



Carbon quantum dot-based sensors for detecting emerging contaminants: synthesis, functionalization, sensing mechanisms, and future perspectives

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Abstract In recent years, carbon quantum dots (CQDs) have emerged as promising nanomaterials for environmental sensing due to their excellent optical properties, tunable surface chemistry, high sensitivity, and low toxicity. CQD-based sensors have attracted increasing attention for detecting various pollutants due to their low cost, sustainability, and potential for practical applications. This review provides a critical

overview of recent advances in CQD-based sensing platforms for emerging contaminants (ECs), with particular emphasis on the relationship between CQD structure, surface chemistry, sensing mechanisms, and detection performance. First, different CQD synthesis methods are discussed, highlighting their advantages, limitations, and effects on CQD properties. Then, strategies for improving sensing performance through metal and non-metal doping, co-doping, and hybridization with other materials, including metal–organic frameworks (MOFs), are evaluated. The review further examines the detection of major classes of ECs, considering not only sensitivity and detection limits but also selectivity, stability, and performance in real samples. In addition, the roles of key sensing mechanisms, including the inner filter effect, fluorescence resonance energy transfer, photoinduced electron transfer, and surface interaction-induced fluorescence changes, are analyzed to provide deeper insight into pollutant recognition processes. Current challenges related to surface heterogeneity, reproducibility, interference from complex matrices, large-scale production, and practical implementation are critically discussed. Finally, future opportunities involving multifunctional CQDs, portable sensing devices, artificial intelligence-assisted analysis, smartphone-based platforms, and sustainable synthesis strategies are highlighted. This review provides insights into the rational design of CQD-based sensors and supports their future development for reliable environmental monitoring and public health protection.

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Introduction

The expansion of industrial and human activities has led to significant environmental issues, such as water pollution, air pollution, global warming, climate change, and the increasing frequency of extreme weather events worldwide. Among various environmental challenges, the presence of emerging contaminants, such as antibiotic residues, microplastics, and endocrine-disrupting chemicals, in water systems has become a serious issue due to their persistence,

toxicity, and widespread distribution (Esteves et al., 2024; Li et al., 2024; Souaf et al., 2025).

Emerging contaminants are natural or human-made substances that are not routinely monitored or regulated in aquatic environments but are gaining attention for their potential impacts on ecosystems and human health (Li et al., 2024; Pierozan et al., 2026). They may enter the environment through continuous release, biological activity, persistence, or the formation of harmful transformation products. ECs include pharmaceuticals, personal care products, pesticides, endocrine-disrupting chemicals, industrial chemicals, per- and polyfluoroalkyl substances, and particulate pollutants such as microplastics (Gardiner et al., 2025; Sabzehmeidani & Kazemzad, 2022).

Table 1 summarizes common ECs detected in the environment. It includes different types of ECs, such

Table 1 List of common emerging contaminants in the environment

Contaminant category	Representative compounds
Pharmaceuticals and antibiotics	Diclofenac Ibuprofen Acetaminophen Carbamazepine Tetracycline Ciprofloxacin Sulfamethoxazole Amoxicillin
Endocrine-disrupting chemicals	17 α -Ethinylestradiol Estrone Estradiol Bisphenol ABisphenol S Di(2-ethylhexyl) phthalate Dibutyl phthalate
Pesticides and herbicides	Glyphosate Atrazine Chlorpyrifos Dichlorodiphenyltrichloroethane Carbaryl
Microplastics and plastic-related pollutants	Polyethylene microplastics, Polypropylene microplastics, Polystyrene microplastics, Polyvinyl chloride microplastics
Per- and polyfluoroalkyl substances (PFAS)	Perfluorooctanoic acid Perfluorooctanesulfonic acid Short-chain PFAS
Personal care products	Benzophenone–3Ethylhexyl methoxycinnamate Triclosan Methylparaben
Industrial chemicals and flame retardants	Polybrominated diphenyl ethers Organophosphate flame retardants Nonylphenol Benzotriazoles

as pharmaceutical residues, endocrine-disrupting chemicals, per- and polyfluoroalkyl substances, and microplastics, which may have significant impacts on the environment (Ehalt Macedo et al., 2025; Sabzehmeidani & Kazemzad, 2022; Shekhar et al., 2024). Due to the complex physicochemical properties of these pollutants, such as differences in molecular structure, polarity, and high stability, conventional wastewater treatment plants face critical challenges in completely removing ECs. Moreover, the coexistence of multiple ECs in water systems may result in combined ecotoxicological effects, further contributing to negative impacts on ecosystems and human health (Ehalt Macedo et al., 2025; Li et al., 2024;

Sabzehmeidani & Kazemzad, 2022; Shekhar et al., 2024).

Recently, ECs have been frequently detected in surface water, groundwater, and even drinking water systems, raising significant concerns for both ecosystem and human health (Alencar et al., 2025; Ehalt Macedo et al., 2025; Souaf et al., 2025).

Figure 1 highlights significant human health risks associated with the accumulation of ECs in global seafood (Pierezan et al., 2026). Countries evaluating multiple persistent organic pollutants, such as Portugal, South Africa, Tunisia, and Brazil, reported significant human carcinogenic risks. Even at low calculated dietary intake (less than $0.01 \text{ ng kg bw}^{-1} \text{ day}^{-1}$),

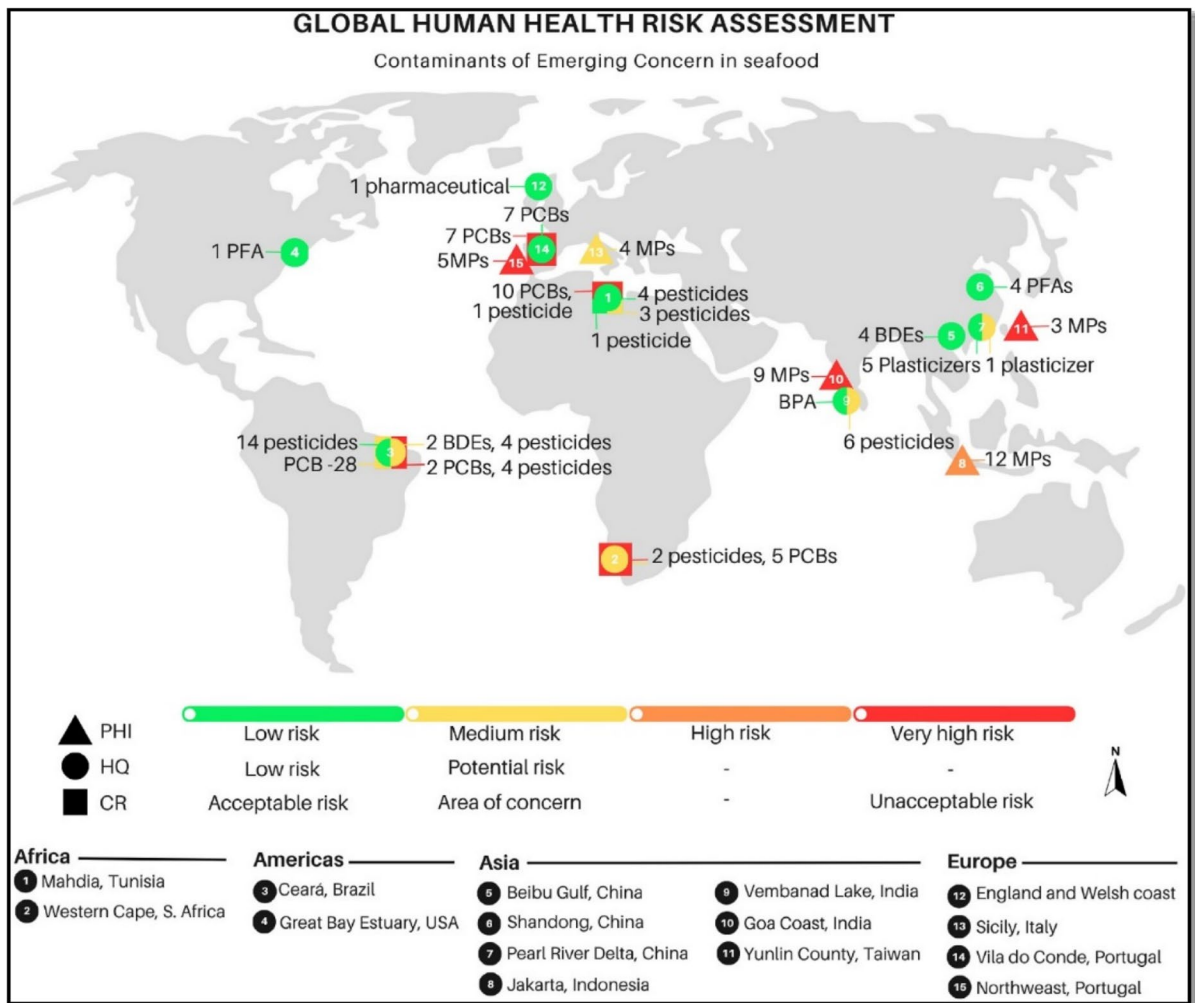


Fig. 1 Human health risk assessments of CECs worldwide, highlighting the risk classifications. Reproduced from (Pierezan et al., 2026) with permission. Copyright © 2026 Elsevier Ltd

EC-related cancer risk still remains, indicating the high carcinogenic potential of these pollutants. The risk map also indicates that ECs exist in all aquatic ecosystems worldwide and can enter the human body through food chains. In particular, microplastics exhibit a major global concern, with high polymer hazard index values in various coastal hotspots such as South Asia (India), East Asia (Taiwan), and Southern Europe (Portugal) (Alencar et al., 2025; Esteves et al., 2024; Gardiner et al., 2025; Lin et al., 2024; Nazar et al., 2025; Pierezan et al., 2026; Souaf et al., 2025). Other coastal regions in Africa (South Africa) and South America (Brazil) exhibit increased carcinogenic risks and hazard quotients, mainly due to pesticide residues and polychlorinated biphenyls. Moreover, the presence of PFAS in North America, the USA, and China, as well as Bisphenol A in India, further highlights the widespread occurrence of different CECs and their effects on marine food chains (Firth et al., 2025; Gardiner et al., 2025; Nazar et al., 2025; Pierezan et al., 2026). The results also suggest that conventional remediation and treatment methods still have various limitations. Thus, reducing the risks of ECs requires the development of different approaches for effective detection, treatment, and prevention at the source, which can further help decrease their transfer to humans through food chains.

As discussed above, the widespread occurrence, persistence, and potential adverse effects of ECs in the environment have driven the development of rapid, sensitive, and cost-effective monitoring technologies.

Common methods widely utilized for the analysis and detection of pollutants like CECs include UV–vis

spectroscopy, high-performance liquid chromatography, liquid chromatography–mass spectrometry, gas chromatography, and gas chromatography–mass spectrometry (Li et al., 2024). However, these methods have some limitations, such as complicated operation, expensive instrumentation, and high maintenance costs.

For example, liquid chromatography–mass spectrometry and gas chromatography–mass spectrometry requires highly skilled operators to handle the analysis and ensure data reliability (Li et al., 2024). On the other hand, the equipment and analytical procedures require multiple steps, such as sample pretreatment, extraction, and purification, which can only be performed in laboratories. As a result, a long time is required to detect and confirm ECs in samples. As a result, developing and economically disadvantaged countries face difficulties in detecting and controlling ECs due to limited scientific and technical infrastructure. To overcome these limitations, the development of advanced sensing platforms for the rapid, highly sensitive, selective, and on-site detection of pollutants such as ECs has been widely explored in recent years (Khizar et al., 2022; Lee et al., 2022; Li et al., 2026).

Table 2 Comparison of the benefits and limitations between sensor-based methods and conventional methods used for the detection of pollutants such as ECs. It shows that sensor-based systems offer several advantages, including fast response times, high sensitivity, portability, low operational costs, simple instrumentation, and minimal sample pretreatment requirements (Li et al., 2024; Mohandoss et al., 2026; Murugesan et al., 2025; Sabzehmeidani & Kazemzad, 2022). Moreover, sensors provide real-time and

Table 2 Comparison between sensor-based and conventional methods for ECs detection

Sensor-based methods	Conventional methods
Instrument: Compact and portable devices	Instrument: Complex, larger size
Sample preparation: easy, simple,	Sample preparation: difficult, requires multiple steps
Operation: easy, low cost, short time, easy maintenance, low-energy consumption	Operation: Difficult, high-cost, highly energy-consuming, requires a highly skilled operator, takes a long time, requires regular calibration and maintenance
Detection sensitivity: High, depending on sensor materials and design	Detection sensitivity: Very high and accuracy
Selectivity: Good, depending on functional materials	Selectivity: Excellent selectivity
On-site monitoring: suitable and easy to apply in the field	On-site monitoring: unsuitable, only available in the lab
Real-time monitoring: Excellent	Real-time monitoring: Limitation
Data accuracy: Good accuracy, affected by environmental interference	Data accuracy: Very high analytical accuracy and reproducibility
Efficient, field-deployable, economical, and easy-to-use	Sensitive and accurate quantitative analysis

continuous monitoring of ECs, which is highly beneficial for early warning and environmental risk assessment. In addition, their compact design and ease of operation also make sensor-based systems suitable for field applications, particularly in regions with limited laboratory infrastructure and analytical facilities. Therefore, sensing technologies have highly promising tools for environmental monitoring and pollutant management.

During sensor design, the selection and preparation of sensing materials are among the most important steps, as their physicochemical properties strongly influence sensitivity, selectivity, stability, and operational performance. Carbon quantum dots (CQDs) have been developed as highly promising materials for sensing applications used to detect various types of pollutants such as heavy metals, ECs, and other organic compounds. Previous studies have demonstrated that CQDs have unique optical properties (excellent fluorescence, flexible photoluminescence, and high photostability) and physicochemical characteristics (superior water solubility, low toxicity, high biocompatibility, and easy surface coating), which contribute to their effective sensing performance (Qandeel et al., 2024; Rani et al., 2020; Rishabh et al. 2025b; Rosales et al., 2025; Sabzehmeidani & Kazemzad, 2022). Moreover, CQDs exhibit high water solubility, excellent photostability, and low toxicity, which contribute to good stability, environmental suitability, and practical utility for ECs monitoring in complex aquatic systems or wastewater.

Compared with conventional analytical methods, CQD-based sensors provide various advantages, such as low cost, simple operation, rapid response, and potential for portable and real-time detection. Their surface chemistry can also be easily modified to improve sensitivity and selectivity. However, CQD-based sensors generally show lower molecular identification capability and may be affected by matrix interference and sensor-to-sensor variation. Therefore, CQD-based sensors are particularly suitable for rapid screening and field applications, while conventional analytical methods are still important for quantitative analysis and confirmation (Rani et al., 2020; Rosales et al., 2025). To better understand CQDs and their applications for detecting emerging contaminants, this review discusses recent progress in CQD-based sensing platforms, focusing on the relationships among material design, sensing mechanisms, and environmental applications. Despite

their potential, CQD-based sensors still face several challenges that limit their practical applications.

For example, the aggregation of CQDs can change their fluorescence properties and reduce their sensitivity, particularly under complex environmental conditions. Moreover, the different surface structures of CQDs, including various functional groups and defect sites, may affect sensing performance and reproducibility. On the other hand, surface modification and heteroatom doping can improve sensitivity, but the selectivity for specific pollutants remains limited. In addition, interference from complex sample components, like natural organic matter, ions, and other pollutants, can decrease sensing performance in real environmental samples. Therefore, this work also discusses current challenges and future opportunities, highlighting the need to improve stability, selectivity, reproducibility, and practical application of CQD-based sensing platforms.

In detail, first we discuss advanced methods for CQD synthesis, highlighting the advantages and limitations of each approach. Next, strategies to improve the properties and sensing performance of CQD-based materials are examined, including metal and non-metal doping, co-doping, and combining CQDs with other materials such as TiO_2 , ZnO , MOFs, and $\text{g-C}_3\text{N}_4$. The application of CQD-based sensors for detecting different classes of emerging contaminants is then evaluated, followed by an analysis of the main sensing mechanisms involved.

Finally, this review explores the development of CQD technologies from laboratory studies to practical applications, focusing on portable devices, paper-based sensors, and smart monitoring systems. The remaining challenges related to CQD stability, reproducibility, large-scale production, and real environmental applications are also discussed. Future improvements in CQD design, surface modification, and integration with smart sensing technologies are expected to enhance detection accuracy, reliability, and practical use, supporting the development of rapid and sustainable environmental monitoring platforms.

Synthesis and modification of CQDs for sensing applications

Methods used to synthesize CQDs

As shown in Fig. 2, carbon quantum dot synthesis can be classified into top-down and bottom-up approaches, along with an overview of their benefits and limitations.

Top-down approaches, including arc discharge, laser ablation, ultrasonication, and electrochemical oxidation, are mainly based on bond cleavage, defect generation, and surface reconstruction using existing carbon sources (graphite, graphene, carbon nanotubes, activated carbon, or biomass) (Mohandoss et al., 2026; Rosales et al., 2025; Trivedi et al., 2026). This method retains the sp^2 carbon framework of the precursor material but makes it difficult to control the size, yield, and surface functional groups of the resulting CQDs or final products. However, CQDs can be synthesized through bottom-up approaches using various methods, including hydrothermal, microwave-assisted, thermal decomposition, chemical vapor decomposition, and combustion. The bottom-up methods are not only easier to operate than the top-down approaches but also can produce high yield, allow easy control of size and functional groups, and produce high-purity CQD-based materials (Devi et al., 2019). As a result, CQDs produced using bottom-up approaches are more suitable for sensing applications, in particular for ECs detection (Anoushka et al., 2025; Goswami et al., 2024; Qandeel et al., 2024; Rishabh et al. 2025b; Tran et al., 2025).

Moreover, bottom-up synthesis corresponds to green chemistry and sustainability concepts, particularly when biomass or waste materials are used as low-cost precursors. In addition, hydrothermal and microwave-assisted processes can reduce the need for organic solvents, further decreasing the environmental impact and cost of CQDs. These advantages support the design of CQDs with target identification compounds, provide high sensitivity, and good performance in environmental sensing applications.

Figure 3 presents the scale-up synthesis of CQDs via a bottom-up hydrothermal method (Jing et al., 2019; Park et al., 2014). The results reported by Jing et al. and Park et al. demonstrate scalable, sustainable nanomaterial synthesis that successfully bridges the

gap between laboratory research and real-world applications. Using the hydrothermal method at 200 °C, waste materials can be converted into high-value CQDs. This process not only reduces solid waste volume but also adds value to waste or biomass sources. It can be considered a potential sustainable method for municipal waste treatment with low cost.

Modification of CQDs

As we discussed above, CQDs show unique properties (excellent aqueous dispersibility and strong photoluminescence), but the direct use of CQDs for environmental sensing still has some limitations. For example, poor molecular selectivity, low quantum yields, low selectivity, and weak signal discrimination in complex environmental matrices (wastewater) significantly inhibit the sensing performance of CQDs. Therefore, modification of CQDs to improve surface states, electronic structure, and optical properties is necessary to expand their applications in sensing. In detail, the modification processes should create selective binding sites, enable modulation of electronic band structures, and enhance fluorescence quantum yield, collectively improving the sensitivity, selectivity, and signal stability of CQD-based sensors under complex environmental conditions (Mohandoss et al., 2026; Murugan et al., 2026; Rani et al., 2020; Rosales et al., 2025; Sabzehmeidani & Kazemzad, 2022). In this review, we focus on three key approaches to enhance the sensing performance of CQDs: metal doping, non-metal doping, and integration with other materials to form hybrid nanocomposites.

Metal-doped CQDs

Metal-doped CQDs have received much attention and are considered a powerful way to enhance the sensitivity and selectivity of sensing. After doping, metal species (Ag, Ni, Cu, Zn, Eu, Fe, Mn, and Au) can significantly enhance analyte affinity, support electron-transfer processes, and drive coordination-driven signal transduction mechanisms (Enyoh et al., 2025; Izgi et al., 2025; Kaur et al., 2023; Yang et al., 2018; Mohandoss et al., 2026; Mohandoss et al., 2026; Rosales et al., 2025; Sun et al., 2023; Liu et al., 2018; Yao et al., 2022; Zhu et al., 2025; Zhuo et al., 2019). Thus, improving the detection sensitivity and sensing performance of organic pollutants, such

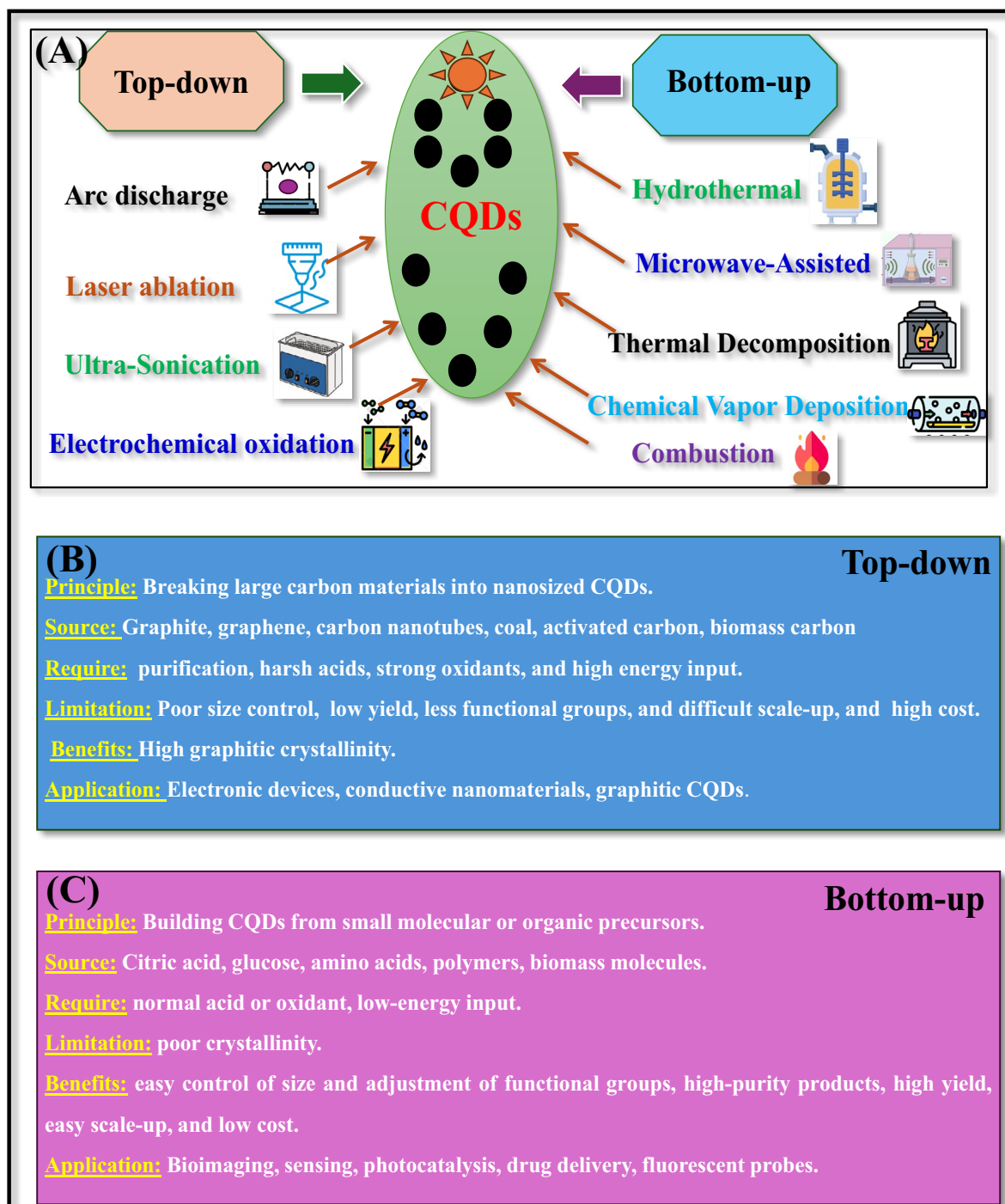


Fig. 2 Summary of different methods used for CQD synthesis: **A** overview of CQDs synthesis methods; **B** top-down approach; and **C** bottom-up approach

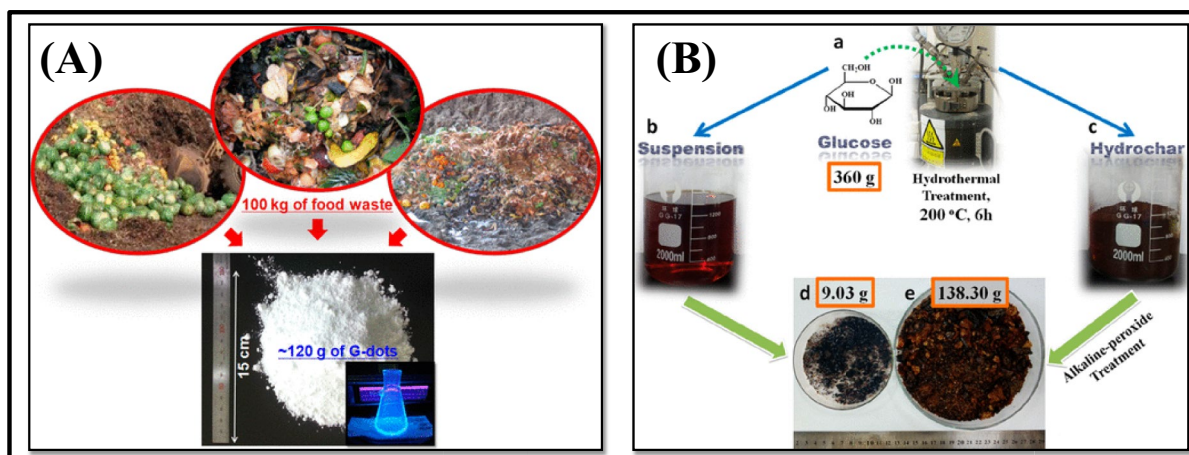


Fig. 3 **A** Scale-up synthesis of CQDs from glucose via hydrothermal and alkaline treatments: **a** hydrothermal treatment of glucose, **b** CQD suspension, **c** glucose-derived hydrochar, **d** dried CQDs from the suspension, and **e** dried CQDs from the hydrochar. Reproduced from (Jing et al., 2019) with permis-

sion. Copyright © 2019 American Chemical Society; **B** Large-scale green synthesis of CQDs using food waste. Reproduced from (Park et al., 2014) with permission. Copyright © 2014 American Chemical Society

as ECs. Figure 4 displays the processes for enhancing the sensing properties and efficiency of CQDs through the metal doping approach. As reported in previous studies, depending on the application and target pollutants, different metals have been applied to modify CQDs, including Ag, Mn, Mg, Zn, Eu, Tb, and Cu. The functionalized CQDs exhibit highly specific response pathways that strongly depend on the electronic structure and coordination chemistry of the target analytes.

Transition metal ions such as Cu^{2+} can efficiently quench fluorescence via photoinduced electron transfer (PET), owing to their partially filled 3d orbitals and redox-active nature. In contrast, closed-shell ions such as Ag^+ and Zn^{2+} , as well as alkaline earth metals like Mg^{2+} , do not participate in redox-mediated PET processes; instead, they modulate fluorescence predominantly through strong Lewis acid–base interactions with surface defect sites on CQDs, leading to static quenching or coordination-induced emission changes. Furthermore, lanthanide ions (Eu^{3+} and Tb^{3+}) introduce additional complexity through f-orbital-mediated energy transfer processes, resulting in characteristic long-lived emissions. Collectively, these mechanistically distinct interaction pathways provide a robust foundation for the rational design of highly selective and multiplexed CQD-based sensing platforms.

Figure 5 provides evidence for the proposed doping effects and enhanced properties of CQDs. TEM and HRTEM analyses (Fig. 5C) confirm the formation of well-dispersed, small CQDs with preserved graphitic structures, increasing available surface sites for analyte interaction (Yao et al., 2022). FTIR and high-resolution XPS analyses (Fig. 5B and 5C) verify the incorporation of metal dopants (Cu^{2+} , Eu^{3+} , and $\text{Tb}^{3+}/\text{Tb}^{4+}$) and reveal oxygen- and nitrogen-containing functional groups as well as metal–ligand interactions (Mohandoss et al. 2026). UV–Vis absorption and bandgap analyses (Fig. 5A) demonstrate changes in optical properties and electronic structure after doping. The findings show that metal doping modifies the surface chemistry, π -conjugated structure, and electronic properties of CQDs, thereby increasing active sites, facilitating charge transfer, enhancing analyte interactions, and improving sensing performance (Kaur et al., 2023).

The fluorescence emission spectra of Ag-CQDs, Cu-CQDs, and Zn-CQDs under different excitation wavelengths ranging from 300 to 420 nm are presented in Fig. 6. The results show that the fluorescence emission peaks of the doped samples are highly stable, with only small wavelength shifts under different excitation conditions (Zhu et al., 2025). The findings also indicate that, after modification, CQDs exhibit uniform fluorescent surface states and stable

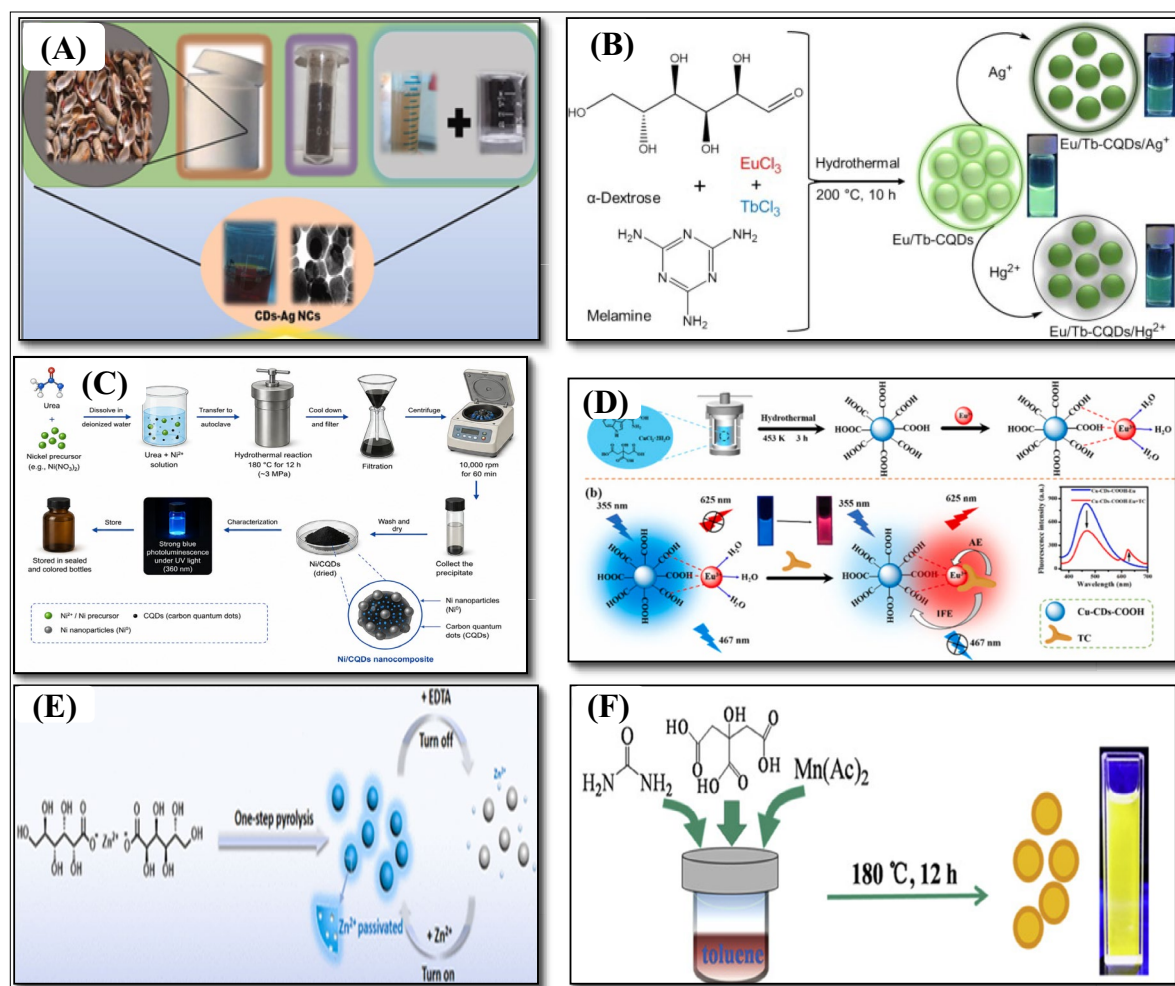


Fig. 4 Metal-doped CQDs: **A:** Sivel-doped, Reproduced from (Kaur et al., 2023) with permission. Copyright © 2023 Elsevier Ltd; **B:** Eu, Tb-doped, Reproduced from (Mohandoss et al. 2026) with permission. Copyright © 2026 Elsevier Ltd; **C:** Ni-doped; **D:** Cu, Eu doped, Reproduced from (Yao et al.,

2022) with permission. Copyright © 2022 Elsevier Ltd; **E:** Zn-Doped, Reproduced from (Yang et al., 2018) with permission. Copyright © 2018 American Chemical Society; **F:** Mn-doped, Reproduced from (Liu et al. Lin et al., 2018) with permission. Copyright © 2018 Elsevier Ltd

light-emission pathways. However, significant differences in fluorescence intensity and excitation-responsive emission behavior were observed for the Ag-CQDs, Cu-CQDs, and Zn-CQDs samples (Zhu et al., 2025). In detail, the maximum fluorescence intensities of Ag-CQDs, Cu-CQDs, and Zn-CQDs were found at excitation wavelengths of 400, 300, and 400 nm, respectively. Also, the corresponding emission peaks were displayed at around 509 nm for Ag-CQDs, 443 nm for Cu-CQDs, and 554 nm for Zn-CQDs. The results suggest that different metal dopants significantly impact electronic structure,

surface defect states, and charge-transfer characteristics of CQDs (Zhu et al., 2025). For example, Cu doping introduces additional redox-active defect sites and enhances photoinduced electron transfer, resulting in fluorescence emission at shorter wavelengths due to changed recombination pathways (Fig. 6B).

Moreover, Ag and Zn dopants mainly influence surface coordination environments and light-emitting trap states, leading to different fluorescence response characteristics (Fig. 6A and C). The excitation-independent emission behavior further indicates that fluorescence modulation is mainly controlled by

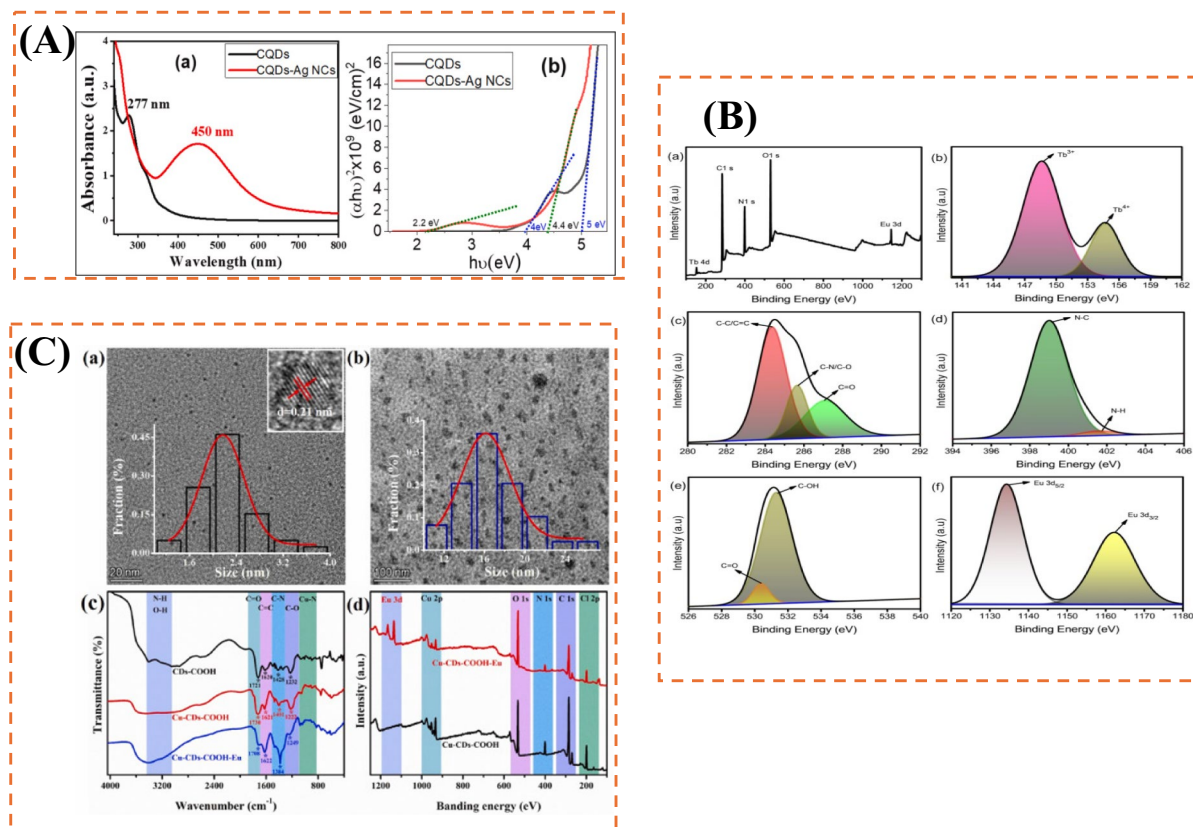


Fig. 5 **a** UV-Vis absorption spectra and **b** bandgap calculation of CDs and CDs-Ag NCs. Reproduced from (Kaur et al., 2023) with permission. Copyright © 2023 Elsevier Ltd. **B** **a** XPS survey spectrum and high-resolution XPS spectra of **b** Tb 4d, **c** C 1s, **d** N 1s, **e** O 1s, and **f** Eu 3d for the Eu/Tb-CQDs surface. Reproduced from (Mohandoss et al., 2026) with permission. Copyright © 2026 Elsevier Ltd. **C** TEM images

(inset: HRTEM images) and corresponding particle size distributions of **a** Cu-CDs-COOH and **b** Cu-CDs-COOH-Eu; **c** FTIR spectra of CDs-COOH, Cu-CDs-COOH, and Cu-CDs-COOH-Eu; **d** XPS spectra of Cu-CDs-COOH and Cu-CDs-COOH-Eu. Reproduced from (Yao et al., 2022) with permission. Copyright © 2022 Elsevier Ltd

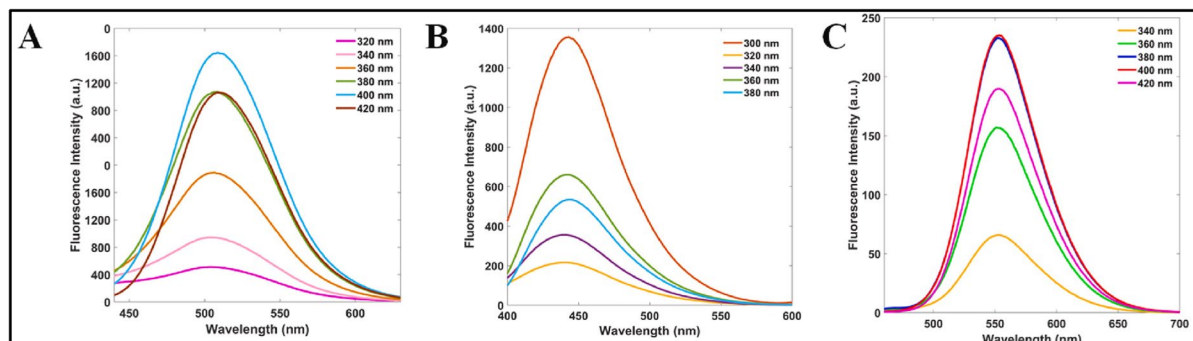


Fig. 6 Fluorescence emission spectra of **A** Ag-CQDs; **B** Cu-CQDs; and **C** Zn-CQDs in different excitation wavelengths. Reproduced from (Zhu et al., 2025) with permission. Copyright © 2025 Elsevier Ltd

metal-doped surface states. These findings suggest that different metal dopants can modify the electronic structure, surface defect states, and charge-transfer behavior of CQDs.

Figure 7 presents another example of Mn-doped CQDs for enhancing optical performance and sensing capability through electronic defect engineering and surface modification (Liu et al., 2018). Unmodified CQDs and Mn-CQDs display excitation-dependent emission behavior, with maximum fluorescence observed at an excitation wavelength of 390 nm (Fig. 7A and 7B). The results suggest that, after doping into CQDs, Mn acts as a fluorescence enhancer rather than creating a new emission mechanism. It also confirmed that main fluorescence mechanism of CQDs remains unchanged after Mn doping. Besides,

Mn doping significantly increases the fluorescence intensity, suggesting a strong enhancement in the radiative emission efficiency of the modified sample (Liu et al., 2018). Moreover, the absorption and fluorescence spectra of CQDs and Mn-CQDs (Fig. 7C) exhibit similar properties with emission peaks located around 550 nm. The results further determine that Mn doping does not significantly affect the intrinsic fluorescence characteristics of CQDs. On the other hand, the enhanced fluorescence intensity of Mn-CQDs is likely related to improved surface passivation and adjustment of surface defect states after Mn doping. In addition, the time-resolved photoluminescence analysis in Fig. 7D shows that the fluorescence lifetime increases from 8.11 to 8.75 ns after Mn doping. It means Mn ions effectively passivate surface defects

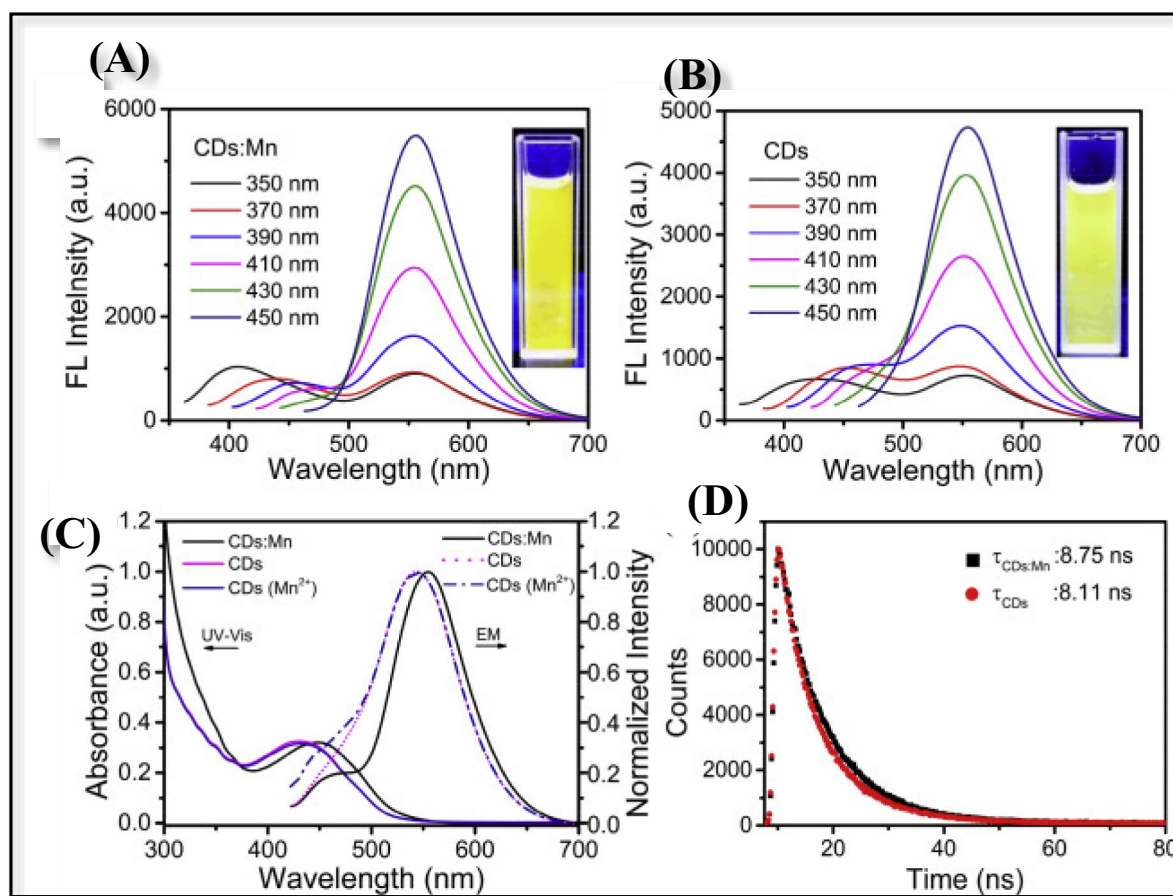


Fig. 7 A: Fluorescence spectra of Mn-CQDs; B: CQDs without addition of manganese ions; C: Absorption and fluorescence spectra; and D time-resolved photoluminescence decay

curves. Reproduced from (Liu et al., 2018) with permission. Copyright © 2018 Elsevier Ltd

and suppress non-radiative recombination pathways, thereby reducing electron trapping and enhancing more efficient radiative recombination. Therefore, Mn-doped CQDs not only enhance fluorescence efficiency but also improve signal stability and sensitivity, which are important parameters for sensing applications in complex environmental matrices like wastewater (Liu et al., 2018).

Further, Christian and co-workers investigated changes in the structural and electronic properties of CQDs after doping with alkaline-earth (Ca, Mg) and transition metals (Zn, Fe) using density functional theory calculations (Fig. 8) (Enyoh et al., 2025). Unmodified CQDs exhibited a HOMO–LUMO gap of 1.79 eV. The band gap energy of CQDs decreased to 1.55 and 1.40 eV after doping with Mg and Fe, respectively. Therefore, metal doping can enhance electronic reactivity and increase charge-transfer potential (Enyoh et al., 2025). The HOMO and LUMO orbital density distributions further reveal that metal doping alters electron density localization in CQDs. Fe- and Mg-doped CQDs exhibit stronger

orbital delocalization around the metal-active regions, which can facilitate electron transfer and strengthen interactions with pollutant molecules. Improved charge-transfer characteristics are highly beneficial for sensing and adsorption applications because they enhance interfacial electronic interactions and improve signal transduction efficiency (Enyoh et al., 2025).

Non-metal-doped CQDs

Non-metal doping is also an effective approach for improving the optical and electronic properties of CQDs (Abd Rani et al., 2020; Anoushka et al., 2025; Bao et al., 2026; Goswami et al., 2024; Kalaiyarasan et al., 2020; Preethi et al., 2022; Vercelli et al., 2021; Yang et al., 2024). Non-metals such as nitrogen (N), sulfur (S), and phosphorus (P) can effectively modulate local charge density, modify band structure, and introduce additional surface defect states that act as fluorescence-active centers (Fig. 9). Therefore, non-metal-doped CQDs can

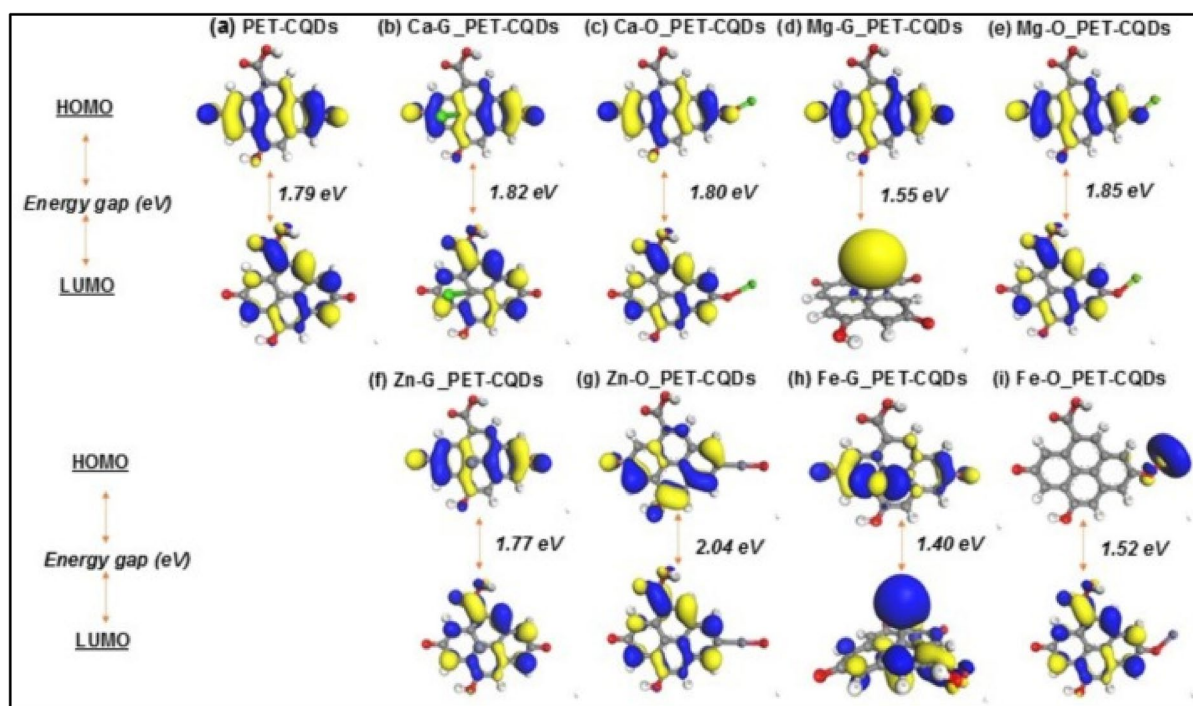


Fig. 8 HOMO–LUMO electron density distributions and energy gaps of pristine and metal-doped CQDs. Blue and yellow isosurfaces indicate electron accumulation and electron

depletion regions, respectively. Reproduced from (Enyoh et al., 2025) with permission. Copyright © 2025 Elsevier Ltd

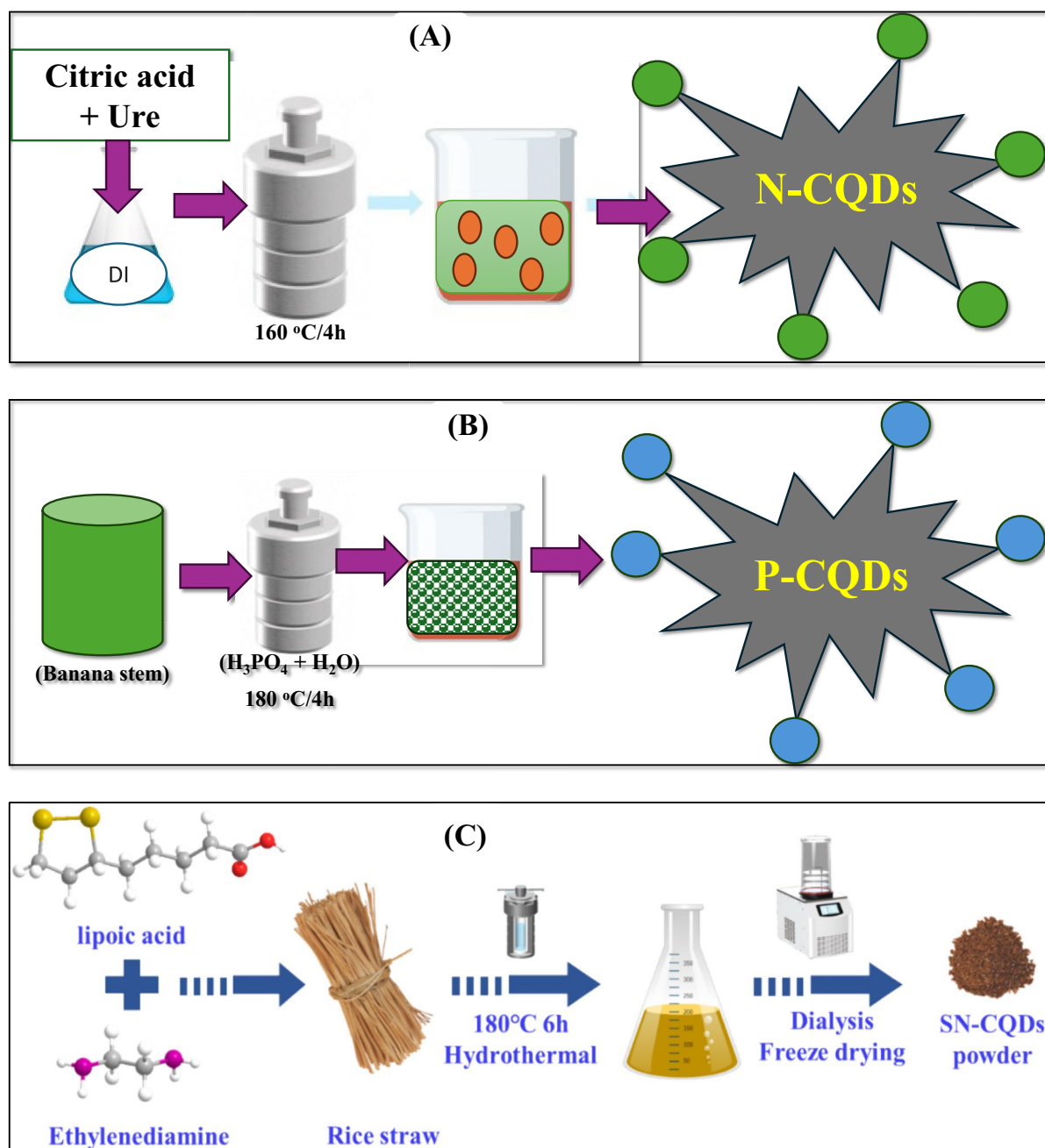


Fig. 9 Non-Metal doped CQDs **A:** N-doped; **B:** P-doped; and **C:** N.S-doped. Reproduced from (Yang et al., 2024) with permission. Copyright © 2024 Elsevier Ltd

enhance photoluminescence efficiency, electron mobility, and interfacial charge-transfer dynamics, which can further improve the sensitivity and selectivity of CQDs, as well as signal transduction.

For example, nitrogen has a similar atomic size to carbon but greater electronegativity, making it an effective dopant. It can be introduced as pyridinic N, pyrrolic N, or graphitic N. Graphitic N donates

electrons to the π -system, enhancing conductivity and facilitating charge transfer. Pyridinic and pyrrolic nitrogen atoms create defect states and localized lone-pair electrons that serve as active sites for molecular interactions. Also, nitrogen doping usually narrows the bandgap, which helps absorb more visible light and boosts electronic transitions (Anoushka et al., 2025; Bao et al., 2026; Ji et al., 2023; Qandeel et al., 2024; Yang et al., 2024).

Further, sulfur, with a larger atomic radius and lower electronegativity than carbon, can induce structural changes or distortions in CQDs after doping. S atoms also create regions of high electron density due to their lone pairs, thereby increasing the reactivity of electron-rich sites (Yang et al., 2024). Therefore, sulfur doping can result in an uneven electronic cloud, which enhances reactivity for the detection of electron-deficient analytes.

In addition, phosphorus has lower electronegativity and a larger atomic radius, leading to noticeable lattice distortion and the formation of defect states (Goswami et al., 2024; Kalaiyarasan et al., 2020). As an n-type dopant, phosphorus increases electron density and introduces shallow donor levels. Phosphorus doping also creates structural defects and enhances electron delocalization throughout the CQD framework, thereby improving electronic conductivity (Preethi et al., 2022; Tammina et al., 2019).

Figure 10 highlights the improved optical and sensing properties of doped CQDs via non-metal doping. In detail, S- and N-doping increased the photoluminescence quantum yield from 6.14% to 62.8%, producing stronger fluorescence signals for sensitive detection. FTIR analysis verified the successful incorporation of hydroxyl, amino, carbonyl, and ether functional groups on the CQD surface (Fig. 10A). These functional groups facilitate surface passivation, promote efficient analyte adsorption and interaction, and contribute to enhanced sensing sensitivity and selectivity (Yang et al., 2024). Moreover, P-doped CQDs also displayed strong, stable fluorescence with excitation-independent emission, a fluorescence lifetime of 10.4 ns, and resistance to photobleaching under extended UV exposure and high-salt conditions (Fig. 10B). These properties provide stable fluorescence signals, making the CQDs effective materials for fluorescence-based sensing (Kalaiyarasan et al., 2020).

Figure 11A shows the optical properties of P-CQDs at different excitation wavelengths ranging from 240 to 400 nm. The emission remains stable at 435–440 nm, indicating excitation-independent behavior, unlike typical undoped CQDs (Kalaiyarasan et al., 2020). The result indicates that P doping creates more uniform surface states and a more stable fluorescence process. Also, the high fluorescence intensity around 300–320 nm excitation

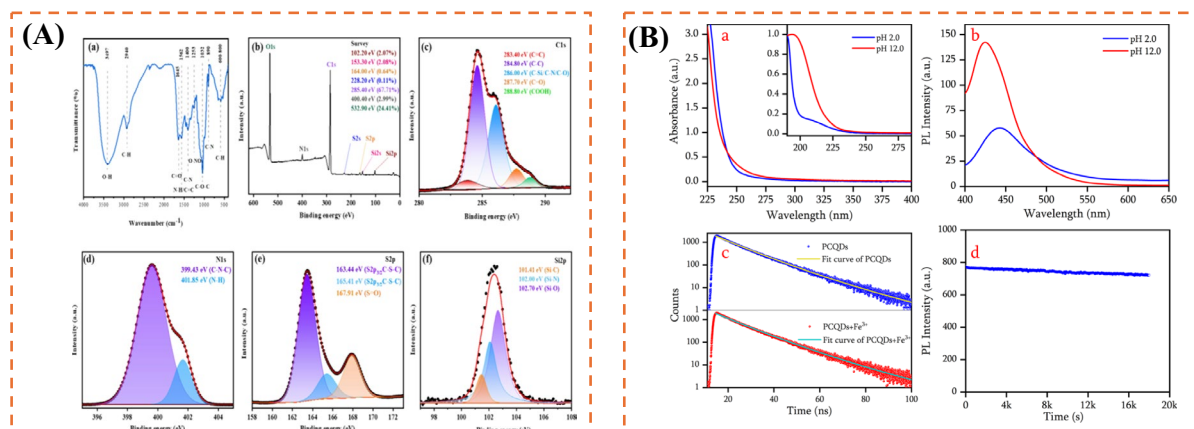


Fig. 10 A Structural characterization of S,N-CQDs: **a** FTIR spectra; **b** XPS survey spectrum; and high-resolution XPS spectra of **c** C 1s, **d** N 1s, **e** S 2p, and **f** Si 2p. Reproduced from (Yang et al., 2024) with permission. Copyright © 2024 Elsevier Ltd. B Optical properties and stability of PCQDs: **a**

UV-Vis absorption spectra; **b** PL spectra at pH 2.0 and 12.0; **c** fluorescence decay curves before and after Fe³⁺ addition; and **d** fluorescence stability under continuous UV irradiation. Reproduced from (Kalaiyarasan et al., 2020)

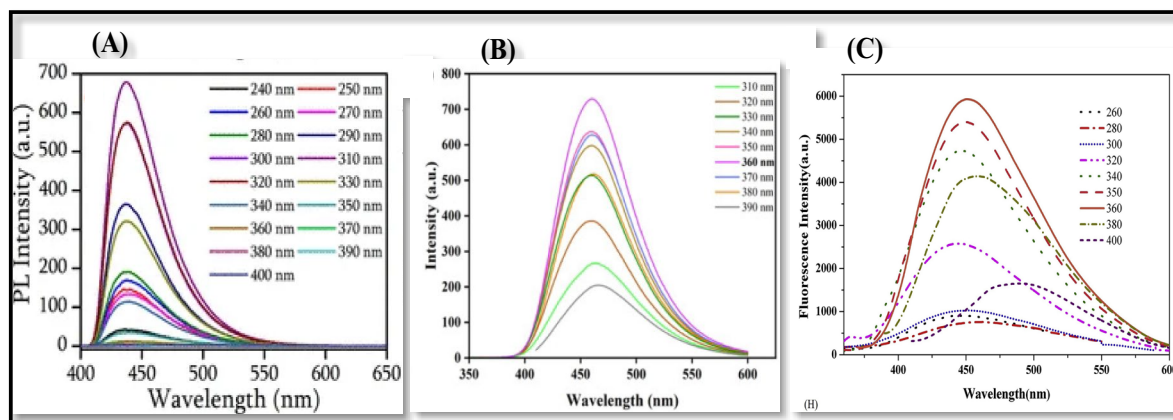


Fig. 11 A: PL spectra of P-CQDs at different excitation wavelengths. Reproduced from (Kalaiyaran et al., 2020); B: fluorescence emission spectrum of N-CQDs. Reproduced from (Anoushka et al., 2025) with permission. Copyright ©

2025 Elsevier Ltd; and C: fluorescence emission spectrum of S-CQDs under different excitation. Reproduced from (Du et al., 2020) with permission. Copyright © 2020 Elsevier Ltd

suggests that P doping can reduce surface defects and increase the electron density of P-CQDs. Moreover, it provides more active sites for interaction with target pollutant molecules and enhances fluorescence stability, which further improves the sensing performance of P-CQDs (Goswami et al., 2024; Kalaiyaran et al., 2020). Therefore, P doping can promote efficient fluorescence quenching through electron or energy transfer processes, making P-CQDs effective fluorescent sensing material for the sensitive detection of pollutants such as ECs.

Figure 11B displays the excitation-dependent emission behavior of N-CQDs, confirming the improved optical properties of the doped material. The modified material exhibits the highest emission intensity at 460 nm under 360 nm excitation, indicating strong and adjustable fluorescence (Anoushka et al., 2025). Besides, the quantum yield of the N-CQDs was 47.5%, indicating highly efficient fluorescence emission from the modified sample.

Moreover, the quantum yield of the N-CQDs was 47.5%, indicating highly efficient fluorescence emission from the modified sample. The introduction of nitrogen into CQDs not only increases electron density and the number of active sites but also enhances charge transfer and interactions with organic pollutants. Therefore, N doping can improve the sensitivity, selectivity, and overall sensing performance of CQDs (Anoushka et al., 2025).

Further, optical properties and electronic transitions of the synthesized S-CQDs were determined (Fig. 11C). The emission peak remains similar at 450 nm when the excitation wavelength increases from 260 to 360 nm. However, the peaks shift to 490 nm at higher excitation wavelengths (380–400 nm), suggesting excitation-dependent fluorescence behavior of S-CQDs (Du et al., 2020).

Previous studies have demonstrated that sulfur doping can improve the optical properties of CQDs by changing their electronic structure and creating additional surface energy levels. Moreover, sulfur-containing groups such as C–S and S=O act as active sites that can strongly interact with target molecules such as ECs. These interactions enhance fluorescence quenching through electron or energy transfer processes, making S-CQDs effective sensing materials for the detection of environmental pollutants.

CQDs combined with other materials

The combination of CQDs with other materials to form hybrid nanocomposite sensing platforms has also developed rapidly. Previous works have shown that CQDs combined with TiO₂, g-C₃N₄, and metal–organic frameworks (MOFs) form highly effective hybrid platforms for advanced sensing applications due to the synergistic modulation of interfacial charge transfer, surface chemistry, and molecular detection processes (Kamyabi & Moharramnezhad,

2022; Liu et al., 2025; Liu et al., 2023; Mahalingam et al., 2026; Murugesan et al., 2025; Sun Liu et al., 2025; Thyda et al., 2025). In CQD–TiO₂ systems, CQDs act as electron acceptors and transport mediators that suppress electron–hole recombination, extend light absorption into the visible region, and enhance photocurrent responses, thereby significantly improving photoelectrochemical sensing performance (Liu et al., 2023). Moreover, in CQD–g-C₃N₄ composites, CQDs introduce defect states and tune band alignment to form efficient heterojunctions, while simultaneously improving electrical conductivity and enabling strong fluorescence and electrochemiluminescence modulation, which is particularly advantageous for highly sensitive optical detection of environmental and biological analytes (Kamyabi & Moharramnezhad, 2022). For CQD–MOF based materials, CQDs serve as conductive and emissive transducers within highly porous, selective adsorption

frameworks, enabling efficient signal conversion via mechanisms such as fluorescence resonance energy transfer and interfacial charge transfer, while MOFs provide molecular sieving and preconcentration, enhancing selectivity and lowering detection limits (Mahalingam et al., 2026; Thyda et al., 2025). After modification, CQD-MOF-based materials are not only fluorescent materials but also multifunctional nanomaterials that enhance charge transfer, optical properties, and adsorption capacity, thereby enabling highly sensitive, selective, and tunable sensing platforms.

Figure 12 highlights the advantages of combining CQDs with other functional materials, such as MOFs, g-C₃N₄, and TiO₂, to enhance their chemical and optical properties for sensing applications. FTIR analysis confirmed the successful incorporation of CDs and Eu³⁺ into the MOF framework and revealed abundant nitrogen- and oxygen-containing functional

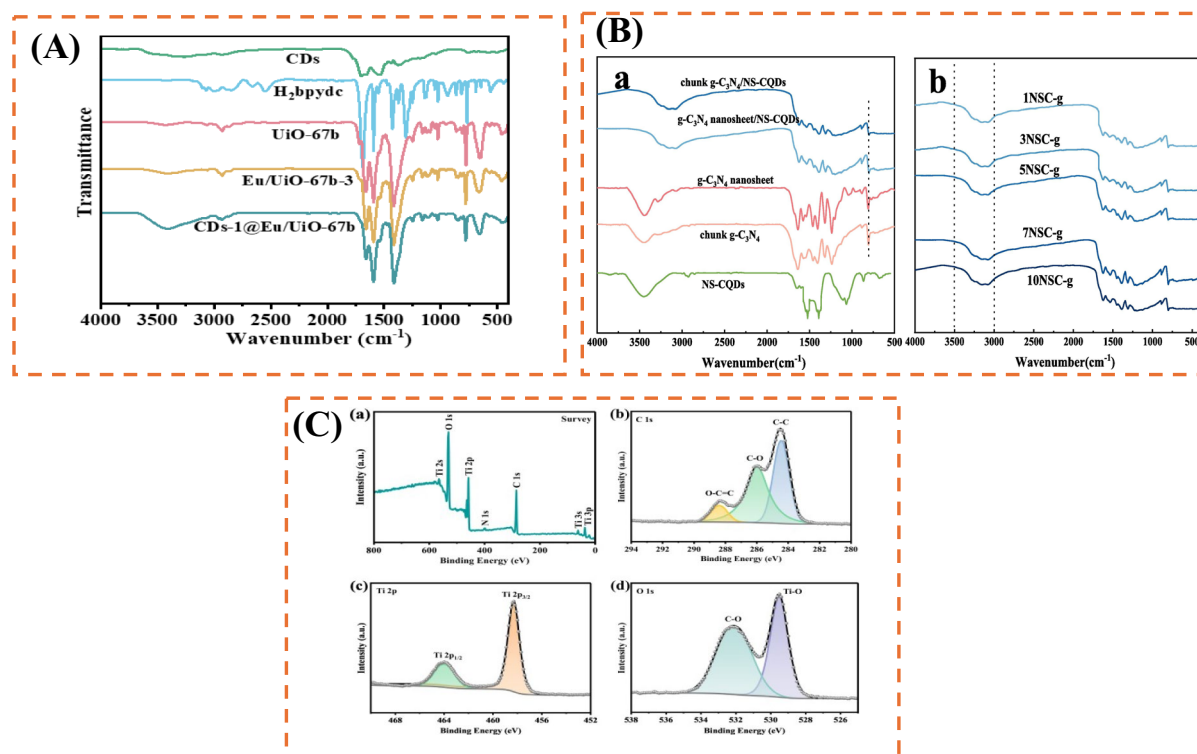


Fig. 12 A FTIR spectra of CDs, UiO-67b, Eu/UiO-67b-3, and CDs-1@Eu/UiO-67b. Reproduced from (Liu et al., 2025) with permission. Copyright © 2025 Elsevier Ltd. B FTIR spectra of a NS-CQDs/g-C₃N₄ composite and b composites with different NS-CQDs doping ratios. Reproduced from (Liu

et al., 2024) with permission. Copyright © 2024 Elsevier Ltd. C a XPS survey spectrum of CQD/TiO₂ and high-resolution XPS spectra of b C 1s, c Ti 2p, and d O 1s. Reproduced from (Liu et al., 2023) with permission. Copyright © 2023 Elsevier Ltd

groups on the hybrid surface (Liu et al., 2025). These surface functionalities, together with the porous MOF architecture, high specific surface area, and Eu–N coordination, provide abundant active sites, enhance luminescence, promote stronger interactions with target analytes, and ultimately improve sensing sensitivity and overall performance (Fig. 12A). Moreover, Fig. 12B confirms the successful formation of the NS-CQDs/g-C₃N₄ composite, with abundant hydroxyl, amino, carboxyl, and sulfur-containing functional groups that enhance surface functionality and provide abundant active sites for analyte adsorption. The extended π -conjugated structures of NS-CQDs and g-C₃N₄ facilitate charge transfer, leading to improved fluorescence responses (Liu et al., 2024). Similarly, the XPS spectra in Fig. 12C verify the successful formation of the CQD/TiO₂ nanocomposite and the presence of carbon–oxygen functional groups. These results indicate strong interfacial interactions between CQDs and TiO₂, which promote efficient charge separation and transfer, thereby enhancing the sensing performance (Liu et al., 2023). Therefore, combining CQDs with materials such as MOFs, TiO₂, and g-C₃N₄ can enhance surface functionality, electronic interactions, and optical properties, resulting in improved sensing sensitivity and analytical performance.

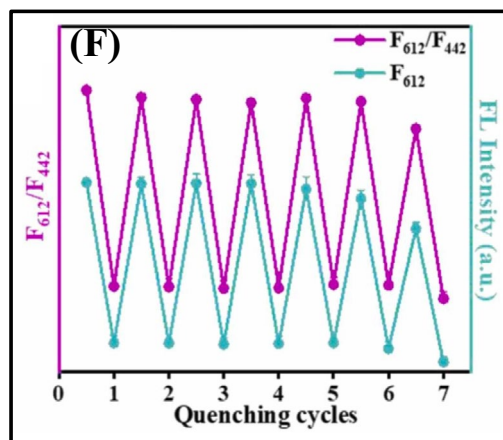
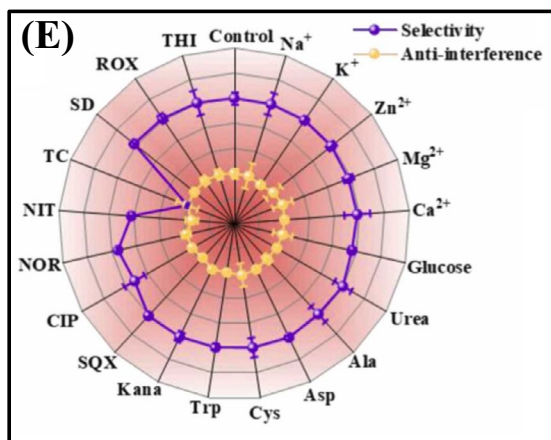
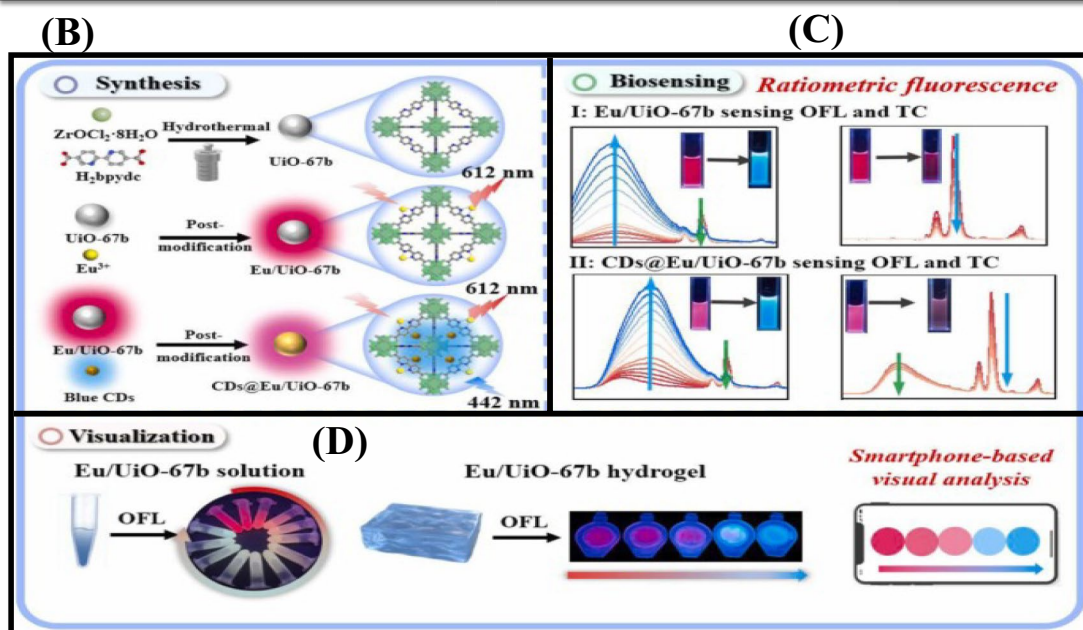
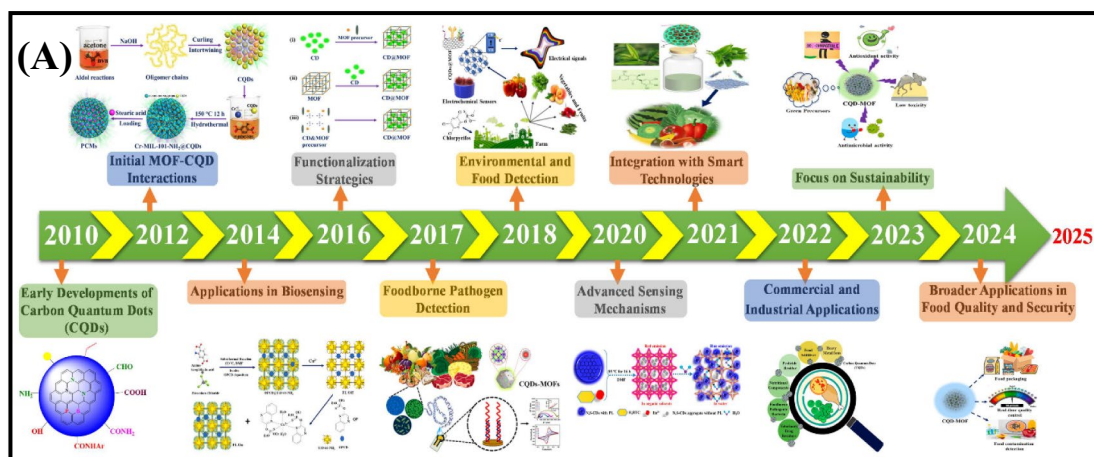
Figure 13A presents the timeline of the development of CQD/MOF-based materials for sensing applications. Research on CQD/MOF-based sensing materials has grown rapidly since 2010. Around 2015, research increasingly focused on the use of MOFs for sensing because of their high surface area, tunable pore structure, and versatile framework (Murugesan et al., 2025). Combining CQDs with MOFs provides complementary properties, including strong photoluminescence, efficient charge transfer, high selectivity, and high sensitivity. Over time, research has shifted from material synthesis and functionalization to bio-sensing applications, environmental and food safety monitoring, smart sensing technologies, and sustainable sensor development. The timeline also highlights the increasing emphasis on practical applications, such as portable sensors, smartphone-based analysis, and commercial development. These trends indicate that CQD/MOF-based materials have strong potential as next-generation sensing platforms for environmental monitoring, particularly for the detection of emerging pollutants (Murugesan et al., 2025).

Figure 13B–E shows an example of a CQDs/MOF-based sensing material used for the detection of antibiotic pollutants (ofloxacin and tetracycline), developed by Liu and co-workers (Liu et al., 2025). They produced a dual-emission fluorescent probe based on a UiO-67b metal–organic framework modified with Eu³⁺ ions and CQDs, with good linear detection ranges (0–60 μ M for ofloxacin and 0–10 μ M for tetracycline). It also displays low detection limits for ofloxacin and tetracycline pollutants of 22 nM and 27 nM, respectively. In addition, the sensor shows excellent recovery (over 98%) in real samples, demonstrating strong potential for practical detection of antibiotic residues (Liu et al., 2025).

Table 3 summarizes the key advantages and limitations of different approaches used to enhance the sensing properties of CQDs. It shows that each method has its own advantages and limitations. For example, metal doping effectively introduces redox-active sites that improve electron transfer and signal response in CQDs, but it may also raise stability and toxicity concerns (metal release).

While non-metal doping offers a more sustainable and biocompatible route, providing adjustable electronic structures with relatively simple synthesis, it often shows limited catalytic contribution. In addition, combining CQDs with other materials, such as MOFs, provides significant advantages by integrating high surface area adsorption with strong fluorescence signaling, leading to improved sensitivity and selectivity (Murugesan et al., 2025; Murugan et al., 2026; Rosales et al., 2025; Sabzehmeidani & Kazemzad, 2022; Tran et al., 2025). However, the hybrid composite still has challenges in practical application due to its poor structural stability and complex synthesis process.

The sensing performance of CQDs is strongly influenced by their physicochemical properties, including particle size, specific surface area, surface functionalities, and quantum yield. Smaller CQDs usually exhibit a higher surface-to-volume ratio and stronger quantum confinement effects, providing more active sites for analyte interaction. A larger specific surface area can enhance adsorption and recognition of target molecules, while surface functional groups (–COOH, –OH, and –NH₂) control the selectivity and interaction strength through hydrogen bonding, electrostatic attraction, and π – π interactions. Moreover, high quantum yield is beneficial



◀**Fig. 13 A:** Timeline of CQDs@MOFs in sensing applications. Reproduced from (Murugesan et al., 2025); **B:** schematic representation of synthesis Eu/UiO-67b and CDs@Eu/UiO-67b; **C** sensing mechanism for OFL and TC detection; **D** visual detection application using a smartphone; **E** selectivity and anti-interference for TC; and **F** recovery performance of CDs-1@Eu/UiO-67b for TC detection. Reproduced from (Liu et al., 2025) with permission. Copyright © 2025 Elsevier Ltd

for fluorescence-based sensing by improving signal intensity and detection sensitivity. Nevertheless, these factors are interdependent, and the sensing performance is determined by the combined effects of CQD structure, surface chemistry, and sensing mechanism rather than by any single parameter.

Detection of emerging contaminants using CQD-based sensing platforms

Table 4 highlights the high flexibility and diversity of CQD-based optical and electrochemical sensing platforms. Various methods, such as hydrothermal, microwave-assisted, pyrolysis, electrochemical, solvothermal, and sol–gel techniques, have been successfully applied to prepare CQD-based materials. Among these approaches, the hydrothermal method appears to be the most efficient technique for preparing metal- and non-metal-doped CQDs. The doping of metals and non-metals such as N, B, S, P, Cu, Ce, and Eu into the CQD structure, as well as the combination with other nanocomposites like AuNPs/N-CQDs, NiMn₂O₄/CQD, and CdTe/CQDs@SiO₂@MIPs, contributes to adjusting the electronic structure and generating more reactive interaction sites (Guo et al., 2022; Ji et al., 2023; Lee et al., 2022; Li et al., 2026; Nobari et al., 2025; Sajwan et al., 2024; Sun et al., 2025; Tran et al., 2025; Wang et al., 2023; Zhang et al., 2020; Zhang & Fan, 2021; Zhou et al., 2022). The sensing performance depends on the type of dopant, synthesis conditions, and sensing mechanism. CQD-based platforms show excellent ability to detect a broad range of antibiotic residues, including tetracyclines, fluoroquinolones, amoxicillin, chloramphenicol, meropenem, and aminoglycosides. The findings suggest that CQD-based platforms have strong potential for monitoring various environmental pollutants. Some reports exhibit extremely low detection limits for antibiotic residues (3 nM for oxytetracycline and doxycycline using N-CQDs,

and 0.0032 μM for gatifloxacin using BP-N-CQDs), confirming the high sensitivity of CQD-based materials. On the other hand, the wide linear working ranges suggest that CQD-based sensing platforms can operate effectively under a wide range of ECs concentrations.

However, detection limits are influenced by several factors like the target analyte, CQD composition, surface functionalization, sensing mechanism and sample matrix. Therefore, reported LOD values should be considered as general indicators of sensor performance rather than evidence of one sensing platform over another. Several studies have demonstrated satisfactory analytical performance of CQD-based sensors in real water samples, highlighting their potential for practical environmental monitoring. For example, AuNPs/N-CQDs successfully quantified tobramycin in real samples with a LOD of 50.41 ng mL⁻¹. In addition, CQD-based sensors have been developed for rapid detection of emerging contaminants from wastewater. The simple operation, rapid response, and compatibility of CQD-based sensors with portable devices make them highly attractive for on-site, real-time water quality monitoring. While CQD-based sensors demonstrate significant potential, additional research is needed to improve their long-term stability, reproducibility, and robustness across diverse environmental conditions before large-scale implementation. The integration of these sensors with smart devices, wireless communication, and Internet of Things (IoT) technologies is anticipated to facilitate automated, remote, and continuous water quality monitoring, thereby supporting more effective environmental management and timely decision-making.

Detection of other pollutants using CQD-based sensing platforms

Further, Table 5 presents the high flexibility of CQD-based sensing platforms for detecting a wide range of other ECS (non-antibiotic pollutants). It also shows that modifications can improve the surface and electronic structure of CQDs, resulting in enhanced sensing properties. For example, doping methods such as B doping and co-doping with elements such as S, N or N,P can significantly improve the fluorescence properties and surface-active sites of CQDs (Tammina et al., 2019; Wei et al., 2022). Moreover, the development of advanced hybrid materials further enhances

Table 3 Summarizes benefits and limitations of different approaches used to enhance CQDs sensing performance

Modification methods	Main effects	Benefits	Limitations
Metal doping	Change surface chemistry and electronic structure Metal sites help bind target molecules easily Enhance selectively and increase sensitivity Change fluorescence through quenching or enhancement Improve electron transfer and signal response Add catalytic signal amplification	Improve fluorescence response and signal strength Provide active metal sites for better analyte binding Enhance electron transfer and sensing efficiency Enable catalytic signal enhancement in some systems Increase sensitivity and selectivity	Complex and less controllable synthesis process Possible metal aggregation or instability over time Risk of fluorescence quenching if doping is not optimized Batch-to-batch variation in structure and performance Potential toxicity concerns for some metal dopants
Non-metal doping	Modify the electronic structure and surface states Create new defect sites that affect fluorescence behavior Improve charge transfer and electron distribution Enhance interaction with target analytes for better sensing Increase the sensitivity and stability of CQD-based sensors	Easy and low-cost doping process Improve fluorescence intensity and stability Tune electronic structure and surface states Enhance charge transfer and sensing response Good biocompatibility and environmental safety	Limited control over exact dopant configuration Possible weak or inconsistent doping effects Lower catalytic activity compared to metal doping Performance depends strongly on synthesis conditions Sometimes reduced selectivity for complex analytes
Combine with other materials	Provide high surface area and porous structures Add strong fluorescence and signal response The combination improves charge transfer and stability Enhances selectivity and sensitivity toward analytes	High surface area and porous structure Strong fluorescence enhances signal output Synergistic effect improves charge transfer and sensing performance High tunability for specific target detection Good sensitivity and low detection limits	Complex and multi-step synthesis process Possible poor stability in water or harsh conditions Difficult control distribution inside Potential aggregation or pore blocking issues Higher cost and scalability challenges

sensing performance and selectivity of CQDs. In detail, the combination of CQDs with transition metal oxides ($\text{NiZn}_2\text{O}_4@\text{CQD}$), magnetic nanoparticles ($\text{N-CQD}/\text{Fe}_3\text{O}_4$), molecularly imprinted polymers (MIP-coated CDs), and graphitic carbon nitride ($\text{CQDs}/\text{g-C}_3\text{N}_4$) creates more specific interaction sites and increases efficient electron transfer (Fatima et al., 2025; Kamyabi & Moharramnezhad, 2022; Liu et al., 2016; Ragu et al., 2023). Through various modification methods, CQD-based sensing platforms can be used to selectively detect a wide range of emerging pollutants. For example, CQD-based platforms exhibit a strong ability to detect endocrine-disrupting compounds such as estradiol and BPA, as well as hazardous organophosphate pesticides and insecticides, including diazinon, chlorpyrifos, and thiamethoxam (Akash et al., 2025; Kamyabi & Moharramnezhad,

2022; Lin et al., 2018; Liu et al., 2016). Therefore, it further highlights the strong potential of CQD-based materials for monitoring complex and multi-component environmental pollution systems.

CQD-Based sensing mechanisms

Previous studies show that CQD-based sensing platforms can detect organic contaminants, including emerging contaminants, through several fluorescence-based mechanisms. These mechanisms often operate simultaneously within a single CQD-based sensor. Their relative contributions depend on the CQD structure, surface chemistry, properties of the target analyte, and detection conditions. As a result, overall sensing performance reflects the combined effect

Table 4 Detection of various antibiotic residues using CQD-based sensing platforms

Material	Synthesis method	Antibiotic	Limit of detection	Linear range	Refs
CQDs	Electrochemical	Chlorotetracycline	16.9 nM	0.8–10 µM	Lee et al., (2022)
N-CQDs	Hydrothermal	Tetracycline	158 nM	0.158–40 µM	Zhou et al., (2022)
CQDs	Microwave	Tetracycline	0.42 µM	0–27.27 µM	Venugopalan and Vidya, (2023)
CQDs	Microwave	Minocycline	273 nM	0.28–0.39 µM	Rahal et al., (2021)
N-CQDs	Pyrolysis	Tetracycline	91.8 nM	0–87.5 mM	Ji et al., (2023)
	Pyrolysis	Doxycycline	78 nM	0–136 µM	Ji et al., (2023)
N-CQDs	Hydrothermal	Tetracycline	0.344 µM	0–30 µM	Wang et al., (2022)
N-CQDs	Hydrothermal	Chlorotetracycline	0.117 µM	30–100 µM	6
N-CQDs	Hydrothermal	Oxytetracycline	0.265 µM	0–30 µM	Wang et al., (2022)
N-CQDs	Hydrothermal	Oxytetracycline	3 nM	0.6–73.3 µM	Wang et al., 2023
N-CQDs	Hydrothermal	Doxycycline	3 nM	0–95.2 µM	Wang et al., (2023)
N-CQDs	Hydrothermal	Tetracycline	6.6 nM	6.5–72.3 µM	Wang et al., (2023)
N-CQDs	Hydrothermal	Minocycline	13.3 nM	10–52.6 µM	Wang et al., (2023)
Ce-N-CQDs	Hydrothermal	Tetracycline	0.25 µM	0.4–35 µM	Zhang and Fan, (2021)
CQDs	Microwave	Tetracycline	6.5 nM	0.01–100 µM	Huang et al., (2022)
N, Cu-CQDs	Hydrothermal	Tetracycline	38.5 nM	3–40 µM	Wang et al., (2023)
N, Cu-CQDs	Hydrothermal	Oxytetracycline	45.4 nM	2–50 µM	Wang et al., (2023)
B-CQDs	Pyrolysis	Amoxicillin	0.825 µM	1.43–429.12 µM	Zhang et al., (2020)
CQDs	Hydrothermal	Moxifloxacin	6.34 nM	0.025–15.0 µM	Sajwan et al., (2024)
N, S-CDs-	Hydrothermal	Amoxicillin	3.40 µM	5–80 µM	Guo et al., (2022)
AuNPs/N-CQDs	Hydrothermal	Tobramycin/ solution	39.18 ng·mL ⁻¹	150.0–350 ng mL ⁻¹	Li et al., (2026)
AuNPs/N-CQDs	Hydrothermal	Tobramycin/ Real sample	50.41 ng·mL ⁻¹	200.0–400 ng mL ⁻¹	Li et al., (2026)
CQDs/AuNPs	Microwave and Hydrothermal	Meropenem	15 nM	60–450 nM	Li et al., (2026)
N-CQDs/AuNPs	Hydrothermal	Meropenem	2.5 nM	8–500 nM	Li et al., (2026)
CQD@Co/Mn-MOF	Solvothermal	Quinolone antibiotic	0.7 µM	1–40 µM	Sun et al., (2025)
NiMn ₂ O ₄ /CQD	Hydrothermal and Pyrolysis	Chloramphenicol	0.491 µM	0.5–143.49 µM	Nobari et al., (2025)
B- CQDs	Hydrothermal	Gatifloxacin	0.008 µM	0.01–100 µM	Zhang et al., (2025)
Cu-CQDs	Hydrothermal	Gatifloxacin	0.13 µM	0.05–280 µM	Chen et al., (2022)
BP-N-CQDs,	Hydrothermal	Gatifloxacin	0.0032	0.266–266	Wang et al., (2025)
Au@CQDs	Pyrolysis	Gentamicin	120 nM	200–2000 nM	ajwan and Solanki, (2023)
Au@CQDs	Pyrolysis	Kanamycin	396.0 nM	200–2000 nM	Sajwan and Solanki, (2023)
Eu,S-CQDs	Hydrothermal	Oxytetracycline	2.31 ng mL ⁻¹	0.05–20 µg mL ⁻¹	Liu et al., (2026)
N-CQDs	Hydrothermal	Chlortetracycline	2.53 µM	0–90 µM	Lotfy et al., (2026)
N-CQDs	Hydrothermal	Doxorubicin	4.02 µM	0–90 µM	Lotfy et al., 2026
N,P-CQDs	Hydrothermal	Doxorubicin	17.2 µM	0.5–6.25 µM	Zhang et al., (2022)
Plum-CQDs	Solvothermal	Doxorubicin	2.84 µM	1–30 µM	Zhu et al., (2021)
PEI-CQDs	Hydrothermal	Doxorubicin	75.2 nM	0.1–150 µM	Yang et al., (2021)
N-CQDs	Hydrothermal	Chlortetracycline	0.073 µg/mL	0.4–20 µg/mL	Zhang et al., (2021)
N-CQDs	hydrothermal	Chloramphenicol	13.1 nM	0.5–25 µM	Rishabh et al. (2025b)

Table 4 (continued)

Material	Synthesis method	Antibiotic	Limit of detection	Linear range	Refs
BSA-Caped O-CQDs	Hydrothermal	Promethazine	0.2 μM	10–90 μM	Viji et al., (2025)
CdTe/CQDs@ SiO ₂ @MIPs	Sol–gel	Ciprofloxacin	90 nM	0–20 μM	Wang et al., (2023)

Table 5 Detection of other pollutants using CQD-based sensing platforms

Material	Synthesis method	Contaminant	Limit of detection	Linear range	Refs
S, N co-doped CQDs	Hydrothermal	Methotrexate	0.33 $\mu\text{mol/L}$	1–300 $\mu\text{mol/L}$	Wei et al., (2022)
S-CQDs	Microwave-assisted	Caffeine	0.05 μM	0.2–70 μM	Nemati et al., (2018)
Boron -CQDs	Hydrothermal	Catechol	0.25 nM	1–50 nM	Ma et al., (2020)
NiZn ₂ O ₄ @CQD	Hydrothermal	Diazinon	0.02–150 μM	0.0044 μM	Akash et al., (2025)
CQDs@WS ₂ /PANI	Hydrothermal Polymerization	Estradiol	13 nM	0.1–100 nM,	Fatima et al., (2025)
N-CQDs	Microwave	Thiamethoxam	2.36 μM	3.43–171.4 μM	Rishabh et al. (2025a)
J-CQDs	Hydrothermal	Chlorpyrifos	7.7 nM	0.057–0.513 μM	Chandra et al., (2022)
CQDs	Hydrothermal	Chlorpyrifos	3 ng/mL	0.01–1.0 $\mu\text{g/mL}$	Lin et al., (2018)
CQDs/g-C ₃ N ₄	Hydrothermal	Chlorobenzenes	0.002 ng/mL	0.25–2500 ng L ⁻¹	Xu et al., (2022)
MIP-coated CDs	Hydrothermal	Bisphenol A	30 nM	100–4200 nM	Liu et al., (2016)
N-CQDs	Microwave	Nizatidine	0.8 μM	2.5–100.0 μM	Qandeel et al., (2024)

of multiple mechanisms rather than a single dominant pathway (Guo & Zhao, 2020; Ahmed & Soylak, 2024; Hira et al., 2025; Kaur et al., 2023; Ma et al., 2020; Mohandoss et al., 2026; Murugesan et al., 2025; Nemati et al., 2018; Raju et al., 2023; Viji et al., 2025; Zhuo et al., 2019).

These sensing mechanisms primarily involve changes in fluorescence intensity resulting from energy transfer, electron transfer, or molecular interactions between CQDs and target analytes. As shown in Fig. 14, static quenching results from the formation of stable, non-fluorescent complexes between CQDs and ECs, typically via hydrogen bonding, electrostatic attraction, or surface complexation (Hassan Ahmed & Soylak, 2024; Nemati et al., 2018; Viji et al., 2025). Dynamic quenching occurs when excited CQDs interact with analytes, resulting in non-radiative energy loss and a reduced fluorescence lifetime. The inner filter effect (IFE) occurs when target molecules absorb either excitation or emission light from CQDs, thereby decreasing fluorescence intensity (Li et al., 2026; Qandeel et al., 2024; Ragu et al., 2023; Rishabh et al., 2025a,

b; Tran et al., 2025). Moreover, Fluorescence resonance energy transfer (FRET) takes place when the emission spectrum of CQDs overlaps with the absorption spectrum of the target analyte, enabling efficient energy transfer. Photoinduced electron transfer (PET) and charge-transfer (CT) processes modulate fluorescence through electron exchange between CQDs and analytes (Li et al., 2026; Ragu et al., 2023; Viji et al., 2025). On the other hand, aggregation-induced emission (AIE) increases fluorescence in CQDs by limiting molecular motion during aggregation (Kaur et al., 2023; Mohandoss et al., 2026; Murugesan et al., 2025; Nemati et al., 2018; Raju et al., 2023; Viji et al., 2025; Wang et al., 2023; Zhuo et al., 2019). In addition to fluorescence pathways, the surface chemistry of CQDs controls molecular recognition and is a key factor in sensor selectivity for emerging contaminants. Functional groups such as carboxyl (–COOH), hydroxyl (–OH), and amino (–NH₂) serve as recognition sites for analyte binding through hydrogen bonding, electrostatic attraction, and π – π interactions. Aromatic contaminants, including antibiotics,

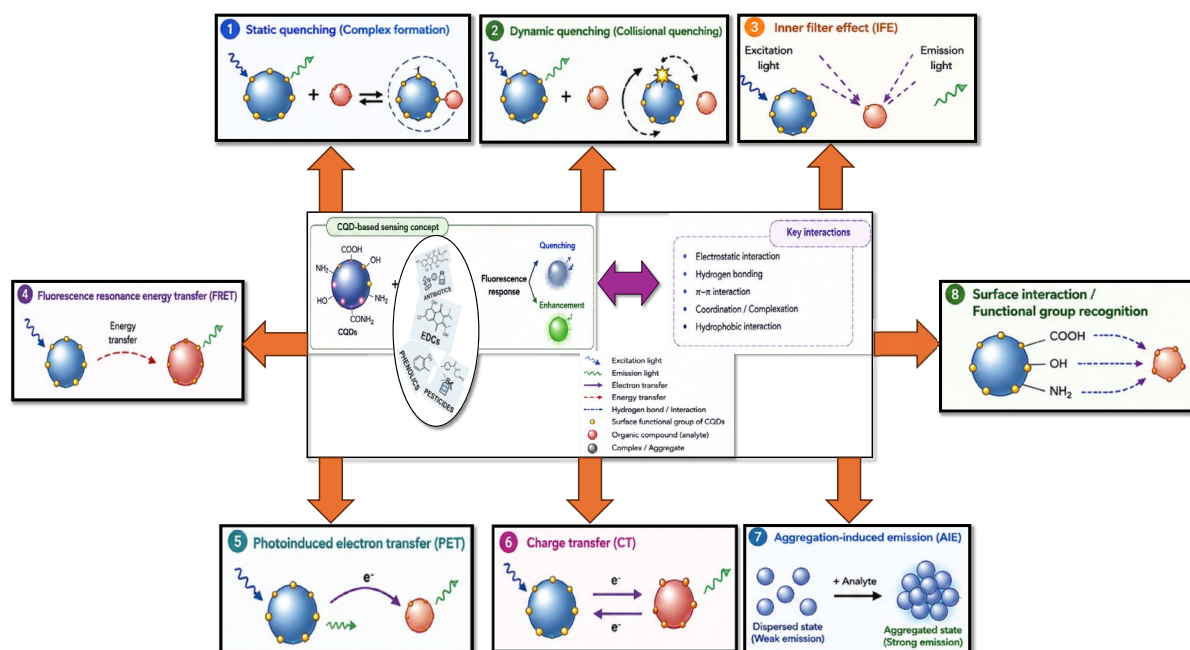


Fig. 14 CQD-based sensing mechanisms for the detection of ECs

endocrine-disrupting chemicals, and pesticides, interact with the sp^2 -conjugated domains of CQDs via π - π stacking. In contrast, polar functional groups form hydrogen bonds with oxygen- and nitrogen-containing surface groups. The surface charge of CQDs, determined by functionalization and solution conditions, regulates electrostatic interactions with charged analytes. Heteroatom doping further modifies the electronic structure and surface polarity of CQDs, promoting electron transfer and increasing affinity for specific target molecules. The combined effects of surface functionalization, electronic properties, and molecular interactions determine the recognition capability and selectivity of CQD-based sensors. The combination of efficient molecular recognition and fluorescence modulation enables CQD-based sensors to sensitively detect a wide range of emerging contaminants, including antibiotics, pesticides, endocrine-disrupting chemicals, phenolic compounds, and pharmaceuticals in environmental samples. A comprehensive understanding of these complementary mechanisms is essential for elucidating the underlying sensing behavior and facilitating the rational design of next-generation CQD-based sensing platforms

with improved sensitivity, selectivity, and practical applicability.

Challenges and future perspectives

Challenges in CQD-based sensing systems

CQD-based materials show strong promise for sensing applications, but their practical use still faces several challenges (Fig. 15A). A key limitation is poor control over particle size, surface chemistry, and quantum yield during synthesis, which creates difficulties for scale-up and commercialization of CQD-based materials (Mohandoss et al., 2026; Rani et al., 2020; Rosales et al., 2025). For example, modifying CQDs with metals can enhance charge transfer and sensitivity, but it often creates uncontrolled defect sites. Moreover, this process improves signal response and sensitivity, while stability and consistency are decreased. In addition, the release of metals from metal-doped CQDs after use raises concerns about environmental pollution and secondary contamination. On the other hand, the combination of CQDs with other materials to form hybrid nanocomposites,

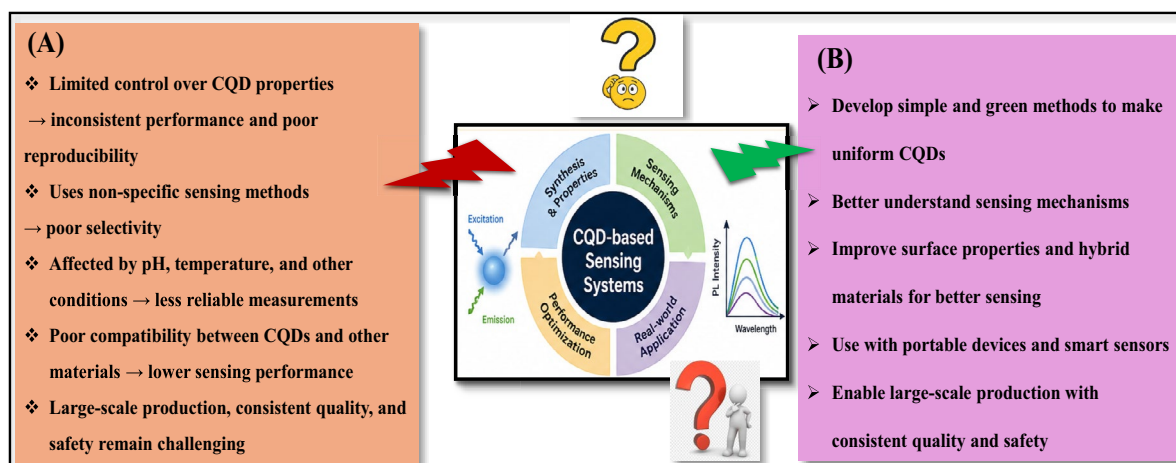


Fig. 15 **A** Challenges and **B** Future perspectives of CQD-based sensing systems

such as CQDs/MOFs, shows some limitations associated with poor interface compatibility, pore blockage, and inefficient electron or energy transfer (Devi et al., 2019; Hira et al., 2025; Murugesan et al., 2025; Qandeel et al., 2024).

Although CQD-based sensors offer strong sensing performance, several limitations hinder their practical use. Response kinetics and sensitivity improvements from surface modification depend on the CQD structure and sensing mechanism and may decline in complex environments. Fluorescence signals are affected by changes in pH, ionic strength, temperature, and photobleaching, which complicates quantitative analysis and reduces reliability in real-world samples. Additionally, poor reproducibility and interference from other pollutants limit sensor accuracy and robustness in field conditions. At the same time, CQD-based sensing technologies are advancing from traditional laboratory fluorescence assays to portable, intelligent, AI-assisted, and field-ready analytical platforms. However, challenges remain, including improving long-term stability, enhancing reproducibility, reducing matrix interference, and ensuring the environmental safety of CQD-based materials throughout their life cycle.

Large-scale production of CQDs also remains a significant challenge. Precise control of reaction conditions is required to achieve uniform particle size, surface chemistry, and optical properties, while scale-up often introduces heat- and mass-transfer limitations that compromise product quality. Moreover,

batch-to-batch variability remains problematic because CQD characteristics are highly sensitive to precursor composition, reaction temperature, and purification procedures. Although continuous-flow synthesis has emerged as a promising strategy for improving production efficiency and reproducibility, further optimization of reactor design and process control is still required. Likewise, scalable purification and quality-control methods remain underdeveloped, as many laboratory-scale techniques are neither practical nor cost-effective for industrial production. Therefore, developing low-cost precursors, scalable and green synthesis routes, efficient purification processes, and standardized quality-control protocols will be essential for the commercialization and widespread application of CQD-based sensing technologies.

Future perspectives

Recently, CQD-based sensing systems are expected to reach higher levels of detection, integration, and field applications. Therefore, future research should focus on improving the properties of CQD-based materials through optimization of the synthesis process (particle size, surface chemistry, dopant distribution, and quantum yield), which would enhance selectivity, sensitivity, and overall sensing performance (Fig. 15B). Besides, understanding basic mechanisms such as photoluminescence and quenching processes is also important to support suitable sensor design

and enhance detection sensitivity (Devi et al., 2019; Hira et al., 2025; Li et al., 2024; Murugesan et al., 2025; Rani et al., 2020; Rosales et al., 2025).

To develop highly selective and high-performance CQD-based sensors, further research should focus on engineering CQDs through metal and non-metal doping and by constructing hybrid materials with supports such as MOFs and MXenes. These strategies can effectively tailor the surface chemistry, electronic structure, and optical properties of CQDs, leading to improved sensing performance. In addition, integrating CQD-based sensors with portable devices, wearable platforms, and smartphone-based systems will facilitate on-site and real-time environmental monitoring.

Computational approaches are also becoming increasingly important for the rational design of CQD-based sensing materials. Density functional theory (DFT) can be used to investigate the effects of heteroatom doping, electronic structure, charge transfer, adsorption behavior, and sensing mechanisms at the atomic level, while molecular simulations help clarify interactions between CQDs and target molecules. Furthermore, machine learning offers a powerful tool for predicting CQD properties, optimizing synthesis conditions, and accelerating the design of high-performance sensing materials. Combining computational modeling with experimental studies will provide deeper insight into structure–property relationships and support the development of more efficient CQD-based sensing platforms.

CQD-based sensors exhibit exceptional analytical performance. Nevertheless, simultaneously optimizing sensitivity, selectivity, stability, cost, and scalability remain challenging, as improvements in one parameter frequently compromise others.

For example, doping, surface modification, and nanocomposite formation can enhance sensitivity and selectivity by increasing active sites and strengthening analyte interactions, but they may also increase synthesis complexity, production costs, and batch-to-batch variability. In contrast, simple and low-cost synthesis methods are more suitable for large-scale production but may provide lower sensing performance. Therefore, future research should aim to achieve a balance among sensitivity, selectivity, stability, cost, scalability, and practical applicability to enable the widespread deployment of CQD-based sensing technologies.

Conclusion

Carbon quantum dot-based materials have garnered significant interest as sensing materials due to their strong fluorescence, easy surface modification, low toxicity, high sensitivity, and broad applicability for detecting emerging contaminants. This review highlights recent progress in CQD synthesis and modification, improving their ability to detect a wide range of emerging contaminants, including antibiotics, drugs, pesticides, and endocrine-disrupting chemicals, with excellent sensitivity and selectivity. Among the available synthesis methods, hydrothermal synthesis remains the most popular because of its straightforward process, relatively low cost, and potential for large-scale production. Additionally, heteroatom doping and hybrid nanocomposites have greatly enhanced the optical properties, selectivity, and sensing performance of CQD-based sensors. Despite these advancements, several challenges remain to be addressed before CQD-based sensors can be widely applied in environmental monitoring. Many reported sensing systems are tested under laboratory conditions, and their performance in complex environmental samples is often limited by matrix interference, reproducibility issues, long-term stability, and batch-to-batch variation. Furthermore, differences in synthesis methods, surface chemistry, and characterization techniques complicate direct comparisons of sensing performance across studies. More reliable experimental evidence is necessary to better understand the effects of heteroatom doping and the sensing mechanisms of CQD-based materials. Future research should aim to develop reproducible and scalable synthesis methods, enhance selectivity and stability in real samples, establish standardized evaluation protocols, and reduce production costs. Combining advanced characterization techniques with theoretical calculations will help clarify structure–property relationships and support the rational design of high-performance CQD-based sensors. Moreover, integrating artificial intelligence with CQD sensing platforms could improve signal processing, minimize interference, and facilitate rapid data analysis. Overcoming these challenges will be crucial for the practical deployment and commercialization of CQD-based sensing technologies for environmental monitoring.

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Declarations

Conflict of interest The authors declare no competing interests.

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