like properties resulting in astounding catalytic performance. These nanostructures, typically less than 10 nm in diameter, possess unique physicochemical and electronic characteristics including tunable photoluminescence, high surface-to-volume ratio, abundant surface functional groups, and excellent electron transfer capabilities. Such properties have driven extensive global research into their application in heterogeneous and homogeneous catalysis. Recent advances in synthesis techniques have enabled the production of carbon nanodots with controlled size, morphology, and surface chemistry, thereby enhancing their catalytic efficiency. Carbon nanodots exhibit exceptional performance as standalone catalysts, co-catalysts, and catalyst supports in photocatalytic degradation, electrocatalytic reactions, environmental remediation, and organic transformations. Their compatibility with green chemistry principles, low toxicity, and derivation from renewable precursors further enhance their significance in sustainable catalytic processes. This review provides a comprehensive overview of the catalytic applications of carbon nanodots, with emphasis on mechanistic insights, structure–property relationships, hybrid catalytic systems, and emerging global research trends. The discussion highlights recent developments in photocatalysis, electrocatalysis, environmental catalysis, and synthetic chemistry, while also addressing challenges and prospects in this rapidly evolving field of nanocatalysis. Overall, CNDs are an ideal metal substitute in catalysis and nanotechnology. Their roles in electrocatalysis, namely, energy conversion and energy storage devices are unavoidable and exemplary. In almost all areas of energy sources, including biorefineries, CNDs are actively integrating with the catalysts and biocatalysts used in transesterification of lipids and fermentation of carbohydrates.

Keywords: Biocatalysis, carbon nanodots, electrocatalysis, environmental catalysis, green catalysis, nanocatalysis, photocatalysis

INTRODUCTION

Nanotechnology has significantly transformed the field of catalysis by enabling the design and fabrication of materials with highly controlled structural, electronic, and surface properties at the nanoscale. Among various nanomaterials investigated, carbon-based nanostructures have attracted substantial attention due to their remarkable stability, conductivity, and tunable functionality. Carbon nanodots (CNDs) represent a relatively new yet rapidly growing class of carbon nanomaterials characterized by their hydrophilicity, polar surface, quasi-spherical morphology and nanoscale dimensions [1].

Originally discovered as fluorescent by-products during purification of carbon nanotubes, carbon nanodots have since been synthesized through diverse top–down and bottom–up approaches using organic molecules, polymers, and biomass-derived precursors. Their abundant functional groups, such as hydroxyl, carboxyl, and amine moieties, enable

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strong interactions with reactants and catalytic species. These features have positioned carbon nanodots as promising candidates for next-generation catalytic systems. The increasing demand for sustainable and energy-efficient catalytic processes has accelerated research into carbon nanodots as environmentally benign alternatives to conventional metal-based catalysts. Their ability to facilitate electron transfer, generate reactive species, and stabilize catalytic intermediates has opened new avenues in nanocatalysis. Global research continues to explore innovative strategies to enhance their catalytic performance and expand their application scope. As the application domain of the CNDs is expanding, the synthetic strategies are also evolving from simple hydrothermal to energy intensive but fast techniques based on microwave irradiation as shown in (Figure 1) [2]. As is the diversity of the synthetic strategies so is the variety of the feedstock that could be employed to produce CNDs and their offspring (heteroatom doped analogues). Simple carbohydrates, like glucose, starch, sucrose, complex carbohydrates like cellulose, carboxymethyl cellulose, and sustainable biomass like the carbohydrate rich marine macroalgae and freshwater microalgae, can be converted to CNDs. Compounds, such as urea, ampicillin, and ammonium carbonate, were used as source of heteroatom doping into the carbon structure [3–5].



Figure 1. Methods used for the synthesis of Carbon nanodots (1–10 nm) [1].

PHYSICOCHEMICAL PROPERTIES INFLUENCING CATALYSIS

The catalytic performance of CNDs is strongly influenced by their intrinsic physicochemical properties and their structure [6]. Their nanoscale dimensions provide an exceptionally high surface-to-volume ratio, enabling greater exposure of active sites for catalytic reactions. Surface functional groups facilitate adsorption of reactant molecules and enhance catalytic interactions [7].

Heteroatom doping plays a crucial role in tailoring catalytic activity. Incorporation of nitrogen, sulfur, phosphorus, or boron atoms modifies electronic structure and introduces defect sites that act as catalytic centers. Nitrogen-doped carbon nanodots, in particular, exhibit improved electron transfer characteristics and enhanced catalytic efficiency in redox reactions.

Optical and electronic properties further contribute to catalytic behavior. Carbon nanodots can absorb light across a broad spectral range and generate electron–hole pairs under irradiation. These properties are especially valuable in photocatalytic systems where efficient charge separation and transfer are essential for catalytic reactions. Their ability to generate reactive oxygen species and participate in photochemical reactions significantly enhances catalytic potential.

PHOTOCATALYTIC APPLICATIONS

Photocatalysis represents one of the most extensively explored catalytic applications of carbon nanodots. Their photoluminescent properties and ability to mediate photoinduced electron transfer

processes enable efficient utilization of solar and visible light energy. Carbon nanodots have been widely investigated for degradation of organic pollutants including dyes, pharmaceuticals, and industrial contaminants.

Upon light irradiation, carbon nanodots generate excited electrons and holes that interact with surrounding molecules to produce reactive species such as hydroxyl radicals and superoxide ions. These species play a critical role in the breakdown of complex pollutants into environmentally benign products. Integration of carbon nanodots with semiconductor materials enhances light absorption and reduces recombination of charge carriers, thereby improving photocatalytic efficiency [8]. Recent advances have focused on developing visible-light-driven catalytic systems. CNDs act as photosensitizers and electron reservoirs, enabling efficient solar energy conversion. Hybrid photocatalytic systems incorporating CNDs demonstrate improved stability, enhanced catalytic activity, and broader spectral response compared to conventional photocatalysts.

ELECTROCATALYTIC APPLICATIONS

Electrocatalysis is another domain in which CNDs have demonstrated remarkable potential. Their excellent electrical conductivity and tunable electronic properties make them suitable for electrochemical reactions such as oxygen reduction, oxygen evolution, and hydrogen evolution. These reactions are critical for energy conversion technologies including fuel cells and electrolyzers. Heteroatom-doped CNDs function as efficient metal-free electrocatalysts. The presence of defect sites and charge redistribution within the carbon lattice facilitates adsorption of reactants and enhances reaction kinetics. Their incorporation into electrode materials improves catalytic performance and durability in electrochemical systems [9]. CNDs have also been integrated into energy storage devices such as supercapacitors and batteries. Their inclusion enhances charge transfer, increases surface area for ion adsorption, and improves overall electrochemical stability. These properties contribute to improved energy density and cycling performance in advanced energy systems. In essence, CNDs are noble metal mimics for catalytic and electrocatalytic application [4, 5]. B and N doped and codoped systems are promising hydrogen storage media [4, 5] while P doped CNDs are soil fertility boosters [10].

ENVIRONMENTAL CATALYSIS

Environmental remediation has emerged as a major area of application for carbon nanodot-based catalysts. Rapid industrialization and urbanization have resulted in increased environmental pollution, necessitating efficient and sustainable treatment technologies. Carbon nanodots have demonstrated exceptional efficiency in advanced oxidation processes for degradation of organic pollutants in wastewater. Their catalytic activity is attributed to their ability to generate reactive species and facilitate electron transfer reactions. Biomass-derived carbon nanodots offer environmentally friendly alternatives to traditional catalysts and align with principles of green chemistry. These nanomaterials can be synthesized from renewable resources and waste materials, reducing environmental impact while maintaining high catalytic performance [11]. Carbon nanodots are also being explored for carbon dioxide reduction and nitrogen fixation processes. Their redox capabilities and surface functionality enable activation of small molecules and facilitate conversion into value-added products. Such applications highlight their potential in addressing environmental and energy challenges.

CATALYSIS IN ORGANIC TRANSFORMATIONS

Carbon nanodots have shown promising catalytic activity in various organic transformations including oxidation, reduction, and coupling reactions. Their surface functional groups and electron transfer capabilities allow them to act as catalysts or catalyst supports in synthetic chemistry. They have been employed in oxidation of alcohols, reduction of nitro compounds, and synthesis of heterocyclic compounds. Hybrid catalytic systems combining carbon nanodots with metal nanoparticles exhibit synergistic effects that enhance catalytic efficiency. Carbon nanodots stabilize metal nanoparticles, prevent aggregation, and facilitate electron transfer between catalytic sites and reactants. Such systems

have demonstrated improved performance in industrially relevant chemical reactions. The specific use of carbon nanodots in organic catalysis supports sustainable chemical synthesis by reducing reliance on toxic reagents and harsh reaction conditions as shown in (Figure 2). Their recyclability and stability further enhance their applicability in green chemistry and industrial processes. Their application in energy related applications including biodiesel production is indispensable [12–30].

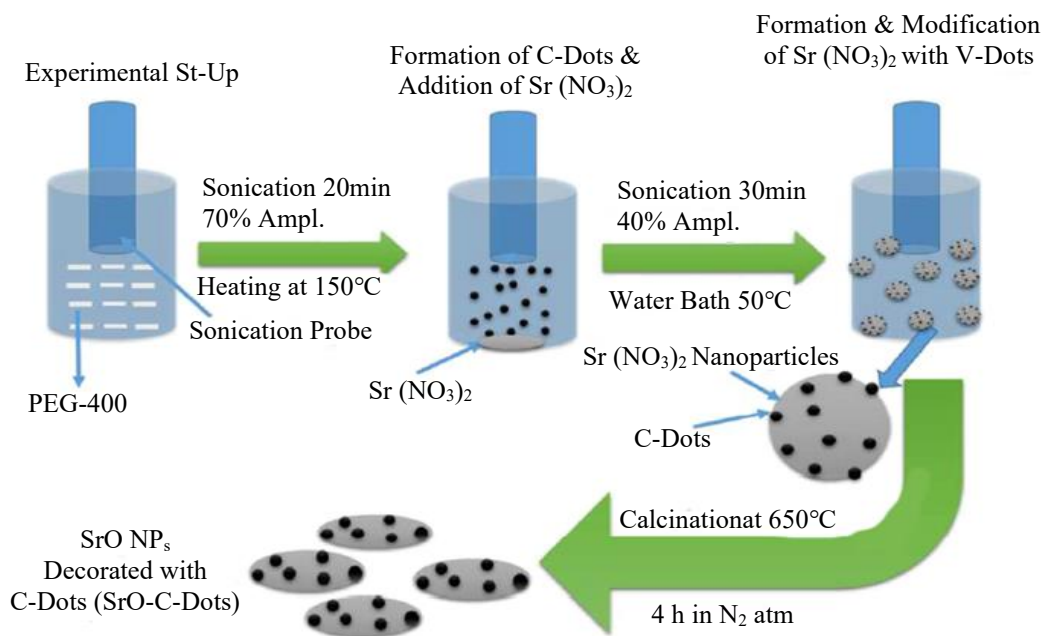


Figure 2. Application of SrO-CND composite as a transesterification catalyst for the atom and energy efficient production of biodiesel.

HYBRID AND MULTIFUNCTIONAL CATALYTIC SYSTEMS

Recent research has focused on the development of multifunctional catalytic systems incorporating carbon nanodots with metals, semiconductors, and polymers. These hybrid systems combine complementary properties to achieve superior catalytic performance. Carbon nanodots act as electron mediators and enhance charge separation in composite catalysts [31]. Multifunctional catalysts capable of simultaneous photocatalytic and electrocatalytic activity are being explored for integrated energy conversion systems. Carbon nanodots also serve as support for enzyme immobilization in biocatalytic processes, improving stability and catalytic efficiency. Such systems demonstrate the versatility of carbon nanodots and highlight their potential in advanced catalytic technologies [32].

CHALLENGES AND PROSPECTS

Despite significant progress, several challenges remain in optimizing catalytic applications of carbon nanodots. Achieving precise control over size, morphology, and surface chemistry is essential for maximizing catalytic performance. Understanding structure–activity relationships and reaction mechanisms remains a key research priority. Scalability and reproducibility of synthesis methods must also be addressed to enable industrial applications. Future research is expected to focus on designing carbon nanodots with tailored electronic properties, improved stability, and enhanced catalytic selectivity. Integration with emerging technologies, such as artificial intelligence-driven catalyst design and continuous flow reactors, may further accelerate progress in this field [33].

CONCLUSION

Carbon nanodots have emerged as highly promising nanomaterials for catalytic applications across diverse fields including environmental remediation, energy conversion, and chemical synthesis. Their unique physicochemical properties, tunable functionality, and environmental compatibility position

them as next-generation catalysts for sustainable technologies including CO₂ electroreduction and as chemozyme analogous to nitrogenase. Continued interdisciplinary research and technological innovation will further expand their catalytic potential and enable widespread adoption in advanced catalytic systems.

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