Carbon Dots and Nanoparticles: Synthesis Strategies and Multifunctional Applications in Modern Science.

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Tóm tắt:

Carbon-based nanomaterials, specifically carbon nanoparticles (CNPs) and carbon dots (CDs), are recognised as significant materials in materials science due to their distinct optical and physicochemical properties. Although these materials have been reviewed individually, a cohesive framework systematically differentiating their structural nuances, size-dependent mechanisms, and complementary applications is rarely presented. Therefore, this review addresses a specific gap in the current literature by rigorously comparing CNPs and CDs. A novel perspective is contributed by critically evaluating the transition from sustainable, 'green' chemistry synthesis using biomass precursors to their advanced, cross-disciplinary integration. The versatility of these materials is demonstrated through a categorised analysis of their applications. In the biomedical field, their utility in regenerative medicine, personalised diagnostics, and photothermal therapies is evaluated. Environmental applications, including massive pollution remediation and agricultural enhancement, are also discussed. Furthermore, the integration of these carbonaceous structures into advanced technologies, such as artificial intelligence, optoelectronics, and macroscopic defense systems, is explored. Finally, the critical bottlenecks associated with industrial scalability, long-term toxicity, and the necessity for standardised production protocols are addressed, providing a comprehensive roadmap for their future technological deployment.

Từ khóa: *carbon dots, carbon nanoparticles, green synthesis, biomedical applications, environmental remediation*

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Introduction

Carbon-based nanostructures are classified into various categories based on their size and structural arrangement. Among these, carbon nanoparticles (CNPs) and carbon dots (CDs) have attracted considerable research interest. (Kotteeswaran et al., 2025) CNPs are generally defined as spherical particles with diameters ranging from a few to several hundred nanometers. They are characterised by high mechanical strength and thermal stability, which makes them suitable for composite materials and energy storage solutions. (Figure 1)

In contrast, CDs are discrete quasi-spherical nanoparticles with sizes typically below 10 nm. (Das et al., 2021) A defining feature of CDs is their strong photoluminescence, which is attributed to quantum confinement effects and surface defects (Boretti, 2025). While CNPs are often amorphous or semi-crystalline, CDs frequently possess a graphitic core and are abundant in surface functional groups. (Varshan et al., 2025) These surface groups facilitate high water solubility and ease of functionalization, rendering CDs particularly advantageous for biological and environmental applications where biocompatibility is required. (Rai et al., 2025)

To systematically address this pervasive literature gap, this review presents a comprehensive, head-to-head comparative framework for carbon nanoparticles (CNPs) and carbon dots (CDs). The distinct structural hierarchies and size-dependent mechanisms of these carbonaceous nanomaterials are critically delineated. Furthermore, a novel perspective is contributed by directly correlating sustainable ‘green’ synthesis strategies with their divergent, cross-disciplinary applications. Specifically, while the quantum-driven, micro-scale functionalities of CDs in personalized medicine and trace sensing are thoroughly evaluated, the macro-scale, bulk electro-mechanical capacities of CNPs in industrial energy storage and extensive environmental remediation are simultaneously highlighted. Ultimately, the critical bottlenecks concerning industrial scalability and long-term nanotoxicity are addressed. Through this rigorous comparative approach, a cohesive, multidisciplinary roadmap for future technological deployment is established, thereby distinguishing this manuscript from previously isolated or application-specific reviews.

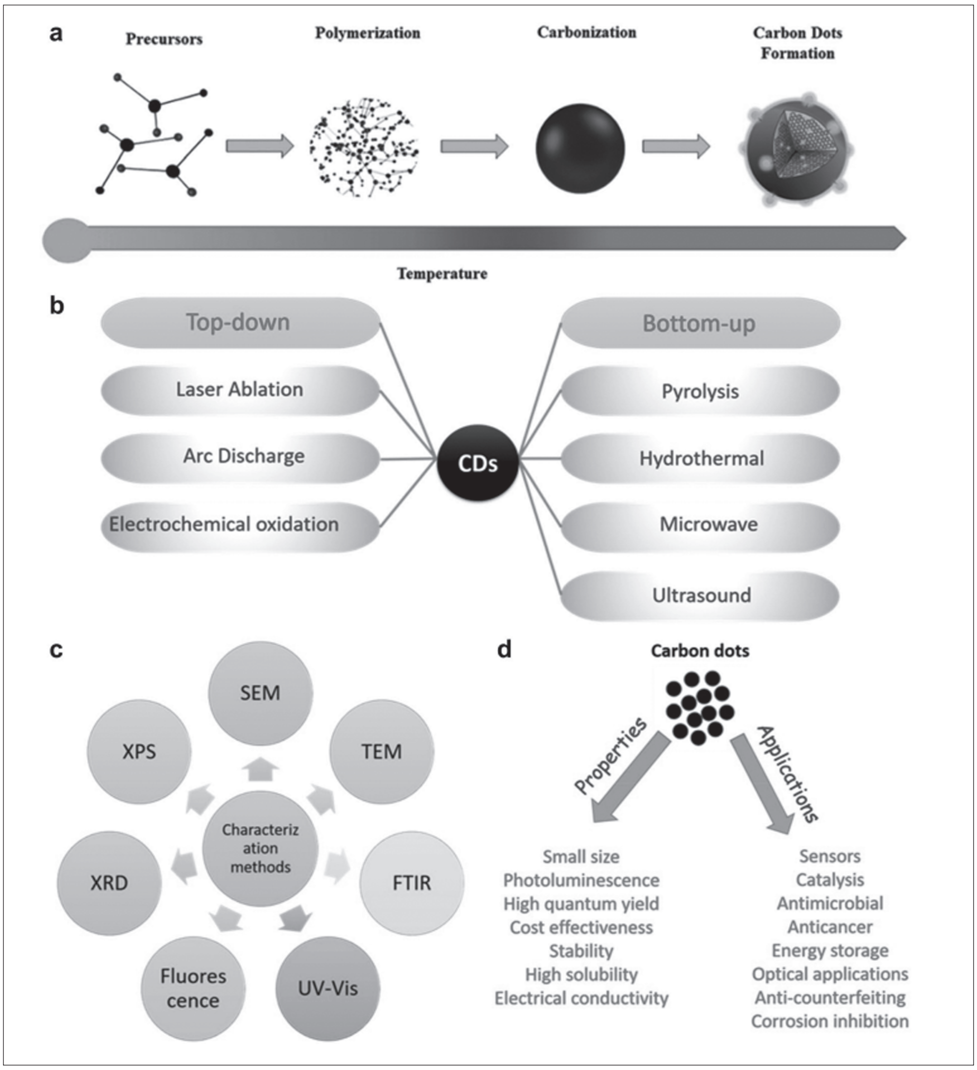
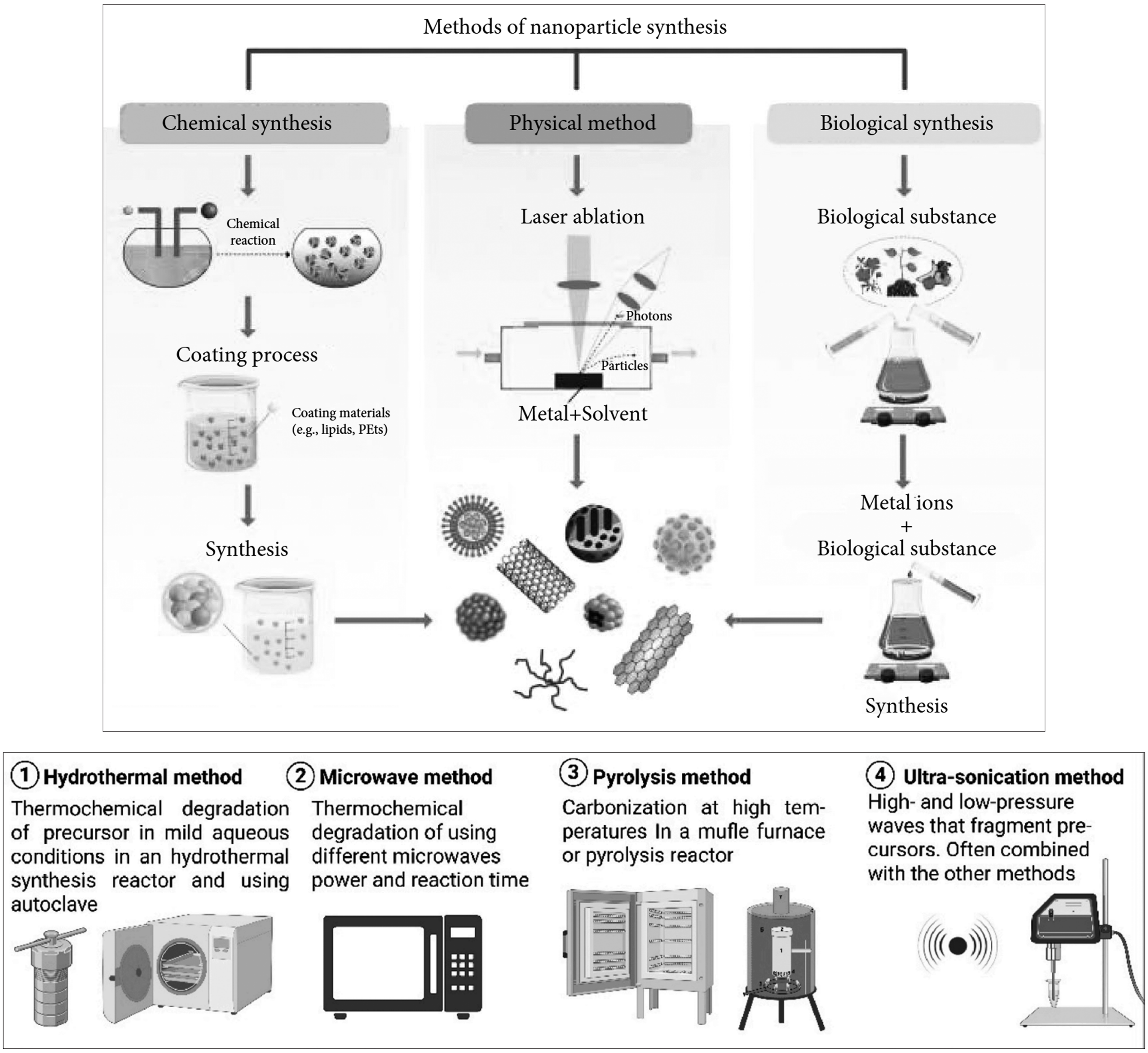


Figure 1. Carbon dots and carbon nanoparticles (Chauhan et al., 2022).

Synthesis and material engineering

Sustainable and green synthesis

Traditional synthesis methods (Figure 1) for carbon nanomaterials, such as chemical vapour deposition or arc discharge, are often associated with high energy consumption and the use of hazardous solvents (Prokisch et al., 2025). Consequently, significant effort is devoted to developing sustainable synthesis protocols. “Green” chemistry approaches are increasingly utilised (Figure 2), where CDs are synthesised from renewable biomass precursors (e.g., plant leaves, coffee grounds, agricultural waste) via hydrothermal treatment or pyrolysis (Alibrahem et al., 2025). These methods are not only cost-effective but also reduce environmental impact by minimising toxic byproducts (Nguyen et al., 2025).



① **Hydrothermal method**
Thermochemical degradation of precursor in mild aqueous conditions in an hydrothermal synthesis reactor and using autoclave

② **Microwave method**
Thermochemical degradation of using different microwaves power and reaction time

③ **Pyrolysis method**
Carbonization at high temperatures In a mufle furnace or pyrolysis reactor

④ **Ultra-sonication method**
High- and low-pressure waves that fragment precursors. Often combined with the other methods

Figure 3. The green synthesis of CNPs and CDs (Martins et al., 2025).

Structural modification and hybridisation

To enhance the intrinsic properties of CDs, doping strategies are frequently employed. The incorporation of heteroatoms such as nitrogen or sulfur into the carbon lattice is performed to modulate the electronic band structure, thereby improving fluorescence quantum yield and catalytic activity (Verma et al., 2025). Furthermore, hybrid systems are developed by combining CDs with other nanostructures, such as graphene quantum dots (GQDs). This synergy combines the charge transport properties of graphene with the chemical stability of CDs, resulting in materials suitable for dual-function applications like photocatalysis and energy storage. (Hou et al., 2025)

Ultra-small nanostructures

Recent research has focused on ultra-small CDs (sized below 2 nm). At this scale, quantum confinement effects are pronounced, leading to unique optical behaviors and enhanced chemical reactivity. (Wang et al., 2025) These structures exhibit high photostability and are under investigation for applications requiring precise cellular interactions, although challenges regarding their large-scale synthesis and characterization remain. (Debnath et al., 2025)

Structural architecture and synthesis of Carbon Nanoparticles (*CNPs*)

While significant attention is often directed toward CDs in recent literature, the synthesis and structural engineering of larger Carbon Nanoparticles (CNPs) remain equally critical and fundamentally distinct. Unlike CDs, whose dimensions are strictly limited (typically < 10 nm) to preserve quantum confinement, CNPs encompass a broader size range extending up to several hundred nanometers. The synthesis of CNPs is frequently achieved through top-down macroscopic methods, such as arc discharge and laser ablation, as well as controlled bottom-up approaches like the incomplete combustion or hydrothermal carbonization of bulky polymeric precursors.

A crucial structural distinction and hierarchical relationship must be emphasized: CNPs can inherently contain CDs within their architecture, yet the two entities are not identical. During the carbonization process, highly ordered, sp^2-hybridized graphitic domains, essentially embedded CDs, are often formed. However, these distinct fluorescent domains are typically encapsulated within a much larger, amorphous sp^3-hybridized carbon matrix to constitute a single CNP. Because of this complex structural hierarchy, the material engineering of CNPs is generally focused on optimizing macroscopic features, such as bulk mechanical strength, thermal stability, electrical conductivity, and mesoporous surface area, rather than solely tuning photoluminescence. Consequently, CNPs are predominantly deployed as robust structural supports, conductive additives in energy storage devices, and reinforcing agents in nanocomposites, perfectly complementing the quantum-driven applications of isolated CDs.

Biomedical and healthcare applications

Regenerative medicine and tissue engineering

CDs are utilised in regenerative medicine due to their biocompatibility and ability to be tracked via fluorescence. In stem cell research, functionalized CDs are used to influence cellular differentiation and to visualize stem cell migration in real-time. (Ilie-Mihai et al.,

2025) Additionally, they are incorporated into scaffolds for tissue engineering. These CD-embedded scaffolds enhance mechanical properties and can be designed to release bioactive molecules or antibacterial agents, thereby supporting tissue repair processes.

Personalised diagnostics and biosensing

In the domain of personalised medicine, CDs function as critical components in biosensors. Their fluorescence is sensitive to specific analytes, allowing for the non-invasive monitoring of physiological parameters, such as blood glucose levels in diabetic patients. (Rezaei & Mehdinia, 2025) Furthermore, high-sensitivity CD-based sensors are being developed for "liquid biopsies," capable of detecting trace tumour markers or circulating tumour DNA, which facilitates early cancer diagnosis. (Zaidi et al., 2022)

Therapeutic delivery and photothermal interventions by Carbon Nanoparticles (CNPs)

While fluorescence-driven diagnostics and imaging are predominantly enabled by CDs, larger Carbon Nanoparticles (CNPs) fulfill distinct and robust biomedical roles. Due to their expanded mesoporous frameworks and large surface areas, mesoporous CNPs efficiently encapsulate and target chemotherapeutic agents—such as doxorubicin, thereby minimizing systemic toxicity in oncological treatments. (Maiti et al., 2019) Furthermore, exceptionally strong near-infrared (NIR) light absorbance is exhibited by these larger carbonaceous structures. Consequently, CNPs are extensively utilized as potent photothermal agents for non-invasive tumor ablation. When exposed to specific NIR irradiation, localized hyperthermia is rapidly generated by the internalized CNPs, leading to the effective and irreversible eradication of malignant cells. (Chen & Shi, 2015; Zhou et al., 2015) Thus, it is clearly demonstrated that while cellular tracking is optimized by the luminescent properties of CDs, deep-tissue therapeutic interventions and high-capacity drug delivery are enabled by the structural and thermal properties of CNPs.

Environmental and agricultural solutions

Pollution monitoring and remediation

The optical properties of CDs are exploited for environmental protection. They are integrated into sensors for the detection of airborne pollutants (NO_x, VOCs) and greenhouse gases (CO_2, methane) (Batool et al., 2025). In aquatic environments, CDs are employed to detect heavy metals and microplastics with high selectivity (Farhangi-Abriz & Torabian, 2025). Beyond detection, CD-based nanofilters utilize adsorption and photocatalysis to neutralize contaminants in air and water purification systems. (Yadav & Lahariya, 2025)

Smart agriculture and food safety

In agriculture, CDs serve as nano-carriers to improve nutrient delivery to plants, potentially enhancing crop growth. (Baker & Baker, 2010) Within the food industry, they are applied in smart packaging. Films embedded with CDs provide antimicrobial protection and can act as colorimetric indicators for food spoilage by reacting with volatile compounds released during degradation. (Vasluianu et al., 2025)

Large-scale remediation and agricultural enhancement by Carbon Nanoparticles (CNPs)

While selective environmental monitoring and smart food packaging are effectively driven by the distinct optical properties of CDs, large-scale environmental remediation is predominantly executed by Carbon Nanoparticles (CNPs). Due to their highly mesoporous architectures and extensive specific surface areas, massive quantities of aquatic pollutants—including heavy metal ions, synthetic dyes, and persistent organic contaminants—are rapidly adsorbed and permanently removed from wastewater by CNPs. (Ali, 2012; Qu et al., 2013) In the agricultural sector, the structural robustness and absorption capacity of CNPs are exploited to engineer slow-release fertilizer matrices. Through the controlled retention and gradual release of essential agrochemicals, soil fertility is sustainably enhanced, and nutrient runoff into surrounding ecosystems is significantly minimized. (Khodakovskaya et al., 2013) Therefore, it is clearly demonstrated that the sensory applications of CDs are fundamentally complemented by the physical pollutant sequestration and bulk soil treatments achieved by CNPs.

Advanced technological integrations

Energy and space exploration

The durability and lightweight nature of CDs are advantageous for aerospace applications. They are investigated as radiation shielding materials to protect astronauts and equipment from cosmic rays. (Haider et al., 2025) Moreover, their ability to convert light energy is applied in solar panels to enhance efficiency under the variable lighting conditions found in space. (Kasouni et al., 2019)

Artificial intelligence and data storage

In the field of computing, CDs are explored for neuromorphic devices that mimic synaptic functions, which is relevant for energy-efficient artificial intelligence (Jayan, 2025). For data storage, the stable fluorescence and multi-color emission of CDs permit high-density optical data encoding, offering a robust alternative to traditional magnetic or optical media. (Haseeb & Hatiboglu, 2025)

Defense and smart materials

Military applications include the use of CDs in stealth technologies. Coatings containing CDs can be engineered to absorb specific wavelengths, thereby reducing radar or infrared signatures (camouflage). (Zhang et al., 2025) Additionally, "adaptive materials" that utilize CDs can self-heal. When integrated into polymer networks, CDs facilitate the repair of micro-cracks in response to external stimuli like heat or light, extending the lifespan of the material. (Kumara et al., 2025)

High-performance energy storage and macroscopic structural reinforcement by CNPs

While optical data encoding and neuromorphic computing in advanced technologies are predominantly dominated by CDs, the macroscopic demands of energy storage and aerospace engineering are successfully met by Carbon Nanoparticles (CNPs). Exceptional electrical conductivity and robust mechanical strength are inherent to these larger carbonaceous structures. In the energy sector, the operational performance of lithium-ion batteries and supercapacitors is significantly enhanced by CNPs, which provide high charge-carrier mobility and extensive ion-intercalation networks through their mesoporous frameworks. (Dai et al., 2012; Simon & Gogotsi, 2008) Furthermore, in aerospace and defense applications, extreme environmental tolerance and lightweight structural reinforcement are achieved by embedding CNPs into macroscopic polymer composites. (Sengupta et al., 2011) Thus, it is evident that the delicate, light-driven functionalities of CDs are perfectly balanced by the heavy-duty, bulk electromechanical capabilities of CNPs.

Niche application: cultural heritage preservation

A specialized application of CDs is found in the conservation of historical artifacts. Their fluorescence allows for non-invasive imaging of artworks to assess structural integrity without causing damage. (Seçme & İlhan, 2025) Furthermore, their antibacterial properties are applied to prevent the microbial degradation of paper, textiles, and wood in archives and museums. (Khatokar et al., 2021)

Summary of functional applications

The versatility of CDs is summarized in Table 1 and 2, highlighting their applications across various sectors. (Atchudan et al., 2023; Lin & Li, 2023)which is used for kidney and liver dysfunctions. Herein, natural nitrogen-doped carbon dots (NN-CDs (Figure 3).

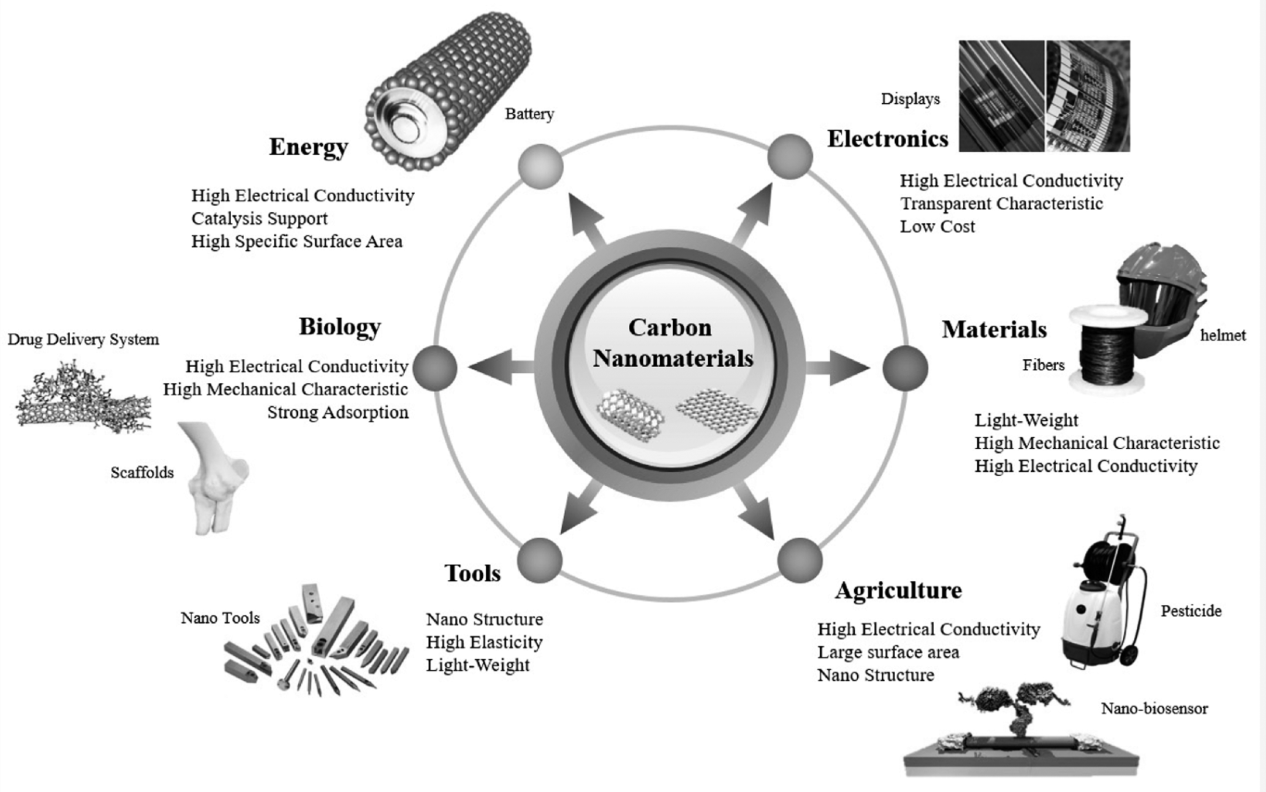


Figure 4. The applications of carbon dots and carbon nanoparticles (Patel et al., 2020).

Table 1. Functional Categorisation of Carbon dots (CDs) Applications.

Sector	Application area	Primary function/ Mechanism	Key benefit	Challenge
Biomedicine	Regenerative Medicine	Scaffold reinforcement; Stem cell tracking	Enhanced tissue repair; Real-time visualization	Long-term *in vivo* toxicity and extended biodistribution are insufficiently documented.
	Diagnostics	Glucose monitoring; Liquid biopsy markers	Non-invasive; High sensitivity	Precise tuning of near-infrared emission is hindered by debated photoluminescence mechanisms.

Sector	Application area	Primary function/ Mechanism	Key benefit	Challenge
Environment	Air/Water Quality	Fluorescence quenching sensors; Nanofilters	Detection of heavy metals/ gases; Pollutant neutralization	Unforeseen ecological hazards arising from large-scale releases of nanomaterials must be rigorously evaluated.
	Microplastics	Fluorescent tagging of polymers	Rapid detection in marine environments	High selectivity in complex aquatic matrices is difficult to maintain without advanced functionalization.
Industry	Food & Beverage	Antimicrobial films; Spoilage indicators	Extended shelf life; Visual safety check	Batch-to-batch consistency is highly compromised by heterogeneous biomass precursors.
	Energy Storage	Supercapacitors; Solar enhancement	High charge density; Improved light conversion	Severe fluorescence quenching is induced by particle aggregation in solid-state matrices.

Sector	Application area	Primary function/ Mechanism	Key benefit	Challenge
Defense	Stealth/ Camouflage	Infrared/Light absorption tuning	Reduced thermal signature	Standardized large-scale production is strictly limited by synthesis inconsistencies.
	Bio-threat Detection	Specific antigen/ toxin binding	Rapid field identification	False-positive signals are frequently generated unless specific surface chemistry is precisely engineered.
Computing	Data Storage	High-density optical encoding	Durable, multi-layer storage	Long-term optical stability is frequently compromised in solid-state integrated devices.
	AI Hardware	Synaptic behavior mimicry	Energy-efficient processing	Precise bandgap engineering is required to assure uniform and predictable synaptic responses.
Heritage	Conservation	Non-invasive imaging; Antimicrobial coating	Damage assessment; Prevention of decay	Prolonged interactions between dots and fragile historical materials are rarely evaluated.

Table 2. Performance comparison of some green CDs-based corrosion inhibitors (Chauhan et al., 2022).

Precursor	Method	Metal surface/ corrosive medium	CR/I.E. (%)/ inhibitor concentration
4-Aminosalicylic acid	Solvothermal 200 °C, 20 h	Copper/0.5 M H_2SO_4	–/89.2/50 mg L^{-1}
4-Aminosalicylic acid	Solvothermal 200 °C, 18 h	Q235 carbon steel/1 M HCl	–/87.2/100 mg L^{-1}
4-Aminosalicylic acid	Solvothermal 200 °C, 16 h	Carbon steel/CO_2 saturated 3.5% NaCl	0.08 g cm^{-2} h^{-1}/93.0/50 mg L^{-1}
4-Aminosalicylic acid and L-histidine	Solvothermal 200 °C, 12 h	Q235 steel/1 M HCl	91.5/50 mg L^{-1}
Citric acid + L-histidine	Reflux 200 °C, 1 h	Q235 steel/0.1 M HCl	96.13/200 mg L^{-1}
Citric acid + L-serine	Hydrothermal 200 °C, 18 h	Copper/0.5 M H_2SO_4	98.5/200 mg L^{-1}
Citric acid + imidazole ionic liquid	Hydrothermal 200 °C, 30 min	Q235 steel/1 M HCl, 3.5% NaCl	92.60/200 mg L^{-1} 83.45/200 mg L^{-1}
Citric acid + isoniazid + thiourea	Hydrothermal 180 °C, 6 h	Mild steel/15% HCl	98.64/200 mg L^{-1}
Tryptophan	Pyrolysis 160–200 °C, 0.5–2 h	Q235 carbon steel/1 M HCl	91/200 mg L^{-1}

Precursor	**Method**	**Metal surface/ corrosive medium**	**CR/I.E. (%)/ inhibitor concentration**
Folic acid + *o*-phenylenediamine	Hydrothermal 200 °C, 6 h	Q235 steel/1 M HCl	95.4/150 mg L^{-1}
Glucose + ascorbic acid + 4-amino-3-hydrazine-5-mercapto-1,2,4-triazole	Hydrothermal 180 °C, 4 h	Copper/3.5% NaCl	88/70 mg L^{-1}
Dopamine	Hydrothermal 180 °C, 6 h	Q235 steel/1 M HCl	96.1/400 mg L^{-1}
Coffea caneophora + urea	Pyrolysis 220 °C, 5 h	Copper/1% NaCl	84.94/1 g L^{-1}
Durian juice	Pyrolysis 125 °C, 12 h	Copper/1% NaCl	86/800 mg L^{-1}

Limitations and future directions

Despite the transformative potential of Carbon nanoparticles (CNPs) and Carbon dots (CDs) demonstrated in laboratory settings, several critical challenges must be addressed to facilitate their transition to industrial and clinical applications.

Heterogeneity and standardization in synthesis

A primary limitation lies in the synthesis process, particularly within "green" chemistry approaches. While the use of biomass precursors (e.g., food waste, plant extracts) is environmentally advantageous, it often results in batch-to-batch heterogeneity. The chemical composition of natural precursors varies significantly, leading to inconsistencies in the optical properties, size distribution, and surface functionalization of the resulting dots. Consequently, the establishment of standardized synthesis protocols and purification methods is required to ensure reproducibility and quality control on a commercial scale.

(Cillari et al., 2025) Simultaneously, the precise control over pore size distribution and graphitic domain uniformity in larger CNPs is severely hindered during traditional bulk manufacturing. Consequently, the establishment of standardized synthesis and purification protocols is urgently required to ensure reproducibility on a commercial scale.

Elucidation of photoluminescence mechanisms

Although the fluorescence of CDs is utilized extensively, the precise mechanism governing this phenomenon remains a subject of debate. It is not yet fully distinguished whether the emission arises primarily from quantum confinement effects, surface energy traps, or molecular fluorophores attached to the carbon core. A deeper fundamental understanding of these optical origins is necessary. Without this knowledge, the precise tuning of emission wavelengths, specifically in the near-infrared (NIR) region for deep-tissue imaging, remains a trial-and-error process rather than a rational design. (Mohammed & Omer, 2025) In parallel, the complex structural relationship between the amorphous carbon matrix and the embedded graphitic domains within CNPs remains unresolved, significantly complicating the optimization of their bulk electrical and thermal conductivities.

Long-term toxicity and environmental impact

While CDs are generally considered biocompatible and less toxic than metal-based quantum dots, comprehensive long-term toxicity studies are lacking. Most current assessments focus on short-term cytotoxicity *in vitro*. *In vivo* studies on the biodistribution, accumulation, and metabolic clearance of these nanomaterials over extended periods are crucial, particularly for clinical applications. Furthermore, as production scales up, the potential ecological impact of releasing large quantities of carbon nanomaterials into water systems must be rigorously evaluated to prevent unforeseen environmental hazards (Gautam et al., 2025). Furthermore, while rapid renal clearance is typically facilitated by the ultra-small dimensions of CDs, significant respiratory hazards and prolonged organ accumulation are potentially posed by the larger particulate nature of CNPs (Oberdörster et al., 2005). Additionally, the ecological impact of releasing massive quantities of these nanomaterials into natural water systems must be rigorously evaluated to ensure environmental safety. (Mauter & Elimelech, 2008)

Future perspectives

To overcome these barriers, future research efforts should be directed toward: machine learning integration: The application of artificial intelligence to predict optimal synthesis parameters can help minimise batch variations and precisely engineer band gaps for specific optical behaviours. (Divya et al., 2025) Hybrid functionalization: Developing advanced surface chemistry strategies to enhance the selectivity of CDs for specific cancer markers or pollutants, thereby reducing false positives in sensing and diagnostics. (Tok et al., 2025) Solid-state device integration: Moving beyond liquid-phase applications to incorporate CDs effectively into solid-state matrices (e.g., LED encapsulants or flexible films) without suffering from fluorescence quenching caused by aggregation. (Kotteeswaran et al., 2025) Addressing these challenges is essential for transforming CDs from a promising academic subject into a reliable industrial material. Macroscopic structural engineering: The precise control over mesoporous networks and bulk conductivity in CNPs must be prioritized so that their load-bearing and energy-storage capacities are maximized in industrial applications.

Conclusion

Carbon nanoparticles and Carbon dots represent a transformative class of materials that bridge the gap between fundamental nanoscience and practical application. Their transition from laboratory synthesis to multifaceted utility in medicine, environmental science, and advanced electronics is driven by their unique combination of fluorescence, biocompatibility, and chemical stability. While significant progress has been made, particularly in green synthesis and functionalization, challenges regarding large-scale production and long-term environmental safety require continued investigation. (Dua et al., 2023; Holzinger et al., 2014) Future research should focus on standardizing synthesis protocols to ensure reproducibility, which will ultimately facilitate the commercial integration of these nanomaterials into sustainable global solutions.

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