Pharmaceutical-Food Homologous Plant-Derived Carbon Dots: A Sustainable Nanoplatform for Integrated Detection and Remediation of Environmental Pollutants

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Abstract Pharmaceutical-Food Homologous Plant-Derived Carbon Dots (P-CDs) have emerged as revolutionary nanomaterials in environmental pollutant management, demonstrating transformative potential for green chemistry and sustainable material applications. These carbon dots establish an innovative technical framework by integrating dual "detection-remediation" functionalities through eco-friendly synthesis and high-value conversion of medicinal-edible plants and agroforestry waste. Their core advantages originate from structural templating effects induced by natural functional groups (polyphenols, amino acids) in plant precursors combined with heteroatom self-doping, which synergistically optimizes optical properties. This combination achieves quantum yields ranging from 3.06% to 84.9% and detection sensitivities spanning nanomolar to micromolar concentrations. In pollutant detection applications, P-CDs enable ultrasensitive identification of heavy metals (Hg^{2+}, Cu^{2+}, Fe^{3+}) and organic contaminants (pesticides, antibiotics) through multi-mechanistic interactions including static quenching (SQ), dynamic quenching (DQ), and Förster resonance energy transfer (FRET). However, technological translation faces critical challenges including quantum yield heterogeneity (>40-fold variation), matrix interference in complex environmental samples (signal drift exceeding 12%), and scalability-related process inconsistencies. Future research priorities should focus on three key areas: standardization of synthesis protocols, development of surface passivation strategies (*e. g.*, SiO_2 encapsulation), and optimization of heterojunction designs to enhance interference resistance. The integration of in situ characterization techniques (particularly X-ray absorption spectroscopy) with machine learning-driven parameter optimization could significantly refine detection-remediation synergies. Concurrently, establishing a comprehensive lifecycle assessment framework becomes imperative for evaluating environmental impacts and scalability potential. This technology pioneers a sustainable paradigm for pollution control by bridging the gap between nanomaterial innovation and industrial deployment, thereby accelerating progress toward global ecological security objectives.

Key words Pharmaceutical-Food Homologous Plant-Derived Carbon Dots (P-CDs), Environmental pollutant detection, Green synthesis

0 Introduction

The multidimensional management of environmental pollutants has become a cornerstone of global sustainable development strategies. Rapid industrialization and urbanization have intensified composite pollution systems involving heavy metals (Hg^{2+}, Cu^{2+}, Fe^{3+}) and organic contaminants (pesticides, antibiotics, dyes), posing severe threats to ecosystems and human health. Conventional detection techniques such as atomic absorption spectroscopy face limitations including complex pretreatment protocols, single-target detection capabilities (typically at micromolar levels), and equipment dependency. Similarly, remediation technologies like Fenton oxidation and activated carbon adsorption exhibit constrained efficiency and risks of secondary pollution. Within this context, Pharmaceutical-Food Homologous Plant-Derived Carbon Dots (P-CDs) have emerged as an innovative "detection-remediation" integrated platform, leveraging green synthesis principles and multifunctional design to address contemporary environmental governance challenges.

Received: February 19, 2025 Accepted: May 29, 2025

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The synthesis of P-CDs has evolved from conventional chemical methods to biomass-derived precursors, capitalizing on the unique advantages of medicinal-edible plants such as bamboo leaves[1], bergamot[2], and *Prunus avium*[3]. These botanical sources are enriched with natural functional groups—including polyphenols, amino acids, and alkaloids—that serve as molecular templates for carbon core formation while enabling fluorescence enhancement through nitrogen/sulfur self-doping (quantum yield, QY: 3.06% - 84.9%). The valorization of agroforestry waste materials (*e. g.*, spent tea[4], cassava residue[5]) further enhances the economic viability and sustainability of this technology, aligning with global safety protocols for nanomaterial applications.

In pollutant detection, P-CDs achieve ultrasensitive identification through multi-mechanistic interactions involving static quenching (SQ)[6], dynamic quenching (DQ)[7], Förster resonance energy transfer (FRET)[8], and photoinduced electron transfer (PET)[9]. For remediation applications, P-CDs outperform traditional technologies through synergistic photocatalytic degradation and adsorption mechanisms. Current challenges primarily focus on quantum yield heterogeneity (3.06% - 84.9%) and matrix interference effects (humic acid shielding rates >40%), necessitating advanced strategies such as surface passivation, heterojunction design, and process standardization for performance optimization.

This review systematically examines green synthesis strate-

gies, structure-function modulation mechanisms, and cutting-edge advances in P-CDs for environmental pollutant detection. It critically evaluates key pathways for transitioning laboratory innovations to engineering applications while providing theoretical foundations for developing high-efficiency, low-cost, and multifunctional green remediation systems.

1 Green synthesis methods of P-CDs

1.1 Resource advantages and precursor types of medicinal-edible plants The green synthesis of nanomaterials is transitioning from conventional chemical routes to biomass-derived precursors, with medicinal-edible plants emerging as ideal candidates for carbon dot fabrication due to their natural functional groups and eco-friendly attributes. Various plant components—including roots, stems, leaves, seeds, and fruits (*e.g.*, bamboo leaves[1], bergamot[2], *Prunus avium*[3])—are enriched with polyphenols, amino acids, and alkaloids. These biomolecules serve dual functions as molecular templates for carbon core formation and fluorescence enhancers through nitrogen/sulfur self-doping mechanisms. For instance, *Lantana camara* flower-derived CDs demonstrate a quantum yield (QY) of 29% while maintaining 76% mammalian cell viability at 100 μg/mL, confirming the biosafety advantages of these precursors[10].

The valorization of agroforestry waste significantly enhances the sustainability of this approach. Cassava pulp-derived CDs synthesized via hydrothermal methods achieve an exceptional QY of 82.7%[5], enabling simultaneous detection of Hg^{2+}, Cu^{2+}, and Fe^{3+} with detection limits of 12.0, 21.7, and 11.2 μM, respectively—performance metrics surpassing those of chemically synthesized counterparts. This "waste-to-sensor" strategy reduces raw material costs while eliminating toxic reagents, aligning with global safety standards for nanomaterial production.

1.2 Overview and comparative analysis of green synthesis methods Innovations in green synthesis techniques for CDs have become pivotal in materials chemistry, driven by expanding applications in bioimaging and environmental monitoring. This section provides a critical evaluation of four mainstream synthesis strategies, focusing on their mechanisms and technical limitations:

(i) Hydrothermal synthesis[11]: It utilizes high-temperature and high-pressure aqueous environments in sealed reactors to drive precursor deoxygenation and functional group reorganization. While its water-only solvent system minimizes environmental impact, low mass transfer efficiency limits production yields.

(ii) Solvothermal synthesis[12]: It employs organic solvents (ethylene glycol, formamide) under similar conditions to enable controlled dissolution, nucleation, and crystal growth. Polar solvents accelerate carbonization kinetics and enhance functionality but introduce concerns regarding solvent toxicity and residual contamination.

(iii) Pyrolysis[13]: It involves high-temperature cracking (300 – 800 ℃) of precursors under inert atmospheres, offering scalability and low energy consumption. However, product heterogeneity hinders device integration.

(iv) Microwave-assisted synthesis: It leverages electromagnetic resonance for millisecond-scale heating, surpassing conventional thermal conduction rates. Challenges persist with uneven energy distribution leading to polydisperse particle sizes.

1.3 Structural and functional properties of P-CDs The performance of CDs is governed by three fundamental characteristics: crystalline structure, size distribution, and surface chemistry[14]. CD cores typically comprise sp^2/sp^3 hybridized carbon domains, with some systems exhibiting graphene-like layered architectures[15]. Porous structures enhance specific surface areas, providing abundant active sites for adsorption, storage, and catalytic processes. Intrinsic defects—including vacancies and heteroatom doping—critically modulate electronic structures and optical properties. For instance, strategic defect engineering enables tunable fluorescence emission, a cornerstone capability for sensing and imaging applications.

CDs generally exhibit sub – 10 nm diameters (1 – 10 nm range), conferring unique physicochemical properties such as cell membrane permeability—a critical feature for biomedical applications[16]. Their optical behavior arises from synergistic mechanisms including quantum confinement, surface state engineering, and heteroatom doping. Fluorescence emission wavelengths span visible to near-infrared regions, with characteristic excitation-dependent behavior. CDs demonstrate superior photostability compared to conventional dyes, showing negligible intensity decay under prolonged irradiation. Broad UV-Vis absorption bands contrast sharply with the sharp peaks observed in semiconductor-based CDs.

These structural and optical attributes not only underpin applications in biomedicine, environmental monitoring, and catalysis but also delineate critical research directions for performance optimization and functional expansion.

2 Environmental pollutant detection using P-CDs

The rapid progression of industrialization and urbanization has transformed environmental pollution from single-contaminant to complex multi-pollutant systems, where heavy metals and organic pollutants synergistically threaten ecosystems and human health. Within this context, P-CDs have emerged as a disruptive solution through their "green synthesis-functional integration" paradigm, advancing pollutant detection capabilities. These nanomaterials achieve simultaneous detection of heavy metals (Pb^{2+}, Hg^{2+}) and organic pollutants (herbicides, dyes) via multimechanistic pathways—including static quenching mechanisms (SQM), dynamic quenching mechanisms (DQM), and energy transfer processes (FRET/PET)—with detection limits spanning nanomolar to micromolar ranges (LOD: 0.59 nM – 36.8 μM), significantly surpassing conventional analytical methods.

The following sections elaborate on detection mechanisms and environmental application efficacy of P-CDs for heavy metals, organic pollutants, and emerging contaminants, with particular focus on critical pathways for transitioning laboratory innovations to environmental engineering applications.

2.1 Metal ion detection Metal pollution, characterized by persistent toxicity and bioaccumulative behavior, represents a critical global challenge for environmental and public health. P-CDs

provide innovative solutions for constructing highly sensitive and selective fluorescent sensing platforms, leveraging their tunable surface chemistry (hydroxyl, carboxyl, amino groups) and superior photophysical properties (quantum yield, QY: 3.06% –84.9%).

For mercury ion detection—requiring ultrahigh sensitivity and anti-interference capabilities—carboxyl-mediated SQM in medicinal-edible plant-derived CDs forms stable Hg^{2+} coordination complexes ($\log K = 5.7$), achieving a detection limit of 5.5 nM (QY = 50.78%) with 91% recovery under 100-fold sodium ion interference[17]. Nitrogen-doped CDs enhance Fe^{3+} detection sensitivity to 0.96 μM (QY = 13%)[3], a capability validated through live-cell imaging applications. Gamma-irradiation strategies further optimize surface defect states, reducing Fe^{3+} detection limits to 14 nM (QY = 38.2%)[18].

2.2 Organic pollutant detection The environmental persistence and biotoxicity of organic pollutants necessitate multidimensional detection systems. P-CDs, with customizable surface functionality and photophysical properties, demonstrate unique advantages in pesticide residue, antibiotic, and emerging contaminant detection.

For pesticide analysis, SQM enables detection limits as low as 11.58 nM (QY = 71.95%) with narrow size distributions (4.3 ± 0.65 nm)[19], while PET mechanisms achieve herbicide detection at 2.9 μM (QY = 17.02%)[20]. Antibiotic detection integrates PET-driven sensing (LOD = 120 nM, QY = 10.05%) with photocatalytic degradation (90% efficiency within 22 min), establishing a detection-remediation synergy[21].

Multiplex detection systems leverage SQM-IFE synergies for simultaneous quantification of CrO_4^{2-} (0.81 μM), Fe^{3+} (0.15 μM)[22], and organic molecules (ascorbic acid: 87.02 μM; L-cysteine: 8.785 μM) across 1.9 – 4 000 μM. Ultrasmall CDs (2.08 nm) mitigate cross-interference via steric hindrance, enabling isomer-specific nitrophenol differentiation (2-NP: 39 nM; 3-NP: 43 nM; 4-NP: 26 nM, QY = 53%)[23]. For emerging contaminants, dual-mode fluorescence-Rayleigh scattering systems reduce microplastic detection limits to 0.4 mg/L (100 × sensitivity improvement)[24], overcoming matrix interference. Ionic liquid grafting enhances probe stability, achieving chlortetracycline detection at 0.17 μM (QY = 15.42%) within a narrowed linear range (0.05 – 0.35 μM)[25].

2.3 Detection mechanism summary and performance comparison SQM and FRET excel in sensitivity (0.59 and 7 nM, respectively) and selectivity (>90%) but require specific coordination pairs or donor-acceptor proximity. IFE and DQM enable rapid (<1 min), wide-range detection (1.9 – 4 000 μM) but suffer from coexisting substance interference. PET is indispensable for antibiotic detection and co-degradation due to redox activity.

Key challenges include QY variability (3.06% –84.9%) and LOD disparities (0.59 nM – 36.8 μM), stemming from precursor biomolecular diversity (polyphenol-dependent π-π conjugation) and synthesis variability (±5 ℃ temperature shifts induce >12% *RSD* in size distribution). Achieving "compositional control-structural tunability-process stability" will drive the transition of P-CDs from laboratory innovation to environmental engineering applications.

3 Challenges and future directions

P-CDs exhibit remarkable potential in environmental pollutant detection and remediation, yet their transition from laboratory research to practical engineering applications faces critical technical barriers. Future research must address the following core challenges and define breakthrough pathways:

3.1 Standardization and process control in synthesis While green synthesis methods (hydrothermal, microwave-assisted) are widely adopted for P-CDs, yield variability (cassava pulp-derived CDs achieve 82.7% QY, whereas other plant-derived CDs drop to 3.06%) and polydispersity (relative standard deviation, *RSD* > 12%) hinder scalability. For instance, ±5 ℃ temperature deviations in hydrothermal synthesis induce significant size distribution shifts, while solvothermal methods, despite accelerating reaction kinetics (72% yield with ethylene glycol), raise ethical concerns over solvent residues. Future advancements demand hybrid techniques (microwave-hydrothermal integration reduces reaction time to 45 min while enhancing crystallinity by 20%) and automated systems to standardize processes (temperature/pH fluctuations ≤ ±1%). Additionally, precursor chemical diversity (polyphenol-dependent π-π conjugation) requires harmonization via plant variety screening and genetic engineering. Gamma irradiation, for example, optimizes surface defect density in neem resin-derived CDs, achieving Fe^{3+} detection at 14 nM.

3.2 Multi-scale structural and functional synergy The QY variability (3.06% –84.9%) and detection limit (LOD) disparities (0.59 nM – 36.8 μM) stem from synthesis inconsistencies and surface chemical heterogeneity. Nitrogen-doped cherry fruit-derived CDs lower Fe^{3+} LOD to 0.96 μM, while *Dunaliella salina* CDs achieve dual Hg^{2+}/Cr^{6+} detection (LOD = 18 nM) via DQM and IFE synergy[26]. Future strategies should integrate defect engineering (sulfur doping enhances Hg^{2+} sensitivity to 5.5 nM) and core-shell architectures (CQDs@TiO_2 heterojunctions suppress charge carrier recombination)[27]. Multifunctional systems, such as papaya seed-derived CDs enabling tetracycline detection (LOD = 120 nM) and photocatalytic degradation (90% efficiency in 22 min)[21], require machine learning to optimize detection-remediation parameters and mitigate cross-interference (38% selectivity loss in tetracycline/oxytetracycline coexistence).

4 Conclusion

P-CDs demonstrate transformative potential in environmental pollutant detection and remediation, driven by their green synthesis pathways and multifunctional integration capabilities. The utilization of natural precursors circumvents the high energy consumption and toxic reagents characteristic of conventional nanomaterial production while enabling ultrasensitive detection (LODs: 0.59 nM – 36.8 μM) and efficient degradation (>90% efficiency in 22 min) of heavy metals and organic pollutants through synergistic self-doping and surface functionalization mechanisms. The

strategic interplay of static quenching mechanisms (SQM), dynamic quenching mechanisms (DQM), energy transfer processes (FRET/PET), and photoinduced electron transfer (PET) has overcome historical limitations in single-target detection systems. Concurrently, advanced interfacial engineering and heterojunction designs have significantly enhanced photocatalytic degradation efficiencies while improving operational stability under complex environmental matrices. To realize this technology's full potential, three critical challenges require resolution: (i) standardization of quantum yield parameters (current range: 3.06% – 84.9%); (ii) mitigation of matrix interference effects (humic acid shielding >40%); (iii) scalable production of monodisperse particles (<5% size variation).

Addressing these challenges through interdisciplinary collaboration—integrating materials science, environmental engineering, and artificial intelligence-driven process optimization—will accelerate the transition from laboratory prototypes to field-deployable solutions. With continued innovation in defect engineering and system integration, P-CDs are poised to emerge as a disruptive, eco-compatible nanotechnology platform, advancing the global transition toward sustainable environmental governance paradigms that harmonize ecological preservation with industrial development.

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