

QUANTUM DOTS IN ENVIRONMENTAL CHEMISTRY: EMERGING APPLICATIONS FOR SENSING, REMEDIATION, AND SUSTAINABILITY

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Abstract

Environmental chemistry has seen a transformation thanks to quantum dots (QDs) because of their nanoscale dimension and adjustable fluorescent properties and their active surface chemistry. The combination of carbon and graphene quantum dots deliver photostable performance and low toxicity characteristics which enable their application in sensing pollutants and catalytic degradation systems and green energy devices. Scientists have proven recent breakthroughs in using heavy metal detection along with organic pollutant identification and pH and oxidative stress indicator analysis through fluorescence quenching and Förster resonance energy transfer mechanisms. The remediation field heavily benefits from QD applications because these nanoparticles excel at dye and endocrine disruptor photocatalysis and membrane systems for wastewater purification using adsorption and catalysis. Bio-derived and microwave-assisted and solvent-free synthesis approaches produce sustainable QD production methods while simultaneously improving QD tolerance to biological systems. The applications of QDs extend to renewable energy through their utilization in solar cell technologies and waste elimination systems. The continued use of quantum dots faces important obstacles because of their potential toxicity and environmental stability issues alongside the absence of specific regulatory systems. The complete sustainable utilization of QD technology requires both IoT and AI integration for real-time environmental tracking and multi-disciplinary collaborations and environmentally friendly policy development. The review integrates new findings about future deployment routes for QDs while explaining their potential environmental-scale sustainable implementation.

Keywords: Environmental Chemistry, Green Nanotechnology, Heavy Metal Detection, Nanosensors, Photocatalysis, Quantum Dots, Remediation, Sustainability

1. Introduction

Niante two decades nanotechnology changed environmental chemistry by creating completely new possibilities to track and manage pollutants at the atomic level. Because of their special properties including surface-area-to-volume ratio enhancement along with selectable surface properties and special optical effects nanomaterials function exceptionally well in solving intricate environmental concerns (Sridharan et al., 2022). Quantum dots (QDs) now receive considerable research interest in the field because they demonstrate three main advantages including luminescence superiority and photostability and environmental adaptability (Kumar et al., 2022; Thangadurai et al., 2022). Quantum dots represent nanoscale fluorescent materials which exist as semiconducting core-shell structures or carbon-based matrices. The low-toxicity and biocompatible carbon quantum dots (CQDs) and graphene quantum dots (GQDs) function as superior alternatives to traditional heavy-metal-based QDs (Yadav et al., 2023; Kumar et al., 2022). Their electronic structure that depends on size along with strong photoluminescence properties and excellent solubility qualities make them suitable for environmental sensor applications and photocatalytic systems and water treatment frameworks (He et al., 2022; Ji et al., 2021). Research demonstrates how QD synthesis process utilizes green and biomass-derived precursors for development that supports circular economy standards while promoting sustainable chemistry principles (Bijoy & Sangeetha, 2024; Huang & Ren, 2025).

Quantum dots have numerous applications in environmental science. Quantum dots exhibit outstanding performance in sensing applications because they detect hazardous pollutants including heavy metals and pesticides and explosives and pharmaceutical residues (Gul et al., 2024; Koç et al., 2022). Quantum dots display adjustable fluorescence characteristics that enable detection of particular analytes through ratiometric and turn-on/turn-off or multicolor detection approaches (Liu et al., 2025; Thakur & Dan, 2021). The detection of mercury, cadmium and lead ions in water matrices has been successfully achieved through fluorescence quenching of carbon dots (Laptinskiy et al., 2022; Sohal et al., 2021). QD sensing performance can be substantially improved through the addition of functional groups including amines, carboxyls and heteroatoms (e.g., N, S, B) according to Sohal et al. (2021) and Yadav et al. (2023). QDs find recent applications in remediation technologies where they operate through photocatalysis and adsorption-based filtration methods. QDs utilize visible or UV light to generate electron-hole pairs which enables their role in wastewater treatment through dye and endocrine-disrupting chemical and emerging contaminant degradation (He et al., 2022; Huang & Ren, 2025). Green CQDs synthesis methods lead to the creation of highly photoactive nanomaterials that effectively degrade organic pollutants using low amounts of energy (Jiang et al., 2024; Zhang et al., 2021). The placement of QDs into membrane systems or adsorbents enables the simultaneous elimination of various pollutant classes thus improving the efficiency and usability of water treatment operations (Mohammadpour & Molaabasi, 2023; Ji et al., 2021).

The development of renewable energy devices and smart packaging and eco-friendly sensing technologies receives substantial support from quantum dots in environmental sustainability applications. Their incorporation into perovskite solar cells combined with photovoltaics results in better energy harvest capabilities alongside biomass-generated quantum dots that provide food and agricultural intelligence with safer packaging alternatives (Litvin et al., 2021; Bijoy & Sangeetha, 2024). Dual-emission carbon dots demonstrate versatility in sustainability-linked innovations because they enable pH detection and real-time monitoring of oxidative stress (Liu et al., 2025; Mohammadpour & Molaabasi, 2023). QDs demonstrate compatibility with IoT platforms together with nanowire-based sensors which enables the creation of smart environmental monitoring systems according to Zhang et al., 2021 and Chen, 2023. The research community needs to conduct a detailed evaluation of QDs' environmental as well as biological safety aspects before their deployment. The potential for cytotoxicity, ecotoxicological accumulation, and long-term persistence in ecosystems necessitates a balanced approach to their deployment (Thangadurai et al., 2022; Hussain et al., 2022). The implementation of polyethylene glycol (PEG) functionalization and heteroatom doping and low-temperature green synthesis methods offers a solution to minimize such risks without sacrificing functionality (Ji et al., 2021; He et al., 2022). Field-ready technologies can only be developed through standard ecotoxicity assessments as well as regulatory framework improvements that begin at laboratory scale. Research on quantum dots has increased exponentially while their environmental impact grows widely so scientists require an extensive thematic review to condense existing knowledge and show directions for future studies. This article fills the knowledge gap by conducting a critical assessment of QD applications in environmental chemistry through three main areas: environmental pollutant detection methods and QD-based remediation techniques and their role in developing sustainable green technologies. The review attends to QD characteristics, synthetic procedures and utility methods and environmental aspects to create a complete scientific and environmental sustainability connection.

2. Overview of Quantum Dots (QDs)

Nanometer-sized particles known as quantum dots exhibit quantum confinement effects that produce singular optical and electronic properties which extend to less than 10 nm diameter. QDs function as versatile nanomaterials in environmental work because their photoluminescence depends on size and their reactive surfaces and energy level adjustability.

2.1 Definition and Structural Characteristics

Quantum dots function as nanoscale semiconductor particles measuring under 10 nanometers that demonstrate quantum confinement properties which yield special optical and electronic features (Thangadurai et al., 2022). QDs exist in three structural categories. Core-only nanocrystals consist of single-component nanoparticles which include carbon dots (CDs) that contain only carbon atoms arranged in crystalline or amorphous structures. QD core-shell structures involve semiconductor cores (CdSe) incorporated inside semiconductor shells (ZnS) which enhances the QD performance by reducing surface defects and photobleaching. The inclusion of heteroatoms into carbon quantum dots like N-CQDs

through dopant or heteroatom modification enhances both surface features and electronic features as well as luminescence output and chemical responsiveness (Sohal et al., 2021; Yadav et al., 2023).

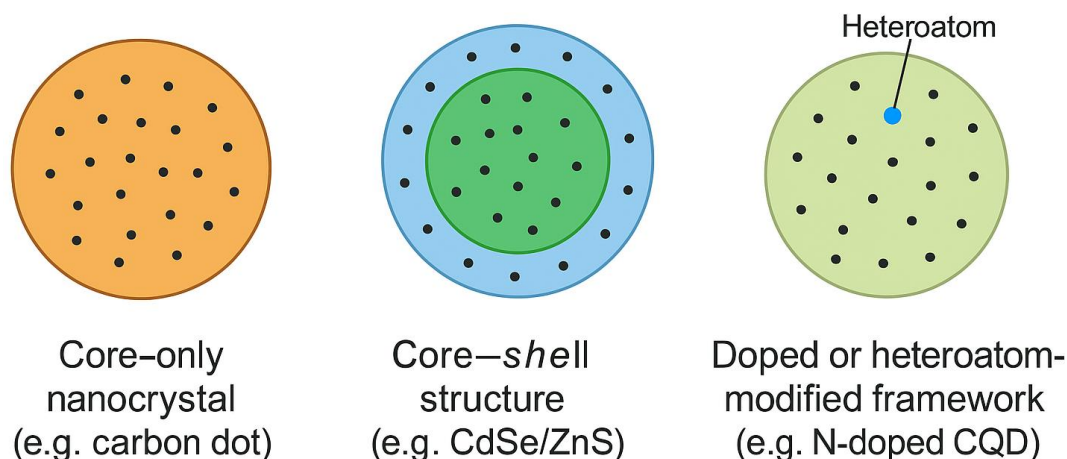


Figure 1: Structural types of quantum dots—core-only, core-shell, and doped frameworks.

Environmental nanotechnology employs three main quantum dot (QD) architectures which are shown in Figure 1. Core-only nanocrystals made from carbon dots consist of one material type which provides basic functionality while maintaining simple design. полнотное структура вида CdSe/ZnS consists of a core-material surrounded by an outer shell that provides better stability in addition to increasing fluorescence intensity and photobleaching resistance. Systems like N-doped CQDs modify QDs by adding foreign atoms which gives control over their performance levels and their chemical reaction with environmental elements. The different structural arrangements of QDs directly affect their performance in pollutant detection and photocatalysis and sustainable remediation systems. The nanostructures demonstrate spherical morphologies or near-spherical shapes that have evolved high surface-to-volume ratios allowing for effortless functional group connection. Connective modifications to such structures result in substantial changes to both surface charge potential and environmental interactions and fluorescence behavior patterns.

2.2 Classification Based on Composition and Origin

The classification of quantum dots (QDs) depends on their chemical composition together with structural features and synthesis origin. The various types of quantum dots possess unique optical and electronic and surface properties that determine their effectiveness in environmental applications.

2.2.1 Carbon Quantum Dots (CQDs)

Carbon quantum dots represent zero-dimensional nanostructures which consist mainly of carbon atoms arranged in amorphous or graphitic structures. The dots demonstrate both strong fluorescence under excitation-dependent conditions and low toxicity levels and excellent dispersibility in water solutions. The photoluminescence properties of these dots stem from surface defects and quantum confinement effects as well as surface functional groups (Yadav et al., 2023). CQDs demonstrate growing application in metal ion detection and photocatalytic pollutant degradation and biosensing systems because of their environmentally friendly nature (Laptinskiy et al., 2022).

2.2.2 Graphene Quantum Dots (GQDs)

The nanoscale fragments of graphene sheets known as GQDs maintain dimensions smaller than 20 nm. Their flat arrangement of extended π -conjugated bonds creates an electrically conductive system that extends their photostability. The combination of carboxyl and hydroxyl and nitrogen-containing functional groups enables GQDs to exhibit strong luminescence properties and selective analyte binding which makes them suitable for fluorescence-based environmental sensors (Thangadurai et al., 2022; Sohal et al., 2021). The sp^2 -carbon networks in their structure enable efficient electron transport which is vital for detecting redox-active pollutants.

2.2.3 Semiconductor Quantum Dots

The band-gap energies of semiconductor QDs can be adjusted through size control because strong quantum confinement effects permit narrow and high-yield bandgaps in II–VI or IV–VI group elements such as CdSe, ZnS, and PbS. The combination of these features makes semiconductor QDs highly suitable for optoelectronic and imaging applications. The application of Semiconductor QDs in environmental chemistry remains limited because of their toxicity properties and their inability to break down naturally (Litvin et al., 2021). Surface passivation together with encapsulation in biocompatible matrices represents standard techniques for decreasing environmental risk in nanomaterials.

2.2.4 Doped and Hybrid Quantum Dots

Scientists introduce heteroatoms (nitrogen, sulfur, phosphorus and boron) to QD crystal structures to optimize electronic features while boosting fluorescence and booster selectivity levels. The integration of PEG and biopolymers with hybrid QDs functions as a solution for enhancing solubility and biocompatibility (Ji et al., 2021). The modifications enable QDs to be used in multi-analyte sensing and bioimaging and sustainable environmental remediation according to Thakur and Dan (2021). Scientists highly value doped quantum dots because they maintain stability in tough environmental settings.

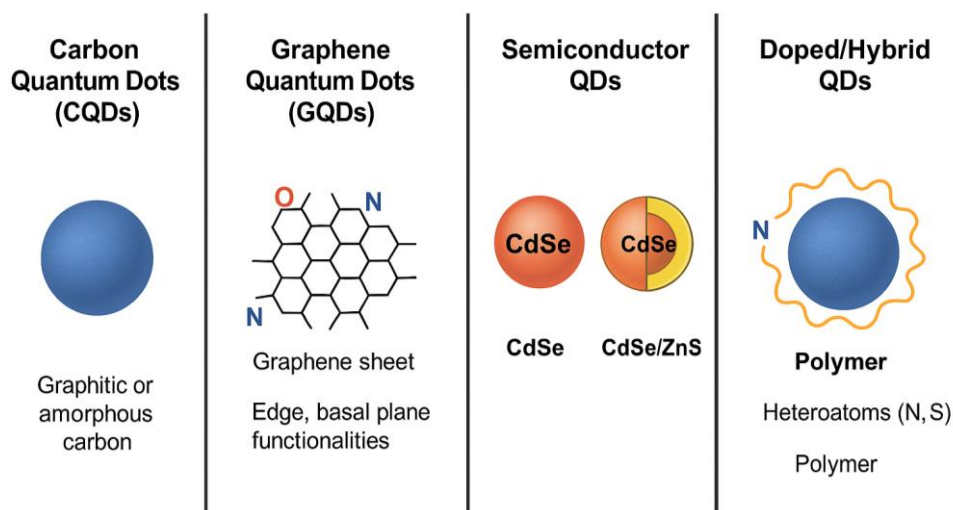


Figure 2: Visual comparison of four types of quantum dots—CQDs, GQDs, semiconductor QDs, and doped/hybrid QDs—highlighting differences in structure, composition, and functionalization.

The schematic in Figure 2 shows four main categories of quantum dots (QDs) which are distinguished by their structural and compositional features. The spherical nanoparticles of carbon quantum dots (CQDs) present uniform carbon matrices and functional surface groups which make them suitable for sensing and imaging applications. Quantum dot graphene GQDs exist as flat layer fragments which present both fast electronic conductivity and active edge properties. Semiconductor QDs demonstrate two distinct structural configurations including core-only and core-shell structures which use CdSe/ZnS as an example but suffer from toxicity issues. Doped/hybrid quantum dots incorporate heteroatomic structures in combination with polymer coverings which improve their specificity and compatibility with biological environments. They also maintain better stability. The side-by-side visual representation demonstrates that structural characteristics control practical use and suitability for environmental applications.

2.3 Physical, Chemical, and Photoluminescent Properties

Quantum dots (QDs) possess physical worth alongside chemical abilities and optical features which makes them outstanding for environmental chemistry applications about sensing and remediation and energy conversion. The physical characteristics of quantum dots depend on their nanoscale dimensions together with their composition and surface states and structural modifications.

2.3.1 Photoluminescence (PL)

Quantum dots exhibit size-dependent and excitation-dependent fluorescence because of quantum confinement effects. The bandgap size of QDs increases with decreasing size which results in blue-shifted light emission while larger QDs produce light that shifts toward the red spectrum. The adjustable emission spectrum enables multicolor imaging together with ratiometric sensing and fluorescent labeling of complex matrices (Jiang et al., 2024; Mohammadpour & Molaabasi, 2023). Environmental monitoring benefits from such features which enable multiple analyte detection as well as environmental condition monitoring through color-coded responses.

2.3.2 Surface Functionalization

QDs obtain superior chemical activity after being surface engineered with functional groups such as carboxyl ($-\text{COOH}$) and hydroxyl ($-\text{OH}$) and amines ($-\text{NH}_2$) and thiols ($-\text{SH}$). These biologically active moieties enhance the ability of QDs to dissolve in water while maintaining dispersion quality as they allow for linking ligands, antibodies or polymers (Yadav et al., 2023; Koç et al., 2022). The surface groups attached to QDs enhance their ability to selectively detect specific contaminants including heavy metals and toxins and organic pollutants while achieving sensitive and low detection limits.

2.3.3 Quantum Yield and Stability

The efficiency of QD light emission from absorbed light is measured through Quantum Yield (QY). The efficiency of fluorescence-based applications depends on this property. The incorporation of heteroatoms like nitrogen or sulfur into QDs through doping enhances QY through the reduction of non-radiative recombination and surface defect passivation (Liu et al., 2025; Zhang et al., 2021). These modifications boost QD stability against thermal and photochemical and chemical factors which enables their effective operation in environmental samples exposed to different pH levels and temperatures and light conditions.

2.3.4 Electrical Conductivity

Graphene quantum dots show high electrical conductivity because they have a sp^2 -hybridized carbon network which results in extended π -conjugation. The high electrical conductivity of GQDs serves as a vital factor in photocatalysis because it reduces electron-hole recombination rates which enhances degradation performance. The fast electron transfer kinetics in electrochemical sensing becomes possible through high conductivity which enables precise and rapid electroactive pollutant detection (He et al., 2022; Hussain et al., 2022). GQDs become beneficial in electronic integration and redox activities applications due to their unique features.

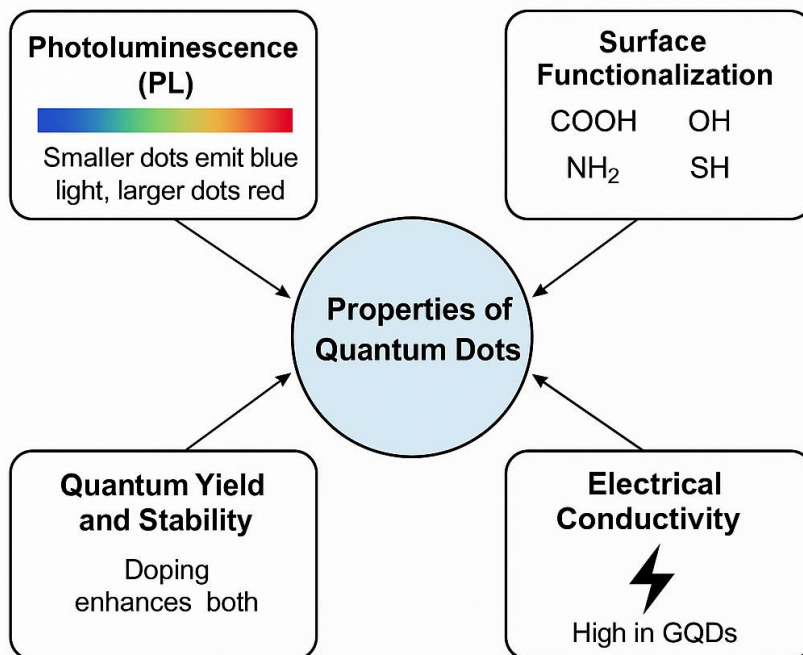


Figure 3: Key functional properties of quantum dots relevant to environmental applications

The four fundamental characteristics of quantum dots (QDs) shown in Figure 3 enable their environmental chemistry applications. The photoluminescence properties of these materials depend on their size and excitation wavelength which enables their use in pollutant detection through multicolour emission. Two functional groups especially -COOH and -NH_2 provide surfaces with improved solubility and selectivity at the same time. The quantum yield reaches higher levels when heteroatoms are added to the system which results in durable and robust fluorescence performance under demanding conditions. Application of graphene quantum dots (GQDs) brings increased electrical conductivity for accelerated charge transfer especially in photocatalytic and electrochemical fields. QDs demonstrate high adaptability within integrated environmental systems because they present these distinctive characteristics.

2.4 Green Synthesis and Biocompatibility

The drive for sustainable nanotechnology focuses on creating environmentally friendly methods to produce quantum dots (QDs) which leads to safer applications. Scientific synthesis has replaced conventional chemical methods by using eco-friendly resources under mild conditions with non-toxic reagents to produce quantum dots having biocompatible and biodegradable characteristics. The modification enables support for environmental chemistry objectives and enhances QDs' use for in vivo diagnostic testing and soil status evaluation and water cleaning processes (Huang & Ren, 2025; Ji et al., 2021).

2.4.1 Biomass-Derived Carbon Sources

Biomass serves as a promising sustainable approach for QD synthesis through the utilization of agricultural waste and natural polysaccharides and fruit peels and sugarcane bagasse. The profuse easily renewable economical nature of these resources makes their use effective for manufacturing carbon quantum dots (CQDs) with controlled optical properties. The synthesis method enables carbon waste reduction while generating valuable products from unused materials (Bijoy & Sangeetha, 2024). The functional groups present in these biomaterials stay on QD surfaces to improve both water solubility and sensing abilities without requiring additional chemical modifications.

2.4.2 Microwave-Assisted Synthesis

Microwave irradiation provides an efficient method to produce QDs with uniform shape and high quantum yield through rapid energy-efficient synthesis. As a reaction technique biomass or organic precursors experience microwave-powered intense heating that leads to localized fast carbonization. The method reduces both reaction duration and temperature requirements thus minimizing energy requirements and decreasing solvent requirements. The production technique enables large-scale environmentally friendly synthesis of CQDs and GQDs (Huang & Ren, 2025).

2.4.3 Hydrothermal and Solvothermal Methods

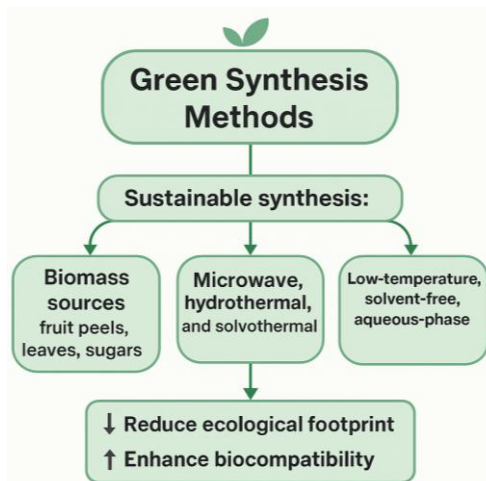
The method uses closed systems under pressure to heat carbon-rich precursors within aqueous or organic solvents which results in QD nucleation and growth. The hydrothermal synthesis method employs water as its solvent which fulfills the criteria of green chemistry. Hydrothermal reaction conditions between plant extracts and amino acids and saccharides produce QDs that exhibit strong fluorescence properties and active surface functionalities. Solvothermal methods allow researchers to use various solvents while green variants focus on using environmentally friendly non-toxic or recyclable solvents (Kumar et al., 2022). The methods allow researchers to control the dimensions of particles and their crystalline structure and their surface chemical characteristics.

2.4.4 Low-Temperature and Solvent-Free Approaches

Two modern advancements in the field involve solvent-free pyrolysis and low-temperature combustion which eliminate every trace of liquid-phase solvents from the process. The methods decrease hazardous waste production while preventing secondary pollution formation. The achievement of QDs with high luminescence and narrow size distributions becomes possible through optimal reaction condition adjustments including temperature and precursor ratios. The synthesis of quantum dots at low temperatures through aqueous solutions provides an advantageous method for safe large-scale production especially when targeting biomedical and environmental applications (Huang & Ren, 2025).

Biocompatibility Considerations

The green synthesis of QDs produces nanostructures that demonstrate both low toxicity to living organisms and quick environmental breakdown which makes them suitable for biological applications and water systems and agricultural fields (Ji et al., 2021). The bio-friendly nature of these QDs results from their minimal heavy metal content and their low stabilizer requirements and their natural passivating agents. Research demonstrates PEG-functionalized QDs and nitrogen-doped CQDs derived from amino acids maintain strong fluorescence properties without showing any toxic effects thus enabling their applications in biosensing and bioimaging and in vivo tracking (Kumar et al., 2022).



ChatGPT said: Figure 4: Green synthesis strategies for quantum dots using eco-friendly routes like biomass precursors, microwave, hydrothermal, and solvent-free methods

The Figure 4 shows how green synthesis methods create functional nanomaterials through environmentally friendly procedures for quantum dots (QDs). The utilizations of biomass-derived methods use agricultural waste and natural compounds to eliminate resource waste while simultaneously creating valuable products from organic residues. The formation of QDs becomes efficient through the rapid and uniform heating capabilities of microwave-assisted synthesis. Hydrothermal and solvothermal synthesis techniques enable researchers to exercise precise control when producing QDs by using water together with low-toxicity solvents or water itself. Exposure to both minimal solvents and cool temperatures acts as approaches to maintain minimal environmental impacts. The production methods generate QDs with superior fluorescence that contain low toxic compounds and degrade easily within the environment for applications such as sensing and remediation of pollutants as well as ecological nanotechnology.

3. Environmental Sensing Applications

Quantum dots (QDs) establish themselves as very sensitive as well as selective nanomaterials which can be used for environmental sensing applications. The combination of photoluminescence tunability and high surface-to-volume ratio along with surface functionalizability allows QDs to detect various pollutants at very low detection limits. Quantum dots demonstrate different usefulness in environmental detection through applications across heavy metals, organic contaminants and continuous environmental status monitoring systems.

3.1 Detection of Heavy Metals

Heavy metal contamination creates substantial environmental risks because these substances remain non-degradable and accumulate within biological systems. Quantum dots serve as effective detectors for toxic metals including mercury (Hg^{2+}), lead (Pb^{2+}) and cadmium (Cd^{2+}) because these nanocrystals show fluorescence changes when exposed to metal ions. The main detection process involves fluorescence quenching because metal ions extract electrons from QD photoexcitation states to reduce their emission output. The detection capability of metal ions achieves such levels of sensitivity that scientists can detect them at nanomolar and picomolar levels through the combined action of Förster Resonance Energy Transfer (FRET) and electron transfer processes. Heavy metals show higher affinity for QDs containing

nitrogen or sulfur doping and thiol (-SH) surface modification. The soft–soft acid–base interaction mechanism enables nitrogen-doped carbon dots to exhibit strong selectivity toward Hg²⁺.

3.2 Detection of Organic Pollutants

Organic contaminants consisting of pesticides along with synthetic dyes and pharmaceutical residues persist in ecosystems and harm human health because they remain in the environment while accumulating in living organisms. QDs function as superior detection platforms for compounds because they demonstrate outstanding fluorescence sensitivity and emission stability together with the capability for molecular recognition elements such as aptamers or antibodies. The interaction between QDs and target organic molecules produces detectable shifts in their fluorescence spectrum because the molecules alter surface charge or electron density. The binding interaction of amine-functionalized QDs with nitroaromatic pesticides and tetracycline antibiotics results in fluorescent brightness loss or wavelength spectrum movement. The detection sensitivity of graphene quantum dots (GQDs) and doped carbon quantum dots (CQDs) significantly improves when they encounter electron-withdrawing groups which are characteristic contaminants in industrial dyes and pharmaceutical residues therefore making these materials suitable for trace-level organic pollutant environmental monitoring.

3.3 Real-Time Monitoring of Environmental Parameters

Quantum dots (QDs) serve as favorable tools for non-invasive real-time environmental parameter tracking of pH values alongside temperature measurements and reactive oxygen species (ROS) and peroxide detection. The wide application of pH-sensitive QDs occurs in aquatic environments through biosensors which detect acidification and microbial activity based on their fluorescence reaction to pH variation. Temperature-responsive QDs alter their fluorescence intensity or emission wavelength with variations in ambient temperature, enabling precise thermal profiling of ecosystems or engineered systems. Quantum dots display fluorescence shift indicators when exposed to oxidation which makes them effective for assessing soil and water quality. Attaining rapid response and multiplex detection while deploying sensors in field locations are possible because quantum dots maintain their natural advantages of quick detection and multiple signal detection with portability.

The table below presents quantum dots (QDs) environmental sensing applications across three domains which include heavy metal detection and organic pollutant sensing and environmental parameter monitoring. Quantum dots detect heavy metals at ultra-sensitive levels by means of fluorescence quenching interactions and FRET mechanisms when sensing Hg²⁺ and Pb²⁺. The detection of organic pollutants including pesticides and dyes leads to QD-based fluorescence changes through surface interactions with high selectivity. QDs enable real-time environmental parameter observation by monitoring their signal output for pH and oxidizing conditions. The various applications demonstrate how QDs provide quick and sensitive environmental monitoring solutions that can be used in field settings.

Table1: Summary of Environmental Sensing Applications of Quantum Dots

Application	Target Analytes	Mechanism	Advantages
Heavy Metal Detection	Hg ²⁺ , Pb ²⁺ , Cd ²⁺	Fluorescence quenching, FRET, electron transfer	Ultra-low detection limits, high selectivity
Organic Pollutant Detection	Pesticides, dyes, pharmaceutical residues	Surface interaction-induced fluorescence changes	High sensitivity, tunable surface functionality
Environmental Parameter Monitoring	pH, temperature, oxidative stress markers	Signal modulation based on physicochemical cues	Real-time tracking, multiplex capability, non-invasive use

4. Quantum Dots in Environmental Remediation

Quantum dots (QDs) now use their sensing and diagnostic functionalities for environmental remediation with dramatically progressive effects. QDs show particular suitability for pollution treatment purposes because of their optoelectronic features combined with extensive surface area and adaptable chemical traits on their surface. QDs demonstrate important applications in photocatalytic degradation operations as well as water purification systems and soil/air remediation processes which build sustainable routes for pollution control.

4.1 Photocatalytic Degradation of Pollutants

Visible or ultraviolet (UV) light exposure causes quantum dots (QDs) to show great efficiency in photocatalytic activity by creating electron–hole (e⁻/h⁺) pairs. The redox reaction sequence starts after this process to break down dangerous environmental pollutants. Light absorption triggers electrons in the valence band to transition to the conduction band while creating positively charged holes behind them. When excited electrons interact with molecular oxygen, they create reactive oxygen species (ROS) including superoxide radicals and holes drive the water molecule oxidation process to hydroxyl radicals (•OH). The strong oxidative power of these radicals enables them to break down a wide range of organic pollutants into harmless end products consisting of carbon dioxide and water. The application of QDs leads to successful degradation of synthetic dyes including methylene blue and rhodamine B and pharmaceutical pollutants such as phenolic compounds and endocrine-disrupting chemicals comprising bisphenol A. QDs function better than conventional photocatalysts such as titanium dioxide (TiO₂) because they have superior visible light absorption abilities and adjustable bandgap energies

and accessible surface interaction points which lead to better pollutant-specific reactions and increased efficiency when operating in regular environmental conditions.

4.2 Water Purification and Wastewater Treatment

Quantum dots (QDs) serve as major components in modern advanced water treatment systems when used for nanofiltration membranes along with adsorptive systems. Once embedded in polymeric membranes QDs deliver superior performance by increasing permeability along with reducing fouling and enabling photo-solid cleaning functions. Collisions between water molecules with carbon and graphene quantum dots (CQDs and GQDs) establish both hydrophilic conditions and electrostatic selectivity capabilities leading to better membrane-water binding while producing fortified contaminant filtering mechanisms. QDs show excellent adsorption properties because they possess high surface area and surface functional groups which enable them to bind heavy metals and organic pollutants. The catalytic activity of doped quantum dots becomes possible through nitrogen or sulfur modifications which enables wastewater contaminant breakdown without requiring additional chemical oxidants. QDs function as dual components in water purification systems because they simultaneously perform filtration and catalytic roles to tackle multiple forms of water contamination.

4.3 Soil and Air Remediation Potential

Solar-activated quantum dots prove useful for air and soil purification technologies because they can function within composite materials.

4.3.1 Soil Stabilization and Decontamination

Quantum dots (QDs) currently receive increased attention for polluted soil decontamination because their properties enable successful heavy metal stabilization while removing persistent organic pollutants (POPs). The toxic compounds create severe environmental and agricultural problems because they persist in the environment and accumulate in living organisms while damaging microbial communities. Soil-conditioning materials including biochar, hydrogels and organic–inorganic hybrid additives effectively accept QDs for remediation purposes. The embedded materials demonstrate robust adsorption properties which enable them to capture and fix contaminants inside the soil structure. Heavy metals including Pb^{2+} , Cd^{2+} and As^{3+} become immobilized in soil due to electrostatic or chemical interactions between their surface functional groups (carboxyl, hydroxyl, or amine moieties) (Bijoy & Sangeetha, 2024). The catalytic activity of doped QDs enables light-driven degradation of organic pollutants including pesticides and POPs which enhances the process of soil detoxification (Huang & Ren, 2025). When soil implements QD-enhanced materials it helps detoxify the rhizosphere space which remains essential for normal root-microbial interaction processes. QDs possess the ability to minimize contamination-related stress in the soil and simultaneously support the development of roots and microbial balances and nutrient intake resulting in better soil fertility and agricultural yields when facing contamination (Kumar et al., 2022). QDs show excellent potential for long-term environmental deployment because they are both biocompatible and have low cytotoxicity when synthesized through green methods. QDs represent an advanced multifunctional solution for soil remediation since they unite adsorption properties with catalytic capabilities and good performance within current soil stabilization methods to manage polluted areas sustainably.

4.3.2 Air Purification Applications

Technology research focuses more and more on quantum dots (QDs) as air purification components because they excel under visible light activation and perform effectively with gaseous pollutants at the molecular scale. The application of QDs in air filters and smart coatings and catalytic surfaces enables photo-induced oxidation processes for degrading volatile organic compounds (VOCs) and airborne microbial pathogens (Huang & Ren, 2025). Light exposure of QDs produces electron–hole pairs which trigger ROS formation that converts harmful VOCs like formaldehyde, benzene, and toluene into harmless products including CO_2 and water. The gaseous phase implementation of this photocatalytic degradation process follows the same mechanism as water treatment applications. Scientists study graphene quantum dots (GQDs) as a material for air filter coatings because their fluorescent characteristics enable both pollutant breakdown and instant environmental contaminant detection via altered fluorescent signals (Thangadurai et al., 2022). QDs integrated with functional textiles and wall coatings provide a passive air cleaning method using ambient indoor lighting to maintain environmental cleanliness. The system provides an energy-efficient sustainable solution to standard filtration systems that need continuous power input and regular equipment replacements (Bijoy & Sangeetha, 2024). The biocompatible and adjustable QDs produced by green synthesis methods demonstrate suitability for residential and medical and industrial indoor applications. QD-based air purification continuously improves as a new air quality management approach which can lead to self-cleaning solutions that react to their environments via energy-efficient methods that support wider environmental remediation initiatives.

5. Quantum Dots for Environmental Sustainability

Quantum dots (QDs) function as detectors and pollution treatment tools but scientists now study their ability to make environmental sustainability progress. The special photochemical together with electronic properties of quantum dots allow researchers to apply these nanocrystals for pollution reduction while supporting renewable power generation and sustainable manufacturing and circular economy practices. The section demonstrates how QDs enable renewable energy development through their application in eco-friendly synthesis and waste valorization processes.

5.1 Renewable Energy and Photovoltaics

Renewable energy technology development flourishes through the application of quantum dots which boosts their solar energy collection capability and photocatalytic H₂ synthesis process. Quantum dots exhibit bandgap properties that depend on their size to enable efficient use of greater light spectra thereby boosting quantum dot-sensitized solar cell performance as well as hybrid perovskite photovoltaic devices (Litvin et al., 2021). The integration of QDs in solar cell matrices functions as both light absorbing and energy transferring components which leads to higher photocurrent density and better device efficiency. The photocatalytic systems that use CdS, CdSe and doped carbon dots QDs enable solar-driven water splitting and CO₂ reduction to produce sustainable fuel (Huang & Ren, 2025). Their tunability, cost-effectiveness, and solution-processable nature position QDs as an enabling material for scalable, next-generation photovoltaic technologies.

5.2 Eco-Friendly Synthesis and Green Chemistry

The essence of sustainability exists in reducing toxic chemicals used during material synthesis operations along with their accompanying chemical byproducts. QDs achieve green synthesis through multiple approaches that utilize biomass precursors such as fruit peels and plant extracts and agricultural residues according to Bijoy and Sangeetha (2024). The biogenic synthesis methods decrease environmental impact through carbon sources that are nontoxic while requiring minimal energy consumption and eliminating the need for dangerous stabilizers or solvents. The synthesis of QDs through green methods results in particles with high optical quality and reduced toxicity to cells while offering better environmental breakdown characteristics which makes them suitable for in vivo applications and reduces ecological damage (Kumar et al., 2022; Ji et al., 2021). The production methods follow green chemistry principles by creating sustainable processes which deliver maximum lifecycle advantages while maintaining performance quality.

5.3 Integration in Circular Economy and Waste Valorization

Quantum dots serve as critical components in developing the circular economy since they help reuse materials through recycling processes that enable constant material regeneration and waste reduction. Research has expanded to explore organic waste conversion into QD precursors which creates a waste-to-nanomaterial approach that enhances discarded biomass value (Bijoy & Sangeetha, 2024; Huang & Ren, 2025). Industrial waste containing carbon along with municipal organic waste can be converted into high-quality carbon quantum dots (CQDs) through either hydrothermal or pyrolysis treatment. The functional surface groups of these CQDs enable their use in environmental sensors and catalysts which completes the material lifecycle. The zero-waste field benefits from quantum dots which function as multi-use components in various sensors and membranes and packaging systems that require low-impact materials. Quantum dots serve as environmentally responsible assets for sustainable material creation because they have extended durability and easy recyclability and adaptable surface engineering features.

The environmental sustainability benefits of quantum dots (QDs) are detailed in Table 2 across three essential areas. Solar cell performance and clean fuel generation through light absorption control and charge separation improvement become achievable in renewable energy systems and photovoltaics through QD implementation. Non-toxic environmentally friendly QDs emerge from biomass precursors while using green chemical synthesis processes that result in self-decomposing QD materials. Through their application in the circular economy QDs transform organic waste together with industrial waste into beneficial nanomaterials which help reduce waste and enable reusable technologies. QD applications integrate them as essential parts for developing sustainable and zero-waste technological breakthroughs.

Table 2: Summary of Quantum Dots in Environmental Sustainability

Subsection	Application Area	Key Mechanism / Role	Environmental Benefits
5.1 Renewable Energy and Photovoltaics	Solar cells, photocatalysis	Light absorption tuning, charge carrier generation, water splitting, CO ₂ reduction	Supports clean energy, enhances solar efficiency, reduces carbon footprint
5.2 Eco-Friendly Synthesis and Green Chemistry	Green nanomaterial production	Biomass-derived carbon sources, solvent-free and low-temp synthesis methods	Minimizes toxic waste, promotes green chemistry, ensures biocompatibility
5.3 Circular Economy and Waste Valorization	Waste-to-QD conversion, sustainable devices	Conversion of organic/industrial waste into QD precursors; use in recyclable technologies	Reduces landfill waste, supports zero-waste systems, promotes resource reuse

6. Toxicity, Safety, and Regulatory Considerations

The wide range of quantum dot (QD) applications in environmental and biomedical areas demands urgent studies on their toxicity and safety aspects. The main problem with QD-based applications stems from the toxic effects of heavy metal QDs including cadmium (Cd), lead (Pb) and selenium (Se). These elements create risks when they release into biological systems because they disrupt cellular operation and DNA replication as well as enzymes so biological cells along with environmental microorganisms experience both oxidative stress and cytotoxic effects. QDs present safety risks because they are both biodegradable and environmentally persistent. The non-biodegradable nature of numerous inorganic QDs enables them to build up in ecosystems with particular accumulation occurring in aquatic environments where plankton

absorbs them leading to their entry into the food chain. The toxicity of carbon-based QDs depends on their dimensions and surface modifications and production methods. The safe assessment of prolonged environmental behavior demands precise analysis of how QDs travel through soil, air and water environments.

The responsible advancement of QD technologies requires strong standardized international regulatory protocols that are developing quickly because of market demands. The current chemical regulations in most countries apply to nanomaterials yet they do not include specific guidelines for quantum dots which account for their nanoscale properties and biological interactions and environmental persistence. Standardized procedures for testing toxicity as well as exposure limits and labeling requirements remain insufficient for QDs used in consumer items and environmental sensors and medical diagnostic applications. International organizations have launched efforts to develop nanotoxicology information systems and sustainable design protocols and entire process evaluations for detailed QD assessments spanning their complete life cycle. The green synthesis of QDs represents a vital approach to decrease toxicity risks because it combines nontoxic solvents with biodegradable precursors to achieve regulatory compliance. The extensive implementation of quantum dots requires extensive testing of safety standards and ecological impact assessment followed by worldwide standards that secure both environmental and human health.

7. Future Prospects and Challenges

Quantum dots (QDs) have proven to be such a promising technology that it is expected to work towards enhancing environmental monitoring, environmental remediation, and sustainability. The widespread use of quantum dots depends on resolving multiple scientific, technical and regulatory obstacles. QD research and development will follow a specific path based on solving scalability problems and integrating systems and fostering cross-sector collaboration.

7.1 Scalability and Commercialization Hurdles

Although versatile, a major obstruction to the application of QDs in real world applications is the scaling up of synthesis methods in a way that yields QDs of high quality, uniformity and most importantly at an affordable cost. Batch to batch variability is a common problem in current laboratory scale production, especially for size distribution, surface chemistry and photoluminescence efficiency. In addition, QD formulations are still based on toxic metals or energy expensive preparation methods that limit commercialization potential and create environmental issues. Robust, green and economically viable synthesis platforms that can provide gram to kilogram quantities of the materials without compromising functional performance are needed to achieve industrial scale production. It also involves tackling such issues as purification and colloidal stability of materials, shelf-life extension, critical for the practical implementation of QDs in sensors, filters, or solar panels, for example. Another way to attain sustainable manufacturing of QD is through the combination of microreactor technology, automated flow synthesis, and biomass derived feedstocks.

7.2 Integration with AI and IoT for Smart Environmental Systems

In addition to material improvements, the digital integration of QD based applications is the future. Combining QDs with Internet of Things (IoT) platforms enables smart and in situ environmental sensing at the point where it is needed. An example would be functionalized QDs to detect pollutants or environmental changes embedded in wireless sensors (and associated data loggers) and cloud platforms for continual monitoring of air, soil, and water quality.

This integration is further enhanced by the use of artificial intelligence (i.e. through predictive analytics, pattern recognition, etc.) and help automate response systems. For example, it could process signals from QD based sensors to analyze complex fluorescence signals to determine new trends of contamination, aid in the ways to optimize energy usage in treatment systems, or automate maintenance alerts for QD enabled devices. The synergy then lends QDs to be vital elements of next generation smart environmental infrastructure, for instance in the context of smart cities and precision agriculture.

7.3 Multidisciplinary Collaboration and Policy Implications

A multidisciplinary effort is required to realize the responsible advancement of QD technologies, and therefore fill the gap between basic material science, environmental engineering, toxicology, public health, and policy-making. To ensure that innovation is consistent with safety, ethical and sustainability goals, researchers will have to work with regulatory bodies, industrial stakeholders and societal institutions in order to create a common approach. Therefore, with regards to policy, the nanoscale properties of QDs present the need for new regulatory frameworks which take into account their nanoscale behavior, their lifecycle impact and fate in the environment. Under DOE authority it will also include developing standardized testing protocols, toxicity benchmarks, and disposal/recycling guidelines. The international cooperation is particularly important for such applications because QDs become an important part of transboundary technologies such as global water monitoring systems, cross border environmental diagnostics, and cloud integrated remediation networks. Moving in parallel, the funding and academic institutions must encourage interdisciplinary education and research training to prepare the next generation of scientists to work across the borders. The combination of nanotechnology, sustainability science, data engineering, and environmental policy will be crucial for achieving improvements in human wellbeing from QD innovation.

8. Conclusion

Having excellent quantum efficiency and being valuable as a nanomaterial for sensing, environmental remediation and sustainability, quantum dots (QDs) are representative of, and are as valuable as, a new class of nanomaterials. It could be stated that the key applications of QDs covered in this review include detection of heavy metals, organic pollutants and

environmental parameters, their integration into photocatalytic systems, water purification technologies and soil and air remediation strategies. Moreover, due to their tunable photophysical properties, high surface reactivity as well as compatible with green synthesis methods they serve as sustainable alternatives to the traditional materials. However, toxicity issues, scale issues, and regulatory oversight remain challenges that necessitate, and should receive concerted effort from, a multidisciplinary team, coupled with people with good common sense and understanding of what is right and what is wrong. The look forward of the integration of QD's into AI and IoT enabled platform will be for the real time and smart environmental monitoring. Finally, there should be further research to develop eco-friendly QD synthesis routes (general and specific) and regulatory frameworks with the aim to enable safe, large scale, and impactful deployment of QD in global environmental sustainability efforts.

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