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Review Article

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FUTURE PERSPECTIVES OF CARBON QUANTUM DOTS: SYNTHESIS, APPLICATIONS, AND ENVIRONMENTAL IMPLICATIONS IN AQUACULTURE

Shella Marlinda[1], Anna Octavera[2*], Harits Atika Ariyanta[3], Irzal Effendi[1], Sulasy Rohmy[1, 2], Shavika Miranti[4], Sri Nuryati[1], and Alimuddin[1]

[1]Department of Aquaculture, Faculty of Fisheries and Marine Science, IPB University, Bogor 16680, Indonesia

[2]Research Center for Freshwater Aquaculture, National Research and Innovation Agency (BRIN), Bogor 16911, Indonesia

[3]Research Center for Biomass and Bioproducts, National Research and Innovation Agency (BRIN), Bogor 16911, Indonesia

[4]Department of Aquaculture, Faculty of Fisheries and Marine Science, Maritim Raja Ali Haji University, Kepulauan Riau 29115, Indonesia

ARTICLE HIGLIGHTS

- Carbon quantum dots enable sustainable applications in modern aquaculture
- Biomass-derived carbon dots support green synthesis and circular economy
- Fluorescent carbon dots enable rapid sensing of pollutants in aquatic systems
- Carbon dots support bioimaging, antimicrobial activity, and gene delivery
- Toxicity risks highlight the need for safety standards and life cycle assessment

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***Corresponding author, e-mail:**
anna.octavera@brin.go.id

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ABSTRACT

Carbon quantum dots (CQDs) have emerged as promising carbon-based nanomaterials owing to their excellent optical properties, high biocompatibility, and versatile synthesis routes. Recent research trends have shifted from fundamental synthesis and characterization to functional applications in bioimaging, biosensing, biomedical therapy, food safety, and aquaculture. Green synthesis using renewable biomass has become the dominant approach, supporting circular economy concepts while reducing hazardous waste. Numerous studies demonstrate that CQDs can act as sensitive sensors for heavy metals and pollutants, stable probes for cellular and in vivo imaging, antimicrobial agents, and efficient nanocarriers for drug and gene delivery. Despite these advances, toxicological findings reveal that CQDs may induce oxidative stress, developmental abnormalities, and ecological risks in aquatic organisms, particularly at high concentrations or when heteroatom-doped. Moreover, the absence of specific regulations highlights the urgent need for standardized safety protocols and life-cycle assessments. This review outlines the progress, applications, challenges, and regulatory considerations of CQDs, emphasizing their potential role in advancing sustainable biotechnology and modern aquaculture.

Keywords: bioimaging, biosensing, carbon quantum dots, green synthesis, sustainable aquaculture

INTRODUCTION

Carbon quantum dots (CQDs) are carbon-based nanomaterials that have attracted widespread attention in the past decade due to their superior optical properties, high biocompatibility, and flexibility in raw material selection. Initially, research on CQDs mainly focused on synthesis and characterization; however, CQDs have now evolved into multifunctional platforms applied in bioimaging, biosensing, biomedical therapy, environmental quality monitoring, and aquatic toxicology. For instance, CQDs have been reported as fluorescent probes for multiphoton bioimaging and cellular imaging due to their stable photoluminescence and biocompatibility (Cao *et al.* 2007; Huang *et al.* 2019). Significant progress has also been achieved through green synthesis approaches using renewable biomass, which not only reduce production costs but also support sustainability principles by converting agro-industrial waste into high-value nanomaterials (Atchudan *et al.* 2020; Xu *et al.* 2025; Kohli *et al.* 2025). In addition, the use of CQDs in water quality monitoring and toxicological studies on aquatic organisms demonstrates their relevance to aquaculture and aquatic ecology, especially because several studies have shown that CQDs may interact with aquatic organisms at different trophic levels and induce biological responses under certain exposure conditions (Yao *et al.* 2018; Chousidis *et al.* 2020; Li *et al.* 2024).

Most previous reviews have discussed CQD synthesis, optical properties, biomedical applications, or sensing performance separately, while limited attention has been given to the comparative role of CQD-based fluorescence sensors and conventional analytical techniques such as atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS) for early detection of environmental pollution. Although AAS and ICP-MS provide high accuracy and sensitivity for detecting heavy metals, these methods generally require expensive instruments, complex sample preparation, trained personnel, and laboratory-based analysis, which may limit their use for rapid and on-site monitoring in aquaculture environments.

In contrast, CQD-based sensors offer potential advantages for early detection because their fluorescence intensity can change through quenching or emission shifts when interacting with metal ions or pollutants, enabling low-cost, rapid, portable, and real-time detection. Recent studies have also shown that biomass-derived and functionalized CQDs can be developed as sensitive fluorescent probes for heavy metals, pollutants, and biological markers, supporting their relevance as alternative or complementary tools for environmental monitoring (Rahmi *et al.* 2023; Qureshi *et al.* 2024; Vyas *et al.* 2024; Zhong & Yang 2024; Xu *et al.* 2025; Kohli *et al.* 2025). Therefore, this review highlights the novelty and importance of CQDs based on evidence from previous studies, especially their advantages in fluorescence sensing, biocompatibility, and potential application in aquatic systems.

REVIEW

CQD Current Research Trend

Research Trend

Research on CQDs has advanced significantly, evolving from fundamental studies on synthesis and optical characterization toward broader, multidisciplinary applications. CQDs are recognized not only for their high fluorescence stability but also as multifunctional platforms for bioimaging, biosensing, phototherapy, antimicrobial activity, and drug delivery (Cao *et al.* 2007; Huang *et al.* 2019; Das *et al.* 2024).

In biosensing applications, CQDs have been widely reported as fluorescence-based probes for detecting heavy metals, pollutants, and biological markers through quenching or emission-shift mechanisms (Wang *et al.* 2017; Qureshi *et al.* 2024; Lamba *et al.* 2024). Current research increasingly emphasizes green synthesis using renewable biomass to reduce production costs, minimize chemical waste, and promote sustainability, as shown by CQDs derived from banana peel, leaves, shrimp shells, lignocellulosic biomass, and other agro-industrial wastes (Gedda *et al.* 2016; Atchudan *et al.* 2020; Ma *et al.* 2020; Xu *et al.* 2025; Kohli *et al.* 2025).

Moreover, their applications in water quality monitoring, aquatic toxicology, and portable biosensor development demonstrate the growing practical relevance of CQDs in addressing environmental and biomedical challenges (Yao *et al.* 2018; Chousidis *et al.* 2020; Rahmi *et al.* 2023; Vyas *et al.* 2024; Zhong & Yang 2024). CQDs is potential as novel fluorescent materials for detecting heavy metals in aquatic environments.

This research stemmed from the global concern over persistent heavy metal pollutants such as mercury (Hg^{2+}), copper (Cu^{2+}), and lead (Pb^{2+}), which are toxic even at trace levels and difficult to

degrade. While conventional detection techniques like AAS and ICP-MS offer high accuracy, they are often costly and instrumentally complex. To address this, biomass-derived CQDs synthesized via a hydrothermal method with heteroatom doping (N, S) have emerged as efficient, low-cost, and real-time fluorescent sensors. Characterization studies revealed nanoscale CQDs (< 10 nm) with strong tunable fluorescence and enhanced optical stability, positioning them as promising eco-friendly alternatives for environmental monitoring applications (Xu *et al.* 2025).

Other studies emphasized the importance of green synthesis approaches in the production of CQD to reduce environmental impact while lowering production costs. This research was rooted in the need for eco-friendly functional nanomaterials, since conventional chemical synthesis methods often involve hazardous precursors, toxic organic solvents, and generate unsustainable chemical waste. Therefore, the authors explored the use of lignocellulosic biomass-such as rice husks, lignin, fruit peels, sugarcane bagasse, and algae as natural carbon sources for CQD production. Through hydrothermal treatment and controlled pyrolysis, these biomasses were successfully converted into fluorescent nanoparticles with uniform sizes (< 10 nm) and good optical stability. Spectroscopic analyses revealed that biomass-derived CQDs possess oxygen-rich (–OH, –COOH) and nitrogen-containing (from residual proteins/ aminosaccharides) surface functional groups, which facilitate further functionalization and improve water solubility (Xu *et al.* 2025).

The optical performance of biomass-derived CQDs is highly promising. Xu *et al.* (2025) reported that the quantum yield (QY) could reach over 30%, depending on the type of biomass and synthesis conditions, approaching or even surpassing some CQDs produced from pure chemical precursors. Furthermore, their fluorescence properties can be tuned by modifying the pH, reaction temperature, or by introducing heteroatom dopants such as nitrogen, sulfur, and phosphorus. This tunability enables CQDs to be widely applied, ranging from cellular and model organism bioimaging, pollutant sensing in water, to photodynamic antimicrobial agents. Another advantage is the potential for large-scale, low-cost production, since agricultural biomass is abundantly available and often remains underutilized as waste.

In aquatic environments, Xu *et al.* (2025) demonstrated that biomass-derived CQDs not only reduce dependence on synthetic chemicals but also support the circular economy by transforming agricultural waste into high-value nanomaterials. These CQDs exhibited lower toxicity than heavy metal–based quantum dots, ensuring safer applications in biological and aquaculture systems. The study emphasized that green synthesis is not merely a sustainable approach but also a fundamental step toward environmentally responsible nanomaterial innovation. Similarly, Kohli *et al.* (2025) reviewed advances in green synthesis and applications of CQDs, identifying biomass precursors such as lignin, fruit peels, leaves, and starch as efficient, eco-friendly carbon sources. Green-synthesized CQDs offer several advantages, including low production cost, oxygen- and nitrogen-rich functional groups, high quantum yield, tunable fluorescence, and strong stability under biological and environmental conditions.

CQDs have shown great promise in diverse applications-ranging from environmental sensing of heavy metals and pesticides to bioimaging of aquatic model organisms such as zebrafish and *Daphnia*, as well as biomedical applications in photodynamic antimicrobial therapy and targeted drug delivery. Kohli *et al.* (2025), further projected that future research will focus on integrating CQDs with portable and IoT-based sensing systems for real-time water quality monitoring and on developing multifunctional CQDs capable of acting simultaneously as sensors and therapeutic agents. Collectively, these studies confirm that green synthesis represents the dominant and most sustainable trajectory in CQD research, bridging fundamental nanoscience with practical applications in environment, health, and aquaculture.

Brief Description of CQDs Source and Methods

CQDs have attracted growing interest for their eco-friendly synthesis, low cost, and flexibility in precursor selection. Natural and synthetic sources, ranging from biomass and agro-industrial waste to simple organic compounds, have been explored for CQD production, yielding diverse optical and structural characteristics. Common synthesis methods include hydrothermal, solvothermal, microwave-assisted, pyrolysis, and ultrasonication methods, each of which influences the size, stability, and fluorescence performance of the resulting CQDs.

Table 1 Sources and methods for Carbon Quantum Dots (CQDs) synthesis

Source material (Precursor)	Synthesis method	Brief description	References
Dwarf banana peel (biowaste)	Hydrothermal	Produces N-doped CQDs with hydrophilic properties, suitable for environmental and biological applications.	Atchudan *et al.* (2020)
Potato starch	Hydrothermal (P-doped)	Produces CQDs with antimicrobial properties, potential for food applications.	Poshtkar *et al.* (2025)
Leaves (natural biomass)	Hydrothermal (N-doped)	CQDs with low toxicity and broad-spectrum antibacterial activity.	Ma *et al.* (2020)
Byproducts bio-refinery (wood biomass)	Hydrothermal	CQDs used for in vitro and in vivo bioimaging with high fluorescence stability.	Huang *et al.* (2019)
Alginate (biopolymer)	One-step hydrothermal	Produces cationic CQDs with good gene delivery properties due to positive charge.	Zhou *et al.* (2016)

Previous studies have shown that precursor type and synthesis technique significantly affect CQD quality and functionality. Biomass-based materials such as banana peels, potato starch, and leaves have been successfully converted into fluorescent CQDs through hydrothermal methods, often enhanced by heteroatom doping (e.g., N or P) to improve photoluminescence and biocompatibility. Moreover, bio-refinery byproducts and natural polymers like alginate have expanded CQD applications from environmental sensing to in vivo bioimaging and gene delivery. Table 1 summarizes precursor sources and synthesis methods, highlighting the diversity of CQD production strategies and their potential applications in biomedical, food, and environmental fields.

Overall, the diversity of precursor sources and synthesis methods demonstrates the high flexibility of CQD production, whether derived from biomass or simple chemical precursors. The resulting optical characteristics, biocompatibility, and biological activities are strongly influenced by the type of raw material and synthesis technique employed. This provides opportunities to design CQDs with specific properties tailored to application needs, ranging from environmental sensing and bioimaging to biomedical therapy. Therefore, after understanding the fundamentals of precursor sources and synthesis methods, it is important to examine the various functional applications of CQDs reported in the literature in order to assess their practical potential and future directions in nanomaterial development.

CQD Applications

Bioimaging Applications of CQDs

Bioimaging represents one of the most explored areas for CQDs because of their exceptional optical properties, such as strong fluorescence, high photostability, and easy surface functionalization with biomolecules. Compared to conventional organic dyes and heavy metal–based quantum dots, CQDs are more biocompatible and environmentally safe by (Cao *et al.* 2007). Their ability to penetrate cells and tissues with stable fluorescence makes them ideal for tracking cellular dynamics, drug distribution, and in vivo biological processes. The study by Cao *et al.* (2007), demonstrated that CQDs can act as efficient fluorescent probes for multiphoton bioimaging, producing strong and stable emission under multiphoton excitation. This foundational work established CQDs as promising nontoxic nanoprobes for biomedical and cellular imaging, creating future opportunities for noninvasive diagnostics and nanotechnology-based therapies.

Huang *et al.* (2019) synthesized CQDs from biomass-derived bio-refinery byproducts and demonstrated their excellent performance for both cell and in vivo bioimaging. The CQDs exhibited high fluorescence stability, strong biocompatibility, and low toxicity, confirming their suitability as imaging probes in biological systems. Similarly, Atchudan *et al.* (2020), developed hydrophilic nitrogen-doped carbon dots (N-CDs) from dwarf banana peel waste. The resulting N-CDs showed

strong and stable fluorescence in aqueous media and were highly biocompatible, making them promising for environmental and biological applications such as bioimaging and biomolecule detection. More recently, Octavera *et al.* (2026) upcycled eucalyptus kraft lignin from black liquor into fluorescent graphene quantum dots (EL-GQDs) and demonstrated their potential as sustainable bioimaging probes. The EL-GQDs exhibited strong visible fluorescence, good aqueous dispersibility, high photostability, and low toxicity, and were successfully applied for in vitro and in vivo imaging of Nile tilapia testicular cells, with labeled cells remaining traceable in recipient gonads for up to 30 days. The cellular mechanism of fluorescent CQDs for bioimaging and biomedical applications is presented in Figure 1.

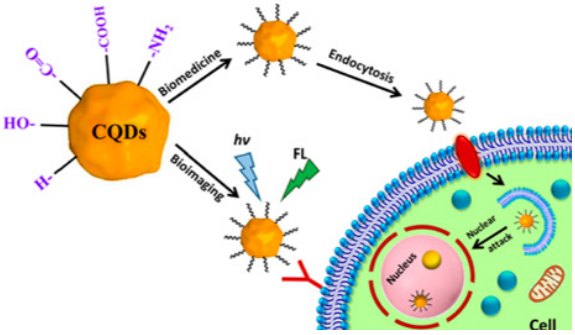


Figure 1 Schematic representation of the mechanisms of action of fluorescent carbon quantum dots (CQDs) within cells for bioimaging and biomedical applications

Notes: Figure 1 is adapted with permission from Das *et al.* (2024) under the terms of the Creative Commons Attribution 4.0 International License.

CQDs possess abundant surface functional groups, such as –COOH, –NH_2, and –OH, which contribute to their water solubility, colloidal stability, and interactions with cellular membranes and biological components. CQDs can be internalized into cells mainly through endocytosis and subsequently distributed within the cytoplasm or associated with intracellular organelles. Upon excitation by light at a specific wavelength, CQDs absorb photon energy and emit fluorescence as the excited electrons return to their ground state. This fluorescence emission enables CQDs to serve as cellular imaging agents for monitoring their localization, distribution, and biological interactions within cells.

Furthermore, the modifiable surface chemistry of CQDs supports their functionalization with biomolecules, therapeutic agents, or targeting ligands, thereby expanding their potential applications in biosensing, drug delivery, cellular labeling, and fluorescence-based biomedical detection. Therefore, cellular internalization, surface functionality, and photoluminescent behavior are the key mechanisms underlying the use of CQDs in bioimaging and biomedicine.

Sensing Applications of CQDs

CQDs are no longer regarded solely as fluorescent materials with superior optical properties but are increasingly being utilized in a wide range of practical applications. One of the most promising areas is the development of CQD-based sensors, given their high sensitivity to changes in the surrounding environment. The surface of CQDs is rich in functional groups, enabling specific interactions with metal ions, organic molecules, or certain biomolecules. These interactions can be directly detected through shifts or decreases in fluorescence intensity, allowing CQDs to serve as sensitive probes that are cost-effective, rapid, and relatively eco-friendly. With these characteristics, CQDs hold great potential to replace conventional fluorescent dyes and heavy metal–based sensors, which are often toxic.

Recent studies have explored the use of CQDs in nanomaterial-based chlorophyll detection. Nazri *et al.* (2023) combined CQDs with triangular silver nanoparticles (AgNPs), utilizing localized surface plasmon resonance (LSPR) to enhance optical sensitivity. This hybrid sensor has been reported to improve precise and stable detection of chlorophyll at low concentrations, offering great potential for environmental monitoring and assessing aquatic ecosystem health. Furthermore, Qureshi *et al.* (2024) reported that CQDs can also serve as sensitive and rapid fluorescence sensors for detecting metal ions, pollutants, and biological biomarkers, reinforcing their versatility in environmental and analytical applications.

CQDs as sensors has been extensively studied for heavy metal detection. Toxic metals such as Pb^{2+}, Hg^{2+}, Cd^{2+}, and Cr6+ are highly persistent and bioaccumulative, posing serious environmental and health risks. Thus, there is a need for detection systems that are sensitive, affordable, and environmentally friendly.

CQDs offer a strong alternative due to their stable fluorescence, high biocompatibility, and ease of surface modification. Biomass-derived CQDs synthesized from lignin, fruit peels, or agricultural waste provide additional sustainability

advantages through green synthesis routes. Various studies have revealed that CQDs detect heavy metals via fluorescence quenching mechanisms, allowing precise quantification at trace levels. Beyond sensitivity, CQDs also hold great promise for developing portable, real-time sensors for environmental and health monitoring (Rahmi *et al.* 2023).

Previous literatures reported CQDs as fluorescent sensors for environmental and biomedical applications. Lamba *et al.* (2024) reported that CQDs possess high optical stability and tunable fluorescence, allowing detection of heavy metal ions, organic pollutants, and biomarkers through fluorescence quenching or emission shifts. Similarly, Wang *et al.* (2017) developed amino acid–derived CQDs as a fluorescence sensor array capable of accurately identifying various toxic metal ions based on specific quenching patterns.

Green synthesis approaches have also been explored. Gedda *et al.* (2016) produced CQDs from shrimp shell waste that selectively detected Cu^{2+} ions, while Gao *et al.* (2016) achieved sensitive Hg^{2+} detection in water samples. Further advances include heteroatom doping and surface modification to enhance selectivity. Molkenova and Atabaev (2019) synthesized phosphorus-doped CQDs for Fe^{3+} detection, demonstrating improved fluorescence quenching response at trace levels. Beyond environmental monitoring, CQDs have been adapted for biomedical sensing. Kudr *et al.* (2017) developed a FRET-based CQD sensor for real-time DNA damage detection, while Xu *et al.* (2019) introduced boronic acid–functionalized CQDs for rapid, selective sialic acid detection, a key cancer biomarker. Collectively, these studies highlighted the potential of CQDs as low-cost, eco-friendly, and highly sensitive sensing platforms for diverse analytical and diagnostic applications. Wang *et al.* (2019) developed sulfur-doped carbon quantum dots (S-CQDs) as highly sensitive and selective fluorescent probes for mercury (Hg^{2+}) detection, demonstrating that sulfur doping enhances CQD sensor performance. Overall, C-dots function effectively as fluorescence-based sensors through quenching or FRET mechanisms, with surface doping (S, P, N) significantly improving detection accuracy at trace concentrations (Table 2).

Table 2 Summary of recent studies on biosensing applications of CQDs

CQD type/ modification	Target detected	Method/ mechanism	Main results	References
Amino acid-derived CDs	Toxic heavy metals (multi-ion)	Fluorescence quenching, pattern recognition	High selectivity sensor array for various heavy metal ions	Lamba *et al.* (2024)
Green-synthesized CDs from shrimp shells	Cu^{2+}	Fluorescence quenching	High sensitivity Cu^{2+} detection, based on eco-friendly biomass	Gedda *et al.* (2016); Gao *et al.* (2016)
FRET-based CDs	DNA damage	FRET (energy transfer)	Real-time DNA damage detection, potential biomedical biosensor.	Kudr *et al.* (2017)
Boronic acid-functionalized CDs	Sialic acid (cancer biomarker)	Fluorescence turn-off	Fast and selective detection of biological biomarkers	Xu *et al.* (2019)
Non-doped CDs	Hg^{2+}	Fluorescence quenching	Sensitive fluorescence probe for Hg^{2+} in water	Wang *et al.* (2019)
Phosphorus-doped CDs (P-CDs)	Fe^{3+}	Fluorescence quenching	Low concentration Fe^{3+} detection, enhanced sensitivity with P doping	Molkenova and Atabaev (2019)
Sulfur-doped CQDs	Hg^{2+}	Fluorescence quenching (blue emission)	Strong blue nanoprobe, very high sensitivity for Hg^{2+} detection	Wang *et al.* (2019)

Table 3 Summary of CQDs applications in biomedical field

CQD type/modification	Applications	Main results	References
CQDs from by-product of bio-refinery	Cell and in vivo bioimaging	High biocompatibility, stable fluorescence, low toxicity	Ma *et al.* (2020)
N-doped CQDs from leaves	Broad-spectrum antibacterial	Low toxicity, disrupts bacterial cell membranes, broad antimicrobial activity	Das *et al.* (2019)
P-doped CQDs from potato starch	Food antimicrobial	Strong antimicrobial activity, promising for food safety and shelf life	Poshtkar *et al.* (2025)
Heteroatom-doped blue luminescent CQDs	Cell labeling and drug delivery (anticancer)	Stable fluorescence, specific target, effective drug delivery	Lin *et al.* (2019)
Cationic CQDs from alginate	Gene delivery	High gene delivery efficiency, low toxicity, safe nonviral vector	Hasanzadeh *et al.* (2020)
CQDs (antimicrobial + sensing)	Biosensing and killing microorganisms	Detects and generates ROS for microbial killing	Lin *et al.* (2019)
CQDs/Poly-L-lysine core-shell	Gene delivery	Stable fluorescence, good biocompatibility, high gene delivery efficiency	Hasanzadeh *et al.* (2020)

Biomedical Applications of CQDs

In the biomedical field, CQDs have attracted growing interest as multifunctional nanomaterials with diverse applications. Their key features, including high biocompatibility, fluorescence stability, nanoscale size, and easily functionalized surfaces, make them suitable for bioimaging, drug delivery, photodynamic therapy, and biosensing of disease biomarkers. Unlike heavy metal-based quantum dots, CQDs are considered safer because they do not release toxic metal ions, offering a more biocompatible and environmentally friendly platform for medical and therapeutic applications.

In the biomedical field, several studies have demonstrated the multifunctional potential of CQDs and their doped derivatives. Ma *et al.* (2020) synthesized nitrogen-doped CQDs (N-CQDs) from leaves and reported strong broad-spectrum antibacterial activity through bacterial membrane disruption, while maintaining low cytotoxicity toward normal cells. Similarly, Poshtkar *et al.* (2025) produced phosphorus-doped CQDs (P-CQDs) from potato starch and verified their antimicrobial efficacy against foodborne pathogens, suggesting their suitability as safe, biomass-derived additives to enhance food preservation and safety.

Beyond antimicrobial functions, Das *et al.* (2019) developed blue-emitting heteroatom-doped CQDs used for cell labeling and anticancer drug delivery, showing excellent biocompatibility and precise targeting capability. Meanwhile Zhou *et al.* (2016) synthesized cationic CQDs from alginate that efficiently delivered genes into cells with minimal toxicity, highlighting their promise as safe non-viral vectors for gene therapy. Collectively, these findings emphasize the versatility of doped CQDs in biomedical, therapeutic, and food safety applications.

Lin *et al.* (2019) explored the dual functionality of carbon dots (C-dots) in microbial detection and elimination. The C-dots acted as fluorescent biosensors for identifying bacteria and fungi, while simultaneously producing reactive oxygen species (ROS) capable of effectively killing microorganisms. This demonstrated their combined potential as biosensing and antimicrobial agents. Similarly Hasanzadeh *et al.* (2020) designed core–shell CQDs/poly-L-lysine nanoparticles for gene delivery, showing stable photoluminescence, high biocompatibility, and efficient gene transfection. The study highlighted the promise of integrating CQDs with biocompatible polymers as innovative and safe non-viral vectors for gene therapy. Research related to the biomedical applications of CQDs is summarized in Table 3.

Toxicological Applications of CQDs in Aquatic Environments

Despite their excellent optical and biocompatible properties, CQDs raise concerns regarding their potential toxicity in aquatic environments. As nanomaterials tend to accumulate in water systems, organisms such as fish, algae, and zooplankton

may experience oxidative stress, membrane disruption, or growth inhibition, especially under high concentrations or prolonged exposure. Yao *et al.* (2018) assessed CQD toxicity in zebrafish (*Danio rerio*), *Daphnia magna*, and *Scenedesmus obliquus*. Zebrafish showed minimal effects up to 200 mg/L, whereas D. magna exhibited mortality and immobility (EC50 = 97.5 mg/L; LC50 = 160.3 mg/L). In *S. obliquus*, growth and photosynthesis declined with increasing doses (EC50 = 74.8 mg/L, 96 h), mainly due to oxidative stress and reduced medium pH.

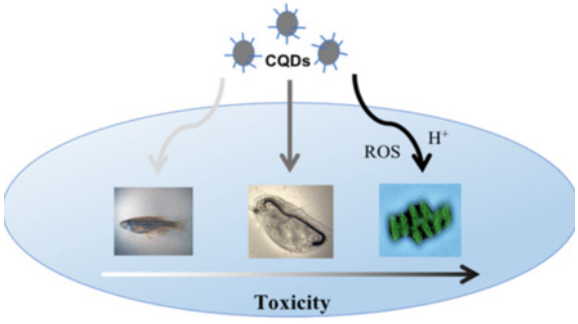


Figure 2 Toxicity of various types of CQDs on aquatic organisms

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Chousidis *et al.* (2020) found that nitrogen and sulfur-doped CQDs caused developmental toxicity in zebrafish (*Danio rerio*) embryos, including cardiac malformations and oxidative stress, whereas non-doped CQDs were relatively safe. The toxicological aspects of CQDs include potential oxidative stress, ROS generation, bioaccumulation, cellular membrane disruption, and alterations in gene expression, particularly in aquatic organisms exposed to CQDs for extended periods. Khan *et al.* (2024) noted that while CQDs act as efficient green photocatalysts for wastewater treatment, their long-term stability and environmental safety remain concerns. Similarly, Li *et al.* (2024) reported that CQDs disrupted photosynthesis in *Phaeodactylum tricornutum*, feeding activity in Artemia salina, and coral morphology, indicating bioaccumulation risks. Meanwhile, Vyas *et al.* (2024) developed a CQD dithizone sensor for trace Pb^{2+} detection, underscoring both their environmental utility and the need for comprehensive toxicity evaluation.

Although various studies have shown the great potential of CQDs in the fields of biosensing, bioimaging, and environmental remediation, toxicological research on aquatic organisms indicate that CQDs are not entirely risk-free. Certain doping types and exposure concentrations can affect the growth, behavior, and physiological functions of aquatic organisms, from phytoplankton to model fish such as zebrafish. This underscores the need for comprehensive toxicity evaluation standards before CQDs can be widely adopted in environmental and aquaculture applications. Therefore, the development of CQD technologies must be accompanied by regulatory frameworks and usage recommendations that ensure the safety of aquatic ecosystems while supporting sustainable innovation.

Table 4 Summary of CQD toxicological studies in aquatic biota

Title	References	Target organism/ system	Key findings
Carbon quantum dot-induced developmental toxicity in *Daphnia* under life-cycle exposure	Ma *et al.* (2023)	*Daphnia magna*	CQDs cause developmental toxicity during the life cycle, reducing symbiotic bacteria related to energy metabolism.
Effects of carbon quantum dots on aquatic environments	Yao *et al.* (2018)	Zebra fish, *Daphnia*, alga	Assessing toxicity differences across various trophic levels; algae are the most sensitive; mechanisms include oxidative stress and pH reduction.
Neglected negative effect of carbon quantum dots (CQDs)	Li *et al.* (2024)	Sea organism (marine)	Examining the effects on growth, photosynthesis, and behavioral changes in marine organisms due to CQDs exposure.

Title	References	Target organism/ system	Key findings
Toxic effects of carbon quantum dots on the gut–liver axis and gut microbiota in the common carp *Cyprinus carpio*	Chen *et al.* (2022)	*Cyprinus carpio*	Chronic exposure to CQDs results in their accumulation in the intestine and liver, leading to organ damage, oxidative stress, and alterations in the gut microbiota.
Toxic or not toxic, that is the carbon quantum dot's	Chung *et al.* (2021)	Zebra fish	Demonstrates that metal-doped CQDs (e.g., Ag-CQDs) exhibit high toxicity in animal cells and bacteria

Regulation and Recommendations

To date, specific regulations that explicitly govern CQDs remain unavailable at both global and country levels. Current frameworks still rely on broader chemical and nanomaterial regulations, such as the REACH Regulation in the European Union, which includes nanoform-specific information requirements through Commission Regulation (EU) 2018/1881, and the OECD guidelines for testing manufactured nanomaterials, which provide internationally harmonized approaches for physicochemical characterization, sample preparation, dosimetry, environmental fate, and ecotoxicological assessment (European Commission 2018; OECD 2025a; OECD 2025b). In the United States, the Environmental Protection Agency (EPA) regulates nanoscale chemical substances under the Toxic Substances Control Act (TSCA) through reporting, recordkeeping, and premanufacture review requirements; however, no CQD-specific regulatory framework has yet been established (US EPA 2026).

This regulatory gap is concerning because toxicological studies have shown that CQD toxicity can vary depending on concentration, surface chemistry, functionalization, and exposure duration. For example, CQDs have been reported to affect aquatic organisms such as *Daphnia magna* and algae at certain exposure levels, while zebrafish-based studies have shown dose-dependent responses and differences in toxicity between CQDs with different surface compositions (Chahal *et al.* 2021; Chung *et al.* 2021; Kuznietsova *et al.* 2023).

In Indonesia, nanotechnology regulation is still in its formative stage, with existing governance mainly related to general nanotechnology standards, food and agriculture applications, pharmaceuticals, cosmetics, and environmental safety. Although Indonesia has developed national nanotechnology-related standards and strategic plans, specific policies and legislation for nanotechnology applications in the food and agriculture sector remain limited (Solikhin *et al.* 2023). Considering the growing application of CQDs in aquaculture and aquatic systems, such as bioimaging, biosensing, and water quality assessment, there is an urgent need to integrate nanomaterial safety protocols into sustainable aquaculture and aquatic ecosystem management frameworks (Kang *et al.* 2015; Nazri *et al.* 2023; Dawood *et al.* 2025).

Recommended actions include: i) establishing standardized toxicity testing protocols using aquatic model organisms, such as algae, *Daphnia*, zebrafish, and cultured fish, with both acute and chronic endpoints; ii) implementing life cycle assessments (LCA) covering synthesis, usage, release, degradation, and disposal phases; iii) developing biomass-derived and eco-friendly CQDs to minimize environmental hazards; iv) adopting a safe-and-sustainable-by-design approach to ensure safety during material development; and v) strengthening collaboration between research institutions, industry, and regulatory bodies to formulate evidence-based nanomaterial policies (OECD 2025b; Dawood *et al.* 2025).

A comprehensive regulatory framework is needed to guide CQD utilization toward safe and sustainable innovation, ensuring that their implementation in environmental and aquaculture systems delivers tangible benefits without posing long-term ecological risks.

CONCLUSION

Carbon quantum dots (CQDs) are promising carbon-based nanomaterials with stable optical properties, high biocompatibility, and potential for green synthesis from biomass, making them applicable in agroindustry, aquaculture, biosensing, bioimaging, and biomedicine. Numerous studies have demonstrated the effectiveness of CQDs as heavy metal sensors, fluorescent probes, antimicrobial agents, and drug delivery systems, while their production from agro-industrial waste supports the principles of a circular economy. However, toxicological studies have shown that CQDs may adversely affect aquatic organisms by inducing oxidative stress, malformations, and behavioral changes, particularly at high concentrations or when specific dopants are used. Therefore, the development and application of CQDs should be accompanied by comprehensive toxicity assessment, life cycle assessments, and appropriate regulatory frameworks to ensure their safe and sustainable use and to maximize their contributions to environmental quality and modern aquaculture.

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