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Fluorescence-based detection of antibiotics in aquatic environments using carbon nanodots: a review

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Antibiotics, widely used in human and animal healthcare, persist in aquatic environments and pose environmental and public health risks, making their quantitative detection essential for monitoring water quality. The application of carbon dots (CDs) provides a simple, highly selective, sensitive, and cost-effective method for antibiotic sensing. Fluorescence-based CDs have shown great potential as sensors for antibiotic detection. However, variations in their production and surface properties pose challenges in understanding the underlying detection mechanisms and achieving consistent high sensitivity. This review provides a comprehensive overview of the production, fluorescence mechanism, and application of CDs for fluorescence-based detection of antibiotics in aquatic environments. It examines the key principles behind CD-based detection, focusing on sensitivity, selectivity, stability, and ease of use. Recent advances in CD synthesis and factors affecting fluorescence are discussed, along with the sensing mechanisms and challenges in detecting antibiotics in water. The review outlines future research directions to improve the sensitivity and selectivity of carbon dots (CDs) for practical applications, highlighting their potential in mitigating antibiotic contamination in wastewater. It also discusses design strategies for enhanced molecular recognition in complex matrices, the limitations of carbon-based nanomaterials, and the challenges associated with industrial-scale implementation. Additionally, the toxicity, biocompatibility, and biodegradability of CD-based sensors for *in vivo* applications are critically examined.

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Sustainability spotlight

This review highlights carbon dots (CDs) as low-cost, sensitive, and selective sensors for environmental analysis, emphasizing their sustainable synthesis from various biomass sources. CDs offer exceptional potential for detecting emerging contaminants and advancing green water monitoring technologies. Owing to their high surface area, tunable surface chemistry, and strong fluorescence and catalytic properties, CDs are presented as versatile materials for addressing pressing water quality challenges. This work promotes the development of eco-friendly, efficient carbon-based sensors, aligning with the UN Sustainable Development Goals related to clean water, sanitation, and responsible consumption, contributing to global efforts toward safe and accessible water for all.

1. Introduction

The rising concentration of antibiotics in aquatic ecosystems represents a significant environmental concern. This phenomenon is largely attributed to the extensive use of antibiotics across human and veterinary medicine, aquaculture, and various other industries, due to their broad-spectrum efficacy, oral bioavailability, low toxicity, and cost-effectiveness.[1–4] However, the introduction of antibiotics into aquatic environments can adversely affect marine organisms and foster the emergence of antibiotic resistance, which compromises the effectiveness of these medications in treating infections in both humans and animals.[5] Antibiotic detection in wastewater has become a significant safety and environmental concern across industrial processes, with concentrations ranging from micrograms per liter (μg L^{-1}) to nanograms per liter (ng L^{-1}).[6–13] Unfortunately, wastewater treatment systems are often ineffective at removing antibiotics, their metabolites, and degradation by-products, allowing these contaminants to reach surface waters, marine environments, groundwater, and drinking water supplies.[14,15] Anthropogenic activities have emerged as a significant driver of environmental pollution.[16] The presence of antibiotics in aquatic environments has become a growing

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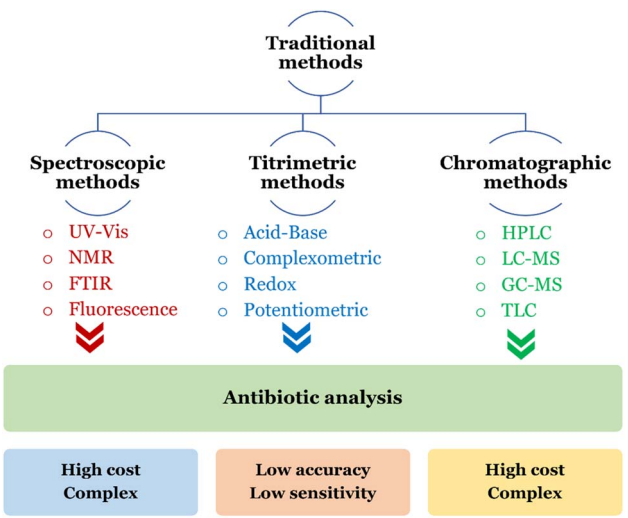
global concern due to their extensive consumption and incomplete removal by conventional wastewater treatment processes. Even at trace concentrations, antibiotics can induce antimicrobial resistance and pose risks to aquatic ecosystems and human health, underscoring the need for sensitive and reliable detection methods. However, the analytical determination of antibiotics in complex water matrices remains challenging because of their ultra-low concentrations and the coexistence of interfering substances.[17] These challenges have driven the development of advanced analytical strategies, particularly rapid, low-cost, and on-site sensing platforms. Among these approaches, fluorescence-based detection has attracted considerable attention owing to its high sensitivity, simplicity, and real-time response. In this context, carbon nanodots have emerged as promising fluorescent nanomaterials for antibiotic sensing in aquatic systems due to their excellent photostability, tunable optical properties, good water dispersibility, low toxicity, and facile surface functionalization. To further improve detection selectivity, molecularly imprinted polymers (MIPs), often referred to as "plastic antibodies," have been widely incorporated as recognition elements in optical sensing platforms, enabling the selective detection of a broad range of environmental pollutants, including antibiotics, ions, organic compounds, gases, and engineered nanoparticles.[18–21]

Multiple established techniques are available for the detection of antibiotics in water samples, such as high-performance liquid chromatography (HPLC),[22] HPLC-mass spectrometry,[23] bio-electrochemical assays,[24] fluorescence-based analysis,[25–28] and capillary electrophoresis.[29] These methods are characterized by their high sensitivity, selectivity, reproducibility, and broad applicability. Nonetheless, traditional detection methods frequently necessitate costly instrumentation, intricate procedures, and labor-intensive sample preparation (Scheme 1).[30,31] This has spurred the development of innovative detection approaches. In addition to carbon dots, a range of other fluorescent nanomaterials have also been explored for antibiotic detection. These include quantum dots, which offer strong brightness and tunable emission properties, as well as metal–organic framework sensors that rely on quenching pathways such as FRET and PET. Gold nanocluster-based photoluminescent sensor arrays have further been reported for antibiotic discrimination, while upconversion nanoparticle probes provide near-infrared excitation features that are useful for monitoring in complex sample environments.[32–35] Among these, carbon nanodots (CDs) have emerged as particularly promising nanomaterials for fluorescence-based detection, owing to their high sensitivity, selectivity, tunable properties, environmental friendliness, ease of synthesis, and straightforward implementation.[36–38] ELISA and related immunosensors, based on antigen–antibody interactions, are widely used for detecting antibiotics in biological samples due to their high selectivity and simplicity. Their direct application in environmental waters is limited by low analyte concentrations, matrix interferences, high instrumentation costs, limited field applicability, and potential cross-reactivity, often requiring sample preconcentration or cleanup.[39,40] Recent advances, including nanomaterial-assisted interfaces, have enhanced sensitivity and reduced interference, enabling more reliable environmental screening.[41] Fluorescence sensors using CDs provide a complementary approach, with high sensitivity, tunable optical properties, and minimal sample preparation for *in situ* detection. Tailored recognition elements and surface functionalization allow CD-based sensors to bridge the gap between laboratory performance and practical environmental monitoring.

Carbon nanodots or carbon dots (CDs) are tiny carbon-based particles, usually under 10 nm in diameter, that possess distinct optical and chemical characteristics.[42–45] These include bright fluorescence, high compatibility with biological systems, good solubility in water, minimal toxicity, and strong resistance to chemical degradation.[46] CDs can be produced from a wide range of organic materials, often sourced from natural biomass, and their light emission can be adjusted depending on their size and surface chemistry (Table 1). These properties make them highly suitable for use in areas such as sensors, imaging, drug transport, and environmental detection.[47–50]

This study intends to provide an in-depth examination of the modification, synthesis, and application of CDs for the detection of various antibiotics. We will evaluate various synthesis techniques employed to produce CDs with customized properties, as well as methods for functionalizing CDs to achieve selective detection of different antibiotics, focusing on their specific sensing mechanisms. Furthermore, we will address the practical application of CD-based detection methods, including the associated challenges and opportunities presented by this emerging technology. By emphasizing the multifaceted aspects of this domain, we aim to position CDs as a viable and sustainable strategy for mitigating antibiotic contamination in ecological systems.

As shown in Scheme 1, many established methods for antibiotic detection depend on sophisticated instrumentation and laboratory facilities. While spectroscopic approaches such as UV-Vis, FTIR, and fluorescence analysis are generally fast, non-destructive, and require few consumables, their routine



Scheme 1 Various traditional techniques for antibiotic detection and associated limitations.

Table 1 CDs compared to traditional methods.[53–58]

Parameter	Carbon nanodots	Traditional methods
Sensitivity	Due to their strong fluorescent properties, CDs are highly sensitive and capable of detecting even trace amounts of antibiotics	Though they sometimes need substantial sample preparation and expensive equipment to reach comparable sensitivity levels, methods like HPLC and ELISA are likewise quite sensitive
Selectivity	The ability to functionalize CDs with certain molecules increases their selectivity towards specific antibiotics, hence increasing their selectivity	While techniques like CE and HPLC are naturally selective, achieving high selectivity may be needed for intricate steps and particular reagents
Tunability	By simply altering the manufacturing process, CDs' characteristics may be tailored to the specific antibiotic that is being targeted	Traditional approaches offer limited flexibility and often demand specialized equipment or reagents for diverse antibiotic classes
Biocompatibility	Since CDs are often environmentally friendly and biocompatible, they can be used in biological and environmental systems	Some conventional techniques include intricate steps or hazardous substances that might not be as ecologically compatible or biocompatible
Cost	Generally low production cost	HPLC and ELISA have high costs; capillary electrophoresis and electrochemical methods have moderate costs
Multiplexing	CDs can be made to use various functional groups or fluorescent markers in order to detect many antibiotics at once	Multiplexing is possible but it can be more difficult and time-consuming, frequently needing different runs or different pieces of equipment
Versatility	Because of their versatility, CDs can be employed in a variety of detection systems, such as optical, electrochemical, and fluorescent sensors	Conventional approaches are flexible in their own right, but they might not be as flexible when applied to various detection systems

application in large-scale environmental monitoring can still be constrained by the high cost and limited availability of the necessary equipment. In this context, carbon dot-based fluorescence sensing is regarded as a cost-effective alternative, not because it eliminates the need for instrumentation, but because it can streamline analytical procedures and lends itself to portable, low-cost detection formats. Recent work has also demonstrated smartphone-assisted carbon dot fluorescence systems as practical substitutes for conventional benchtop spectrofluorometers, enabling more accessible onsite monitoring.[51,52]

2. Antibiotics in aquatic environments and health impacts

Antibiotics are a class of chemical compounds, either naturally produced by microorganisms (such as bacteria or fungi) or synthetically manufactured, that have the ability to inhibit the growth of or destroy harmful bacteria (Fig. 1). They are specifically used to treat bacterial infections, although they do not work against viruses, fungi, or other non-bacterial pathogens.[59] This class of antibiotics is commonly used to treat infections in humans and animals caused by both Gram-positive and Gram-negative bacteria. Notable members of this group, such as tetracycline (TC), oxytetracycline (OTC), chlortetracycline (CTC), and doxycycline (DC), were developed in the late 1940s. These antibiotics function by binding to the 30S ribosomal subunit of bacteria, thereby inhibiting protein synthesis and preventing bacterial growth.[60,61] Due to their wide range of antibacterial properties against pathogenic microorganisms, these antibiotics show powerful action against bacterial and viral infections.[62,63] Because of their low cost and wide-ranging antibacterial activity, they are widely used, particularly in human medications, nutritional supplements, and sterilization.[64–66]

An increasing amount of research shows that consuming TCs from regular foods like milk, eggs, and vegetables over a long period of time can have negative side effects, such as bacterial resistance, allergic reactions, and tooth discoloration.[67–69] Overuse of DC and TC can pose serious health risks, including allergic reactions, liver damage, gastrointestinal issues, and other complications.[70,71] Due to the widespread use of antibiotics in both human and veterinary medicine, it is critically important to monitor their levels in various environments, particularly in water bodies and pharmaceutical products. The accumulation of antibiotics in aquatic ecosystems poses significant risks, such as promoting antibiotic resistance and negatively impacting both aquatic organisms and public health. Therefore, there is an urgent need to develop and implement new and advanced analytical methods for the accurate detection and quantification of antibiotics. These methods will play a key role in ensuring water quality, reducing environmental pollution, and safeguarding human health.

3. Carbon nanodots, properties, synthesis, and applications

Carbon is an abundant substance in the natural world, existing in different forms and participating in various chemical processes. Carbon nanomaterials have exceptional properties

that make them highly suitable for various applications across various fields, resulting in significant interest and focus in recent times. Carbon nanomaterials include various forms, such as zero-dimensional fullerene, one-dimensional carbon nanotubes, two-dimensional graphene, and carbon nanodots (CDs). CDs are a new type of zero-dimensional (0D) photoluminescent carbon nanoparticle that is monodispersed and spherical, with a particle size smaller than 10 nm. They exhibit high fluorescence.[72–75]

The initial discovery of CDs by Xu *et al.*[76] in 2004 occurred unexpectedly during the process of electrophoretic purification of single-walled nanotubes. The fluorescent material of the fast-moving band demonstrated a variety of colors when exposed to UV light. Characterization results revealed that the material was entirely metal-free and primarily composed of carboxyl groups. The composition, as determined by analysis, was found to be 53.93% carbon, 2.56% hydrogen, 40.33% oxygen, and 1.20% nitrogen.[76,77] Furthermore, CDs were fortuitously found by scientists when purifying single-walled carbon nanotubes (SWCNTs) that were created using arc-discharge techniques. During the gel electrophoresis process, the suspension of single-walled carbon nanotubes (SWCNTs) unexpectedly divided into three unique categories of nanomaterials. One of these categories consisted of a rapidly moving band of extremely luminous material, which surprised the researchers. Additionally, they discovered that this carbonaceous substance could be separated into various components that exhibit luminous features based on their size. Although the researchers did not find the specific single-walled carbon nanotubes (SWCNTs) they were searching for, they proceeded to examine the fundamental characteristics of this previously unidentified fluorescent nanomaterial. They made the critical statement that these nanomaterials had the potential to be attractive in their own right.[76] Following their discovery, these substances have been identified as CDs, carbon dots or carbon nanodots.[53,76]

In recent decades, the preparation methods for fluorescent CDs have been improved by employing a wide range of techniques. The most selected synthesis techniques, focused on their excellent optical properties, have been the top-down and bottom-up methods, as shown in Fig. 3C.

The first approach, top-down, involves breaking down substances like graphene, carbon nanotubes, and graphite into smaller CD structures using techniques such as laser ablation, electric arcs, and chemical treatments. This method was initially used to produce fluorescent carbon materials. However, some studies have successfully produced water-soluble CDs with potential uses.[76,78] Xiangcheng *et al.*'s[79] work showed that autothermal processes are an efficient way to turn ammonium citrate dibasic (ACD) into CDs. Using this technique, ACD was dissolved in deionized water and then heated in a domestic

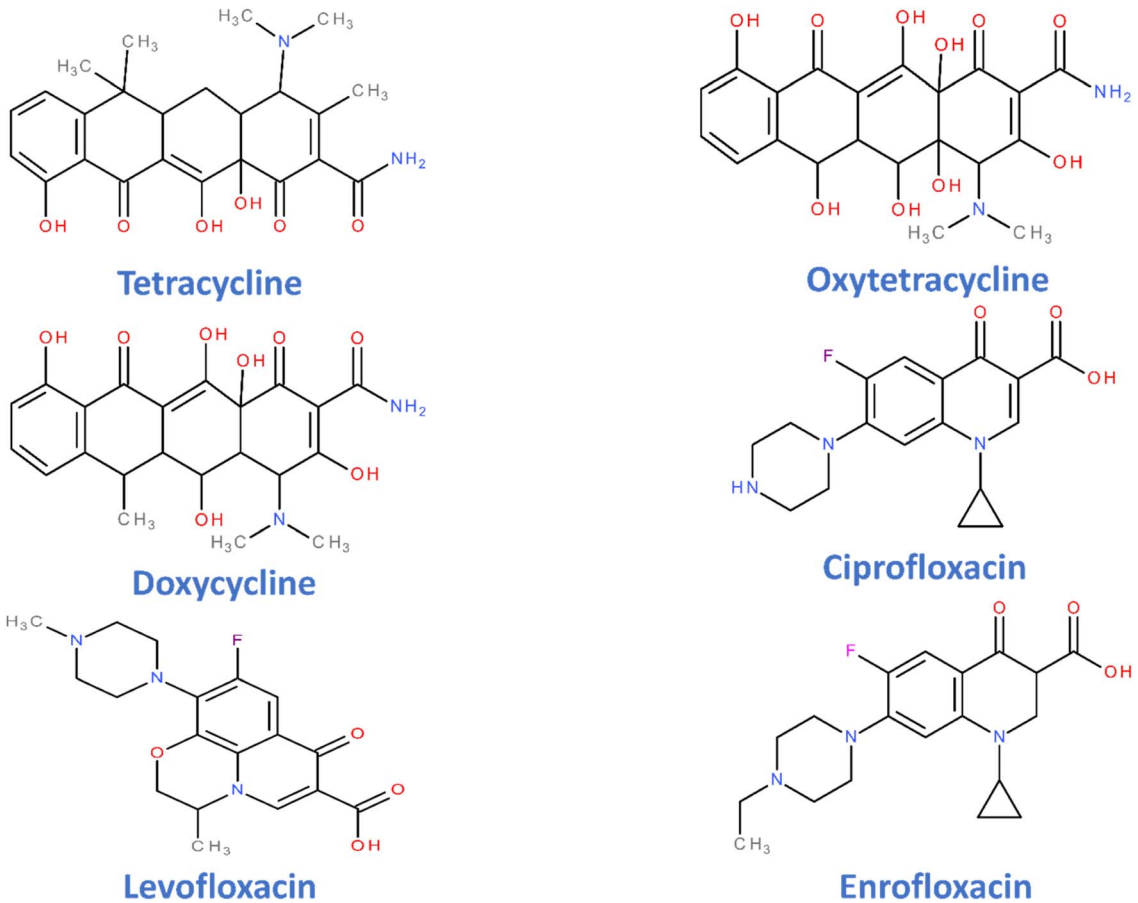


Fig. 1 A common antibiotic prescription.

800 W oven for 40 s to promote the creation of water-soluble fluorescent CDs.

These tiny particles exhibit a decrease in fluorescence in response to Fe^{3+}. This characteristic makes it possible to quantify Fe^{3+} ions *via* the quenching mechanism. It's interesting to note that adding OTC can restore fluorescence and make it possible to recognize it.

On the other hand, the bottom-up strategy is another way of constructing CDs from smaller molecules. This approach offers precise control over CD properties, utilizing readily available and often non-toxic precursors such as citric acid. Through hydrothermal or microwave treatments, these molecules undergo carbonization, forming graphitic or amorphous cores with functional groups on the surface.[80] Recent advancements focus on enhancing CD characteristics by incorporating heteroatoms into the structure. The hydrothermal method is particularly favored due to its simplicity and ability to produce CDs with uniform size and high quantum yield, as demonstrated by Zeng *et al.*[81] who used citric acid and ethylenediamine as carbon and nitrogen sources in a one-pot hydrothermal route at 150–300 °C for 5 h.

4. Analytical techniques for detection of antibiotics

In recent decades, significant efforts have been made to develop effective techniques for identifying traces of antibiotics in agricultural and meat products.[11,82–84] These include flow injection analysis (FIA),[85] enzyme-linked immunosorbent assay (ELISA),[86] high-performance liquid chromatography (HPLC),[87] capillary electrophoresis (CE),[88] and electrochemical aptasensors.[89] These techniques typically have some limitations, such as being expensive, requiring laborious and time-consuming sample preparation, and/or necessitating the use of advanced instruments. ELISA has been widely applied for antibiotic residue screening in food and biological matrices, and recent studies have also highlighted its feasibility as a cost-effective high-throughput tool for large-scale environmental monitoring.[90] Consequently, these problems render them inappropriate for routine monitoring of environmental and food safety.

Therefore, it is crucial and extremely desirable to create novel methods for the detection of antibiotics that possess a high level of sensitivity, selectivity, and simplicity. Efforts have been focused on investigating fluorescent probes that have both high selectivity and sensitivity for the purpose of rapid analytical detection. Various carbon-based nanomaterials, including carbon nanotubes, graphene, fullerene, carbon quantum dots (CQs), and CDs (Fig. 2D),[91–93] have been explored. Graphitic carbon nitride (g-C_3N_4) is a metal-free semiconductor material that has been extensively studied and applied in various fields such as sensing, catalysis, fluorescence imaging, and cancer treatment. This is due to its distinctive electronic structure, exceptional chemical and thermal stability, and favorable biocompatibility[94] (Fig. 2B).

5. Toxicity, biocompatibility, and biodegradability of the carbon nanodot-based sensors for in vivo applications

While the present review is primarily devoted to fluorescence-based carbon nanodot sensors for antibiotic detection in aquatic environments, consideration of toxicity, biocompatibility, and biodegradability is essential when evaluating the broader applicability of these materials, particularly with respect to potential *in vivo* or bioanalytical use. Carbon nanodots have attracted significant attention in biomedical research due to their carbonaceous composition, tunable surface chemistry, high aqueous dispersibility, and generally favorable safety profiles reported in the literature. Numerous studies indicate that CDs synthesized from low-molecular-weight organic compounds or renewable biowaste and biomass precursors exhibit low cytotoxicity, acceptable biocompatibility, and, in some cases, partial biodegradability. These attributes have supported their exploration in bioimaging, tissue engineering, drug delivery, and theranostic applications.[96–98] Experimental investigations have demonstrated that fruit-derived and biowaste-based CDs, as well as inulin-functionalized and heteroatom-doped CD systems, are well tolerated in both *in vitro* and *in vivo* models at moderate concentrations, enabling effective fluorescence imaging in zebrafish and mammalian systems. In addition, systematic biocompatibility studies of carbon quantum dots report minimal cytotoxicity and limited immunogenic responses during short-term exposure, supporting their suitability as optical probes. However, it is increasingly recognized that biosafety is not an intrinsic property of all CD formulations. Toxicological outcomes are strongly influenced by synthesis parameters, precursor composition, particle size, surface passivation, heteroatom doping, surface charge, and the presence of residual synthetic byproducts.[98,99]

Comprehensive reviews of CD-based bioimaging and cancer theranostics emphasize that surface chemistry critically governs cellular uptake pathways, organ distribution, and potential genotoxic effects, while also noting that standardized and long-term toxicological data remain scarce for many reported systems. Recent studies have further shown that specific surface functionalities, such as oxidized sulfur-containing groups, can induce elevated *in vivo* toxicity despite favorable *in vitro* cytocompatibility, underscoring the limitations of relying solely on cell-based assays. Comparative analyses across nanocarbon materials also reveal that biodistribution, bioaccumulation, and clearance mechanisms are dictated by particle size and surface characteristics, with renal clearance and partial metabolic degradation reported for small, hydrophilic CDs, whereas prolonged retention in major organs has been observed for larger or more hydrophobic analogues.[100,101]

Regarding biodegradability, some CD systems, particularly those derived from natural precursors or incorporated within degradable polymeric or biological matrices, have been

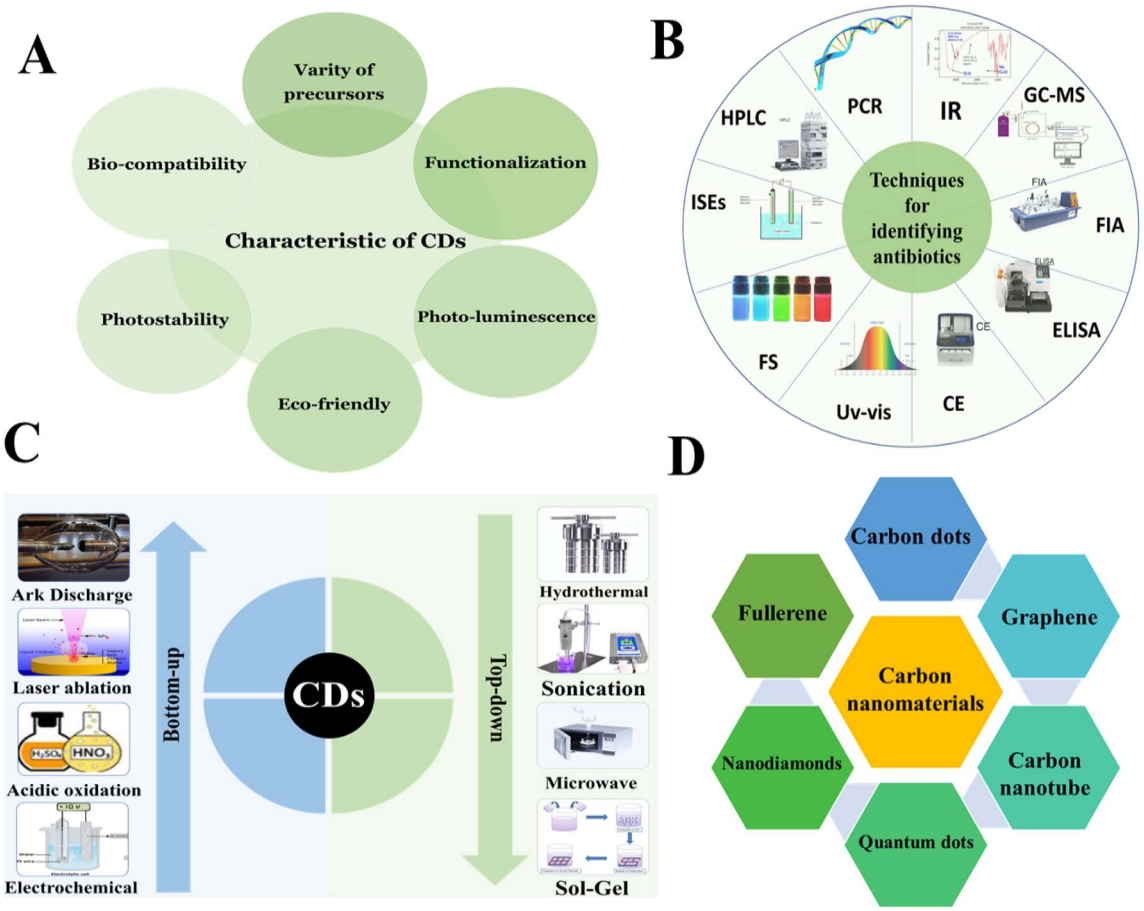


Fig. 2 (A) Representation of the tunable properties of CDs. (B) A summary of the methods used to determine antibiotics. (C) An illustration of the top-down and bottom-up methods used for CD preparations with tailored properties. (D) Carbon-based fluorescence nanomaterials. Adapted/reproduced from ref. 95 with permission from Springer, copyright 2026.

described as partially biodegradable and compatible with regenerative medicine strategies. Nevertheless, degradation behavior is highly system-dependent, and comprehensive preclinical and clinical evidence remains limited. Therefore, before CD-based sensing platforms can be reliably translated from environmental monitoring to *in vivo* applications, rigorous and standardized toxicity assessments, dose- and time-dependent biodistribution studies, and long-term evaluations of degradation and excretion pathways are required. The adoption of safety-by-design principles, including the use of benign precursors, avoidance of heavy metals and persistent coatings, precise control of surface charge, and development of inherently degradable architectures, will be essential to reconcile high sensing performance with acceptable toxicological and biocompatibility profiles.[100,102]

6. CD-based detection of antibiotics in water bodies

In order to treat and prevent illnesses in both humans and animals, antibiotics are essential. They are, nevertheless, widely present in the environment as a result of their ubiquitous use. Soil, sludge, groundwater, wastewater, tap water, surface water, plants, and aquatic life are only some of the many natural and man-made systems discovered to contain antibiotics. The most frequent locations for their detection are wastewater treatment plants (WWTPs).[103,104] Studies have shown that the sewage sludge from WWTPs in the USA, Canada, China, Spain, and Sweden contains a noticeable amount of antibiotics.[105–111] A study of 45 WWTPs in 23 Chinese towns found that quinolones are the most common class of antibiotics; concentrations as high as 29 647 mg kg^{-1} were found in residential sludge from Shanxi Province.[112] The misuse of common antibiotics, such as tetracyclines (TCs), quinolones, sulfonamides, and glycopeptides, has become a major public health issue despite their easy accessibility.[113] Effective detection and monitoring techniques must be developed in order to address this problem. The use of carbon-based fluorescence sensors, which offer accuracy, reliability, and a straightforward technique, is a viable alternative for the sensitive detection of antibiotics. Table 2 lists the usage of CDs as a sensitive and specific sensor for the detection of harmful antibiotics in water bodies.

6.1. Tetracycline

Recent research has demonstrated the effectiveness of heteroatom-doped CDs as powerful fluorescent and

Table 2 Fluorescence-based systems for antibiotic detection in various matrices

Carbon precursor	Preparation methods	Type of sample	Linearity	Limit of detection	Fluorescence mechanism	Antibiotic type	References
Crab shell waste	Pyrolysis	Pharmaceutical waste water	0 and 100 mg L^{-1}	0.005 mg L^{-1}	Static quenching	TC	114
Sucrose, phosphoric acid, and ethylenediamine	Reflux	Wastewater	0–150 μM	1.73 nM	Turn-off	TC	115
DL-malic acid and glycine	One-pot solid pyrolysis	Tap water and lake water	1.0 to 15.0 μg mL^{-1}	0.16 μg mL^{-1}	On-off-on	Enrofloxacin	116
Tobacco stems	One-pot hydrothermal	Tap water and lake water	0.0 to 200.0 μM	20–80 μg mL^{-1}	Turn-off	TC, OTC	117
Orange peel & watermelon peel	One-step hydrothermal	Tap water and lake water	2–100 μmol L^{-1} and 0.25–100 μmol L^{-1}	40 μmol L^{-1}	Turn-off	OTC	118
Lysine	Microwave methods	Sensor for real samples	0–250 μM	50 nM	Off-on-off	TC, OTC, DC, MTR, CTE, SDI	65
Ascorbic acid and diethylenetriamine (DETA)	Microwave method	Pharmaceutical waste	3.72–33.40 μM	0.25 μM	Turn-off	Doxycycline	119
Osmanthus fragrans leaves and polyethyleneimine	Hydrothermal treatment	Environmental water	0–60 nM	0.0127 nM	On-off	Ciprofloxacin	120
Waste papaya seeds (PS) with ethylenediamine	One-step microwave-induced pyrolysis	Water and food samples	—	120 nM	Turn-on	TC	121
Nicotinic acid and boric acid	Hydrothermal treatment	Tea drinks	0.2 to 60 μg L^{-1}	0.1 μg L^{-1}		OTC	122
Ammonium citrate and L-cysteine	Microwave method	Water sample	13.5 nM to 0.9 μM	6.9 nM	Ratiometric	Levofloxacin	123
Potato	Hydrothermal treatment		0.05–0.95 μM	0.311 μM	Static quenching	Cephalexin	124
Rice residue and glycine	Hydrothermal treatment	Water sample	3.32 to 32.26 μM	0.2367, 0.3739, 0.2791 μM	Static quenching	TC, OTC and CTC	125
Citric acid and glutathione	Hydrothermal treatment	Tap water sample	1.88–60 μM	0.56 μM	Turn-off	TC, OTC and CTC	126
		River, tap, and mineral water	0–40 μM	0.41 μM	Ratiometric	OTC	127
Urea and citric acid	Hydrothermal treatment	Tap water and lake water	0–12.5 μM and 10–25 μM	3.133 nM	Ratiometric	TC	128

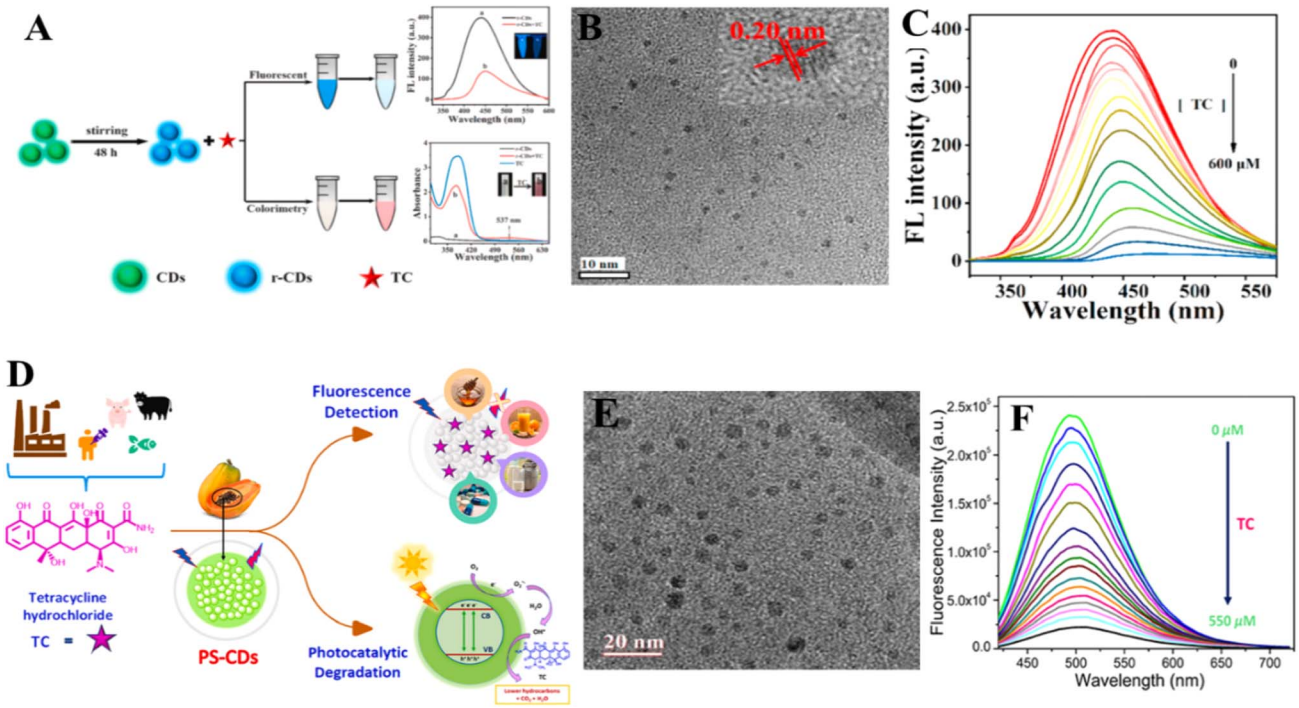


Fig. 3 (A) A schematic of r-CDs and their sensing capabilities for both fluorescence and colorimetric detection. (B) TEM images of the r-CDs. (C) Spectra showing the effect of TC on fluorescence intensity. (D) A schematic of N-CD preparation and applications. (E) TEM images of N-CDs at 20 nm. (F) The influence of TC on the emission intensity of N-CDs. Adapted/reproduced from ref. 134 and 135 with permission from Elsevier, copyright 2026.

colorimetric sensors for detecting tetracycline.[129–133] Fu *et al.*[134] developed reduced CDs doped with nitrogen, phosphorus, and boron through a reduction process that transformed carbon-oxygen double bonds into hydroxyl groups. These r-CDs exhibited strong fluorescence properties with a quantum yield of 18.8% and showed high stability and small particle size 0.20 nm. The presence of TC triggered fluorescence quenching *via* Förster resonance energy transfer, while a noticeable color shift from colorless to red enabled simultaneous colorimetric detection. The r-CDs displayed a strong correlation between TC concentration (0–150 μM) and absorbance at 537 nm, achieving impressive detection limits of 0.46 μM for colorimetry and 1.73 nM for fluorescence as shown in Fig. 3A–C. Similarly, Laddha *et al.*[135] synthesized nitrogen-doped carbon dots (N-CDs) using a single-step microwave pyrolysis method with papaya seeds and ethylenediamine with an approximate size of 4.68 nm. These N-CDs emitted fluorescence at 499 nm and selectively responded to TC through fluorescence quenching, which was attributed to an inner filter effect (IFE) mechanism. By analyzing the fluorescence intensity at varying TC concentrations, they achieved a detection limit of 120 nM. Additionally, these N-CDs exhibited dual functionality, not only detecting TC but also aiding in its degradation in real-world samples like milk, orange juice, tap water, and honey, as demonstrated in Fig. 3(D)–(F). In another study, Yang *et al.*[136] synthesized nitrogen and sulfur co-doped carbon dots (N,S-CDs) from waste tobacco stems using a one-pot hydrothermal method. These biomass-derived C-dots showed a concentration-dependent fluorescence decrease due to the IFE mechanism, enabling highly sensitive and selective, label-free detection of TC. With a detection limit of 1.32 nM in real water samples, they proved to be an effective tool for environmental monitoring. Collectively, these studies underscore the potential of doped CDs as reliable, sensitive, and selective platforms for detecting and breaking down TC in diverse environmental and biological settings.

6.2. Enrofloxacin

Guo *et al.*[137] reviewed the use of nitrogen-doped fluorescent carbon dots (N-CDs) as an effective sensing platform for detecting enrofloxacin (ENR), a widely recognized environmental pollutant. They synthesized N-CDs using a simple one-pot solid pyrolysis method, employing glycine and DL-malic acid as carbon and nitrogen precursors, respectively. The resulting N-CDs exhibited strong fluorescence properties with a distinct absorption peak at 368 nm, attributed to the n–π^* transition of the carbonyl group (Fig. 4A).[59] Under ultraviolet excitation, these N-CDs emitted a bright blue fluorescence. A detailed analysis of their fluorescence excitation and emission spectra was conducted to understand their sensing behavior. The detection mechanism was based on a Cu^{2+}-mediated fluorescence quenching effect. Specifically, the introduction of Cu^{2+} ions significantly reduced the fluorescence intensity of the N-CDs, but upon the addition of ENR, fluorescence was restored in a concentration-dependent manner (Fig. 4B). Leveraging this interaction, Guo *et al.* developed a highly sensitive ENR detection method using the N-CDs–Cu^{2+} system, achieving a detection limit of 0.16 μg mL^{-1}. The effectiveness of this approach

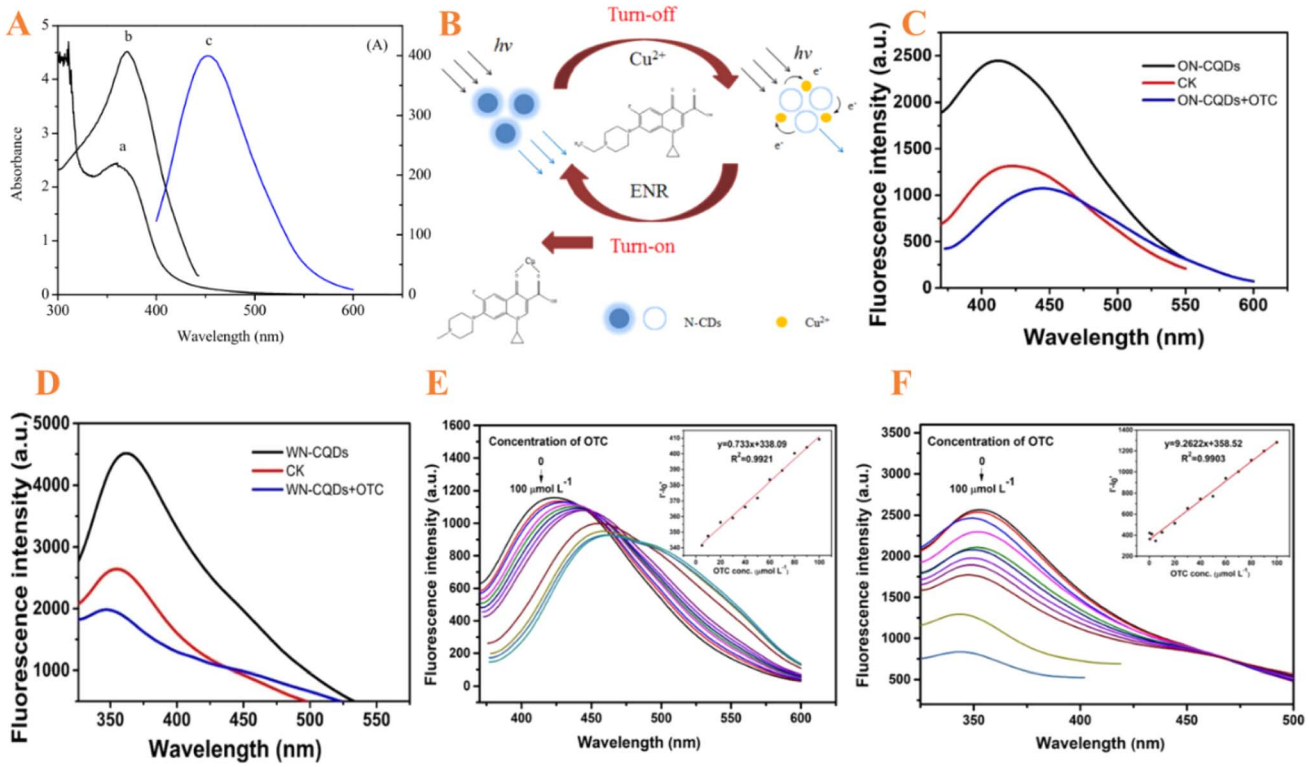


Fig. 4 (A) UV-Vis absorption spectrum of N-CDs (a), along with their fluorescence excitation (b) and emission (c) spectra. (B) Schematic illustration of the N-CD fluorescent probe for ENR sensing. (C) Emission spectra of ON-CQDs excited at 320 nm, and (D) emission spectra of WN-CQDs excited at 280 nm. (E and F) Progressive fluorescence quenching of ON-CQDs and WN-CQDs, respectively, with increasing OTC concentrations (0–100 μmol L^{-1}). Adapted/reproduced from ref. 137 and 138 with permission from Elsevier, copyright 2026.

was further validated through real-sample analysis in tap and river water, demonstrating reliable detection across ENR concentrations ranging from 1.0 to 15.0 μg mL^{-1}.

6.3. Oxytetracycline

Gao *et al.*[138] conducted a comprehensive study on the application of nitrogen-doped carbon quantum dots (N-CQDs) for the sensitive detection of oxytetracycline (OTC) in an environmental matrix. N-CQDs were prepared through a hydrothermal process from both orange and watermelon peels, serving as CD carbon dot sources, yielding spherical nanoparticles with a size less than 5 nm. To assess the N-CQDs' sensitivity to OTC, the researchers added varying amounts of OTC to different water and soil samples and evaluated the fluorescence intensity of N-CQDs in the presence of OTC. A notable decrease in fluorescence intensity of both ON-CQDs and WN-CQDs was observed with increasing OTC levels, as depicted in Fig. 4C and D. This phenomenon was attributed to the FRET mechanism between the N-CQDs and OTC molecules, where the electron-deficient aromatic rings in OTC interacted with the $-NH_2$ groups of the N-CQDs.[139] The linear relationship between OTC concentration and fluorescence quenching enabled the development of a quantitative detection method. Remarkably, both ON-CQDs and WN-CQDs demonstrated exceptional sensitivity to OTC, with detection limits of 0.077 μmol L^{-1} and 0.973 μmol L^{-1}, respectively. Fluorescence intensity of N-CQDs decreased with the increase in OTC concentration. Adding 2–100 μmol L^{-1} and 0.25–100 μmol L^{-1} of OTC to ON-CQDs and WN-CQDs, respectively, showed a good linear relationship between them, as shown in Fig. 4E and F. These findings underscore the promising application of N-CQDs as effective fluorescent probes for monitoring OTC in environmental samples.[138]

6.4. Doxycycline

A study was conducted to investigate the prevalence of DC in various environmental samples, with a particular focus on pharmaceutical waste by Raut *et al.*[140] They synthesized nitrogen-doped carbon quantum dots (N-CQDs) from ascorbic acid and diethylenetriamine (DETA) using a simple microwave-assisted method. The N-CQDs produced blue-luminescence emission, and were used to detect doxycycline. Fig. 5A shows the selectivity of N-CQDs for DC, rigorously evaluated by assessing fluorescence changes in the presence of various antibiotics, including TC derivatives (TC, OX, and minocycline) in a PBS solution at pH 7.4. Remarkably, only TC derivatives exhibited the ability to completely quench the fluorescence of N-CQDs, while other antibiotics had no effect.[140] This phenomenon can be attributed to the structural similarities between DC and other TC derivatives, which interact with the recognition sites of N-CQDs, leading to fluorescence quenching. To improve the ability to specifically detect DC, additional experiments were carried out. Using different amounts of DC, we found that as the

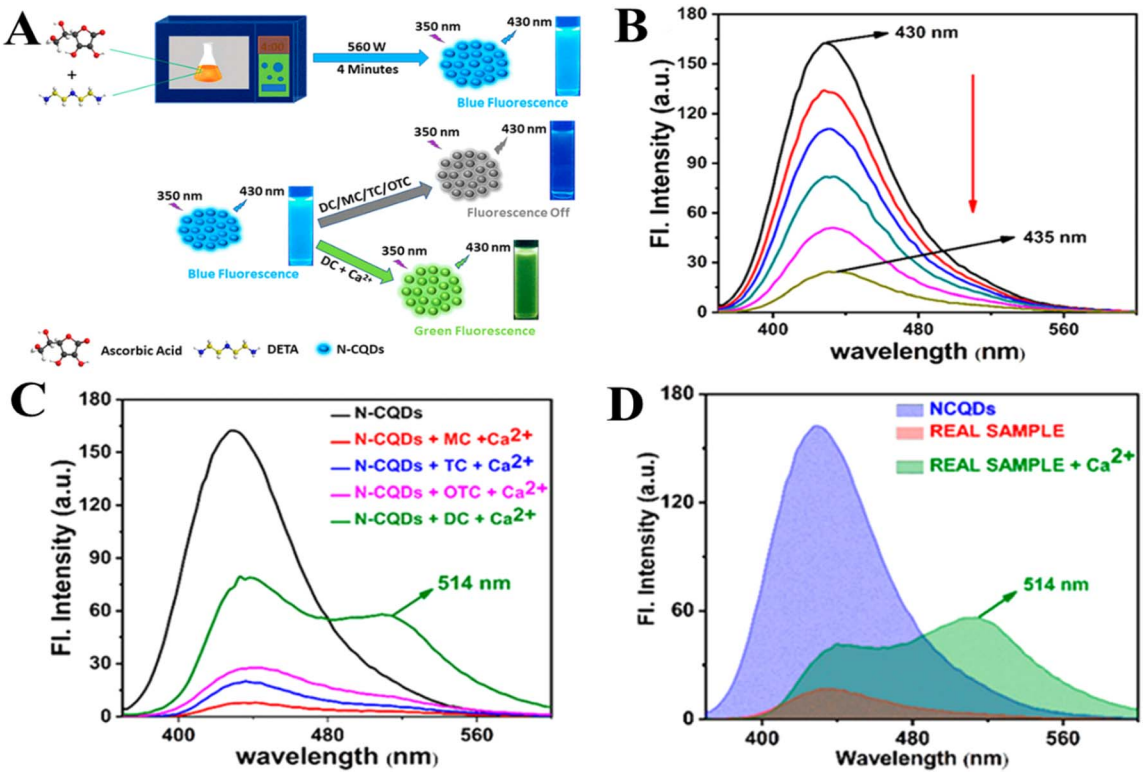


Fig. 5 (A) A schematic illustrating the synthesis and measurement of N-CQDs' DC properties. (B) N-CQDs' fluorescence emission spectra measured in PBS at pH 7.4 with varying DC concentrations, with excitation at 430 nm. (C) N-CQDs' fluorescence emission spectra indicating interactions with TC derivatives (MC, TC, OTC, DC) and calcium ions. (D) Fluorescence emission spectra of N-CQDs in a real-world sample. Adapted/reproduced from ref. 140 with permission from ACS, copyright 2026.

concentration of DC increased, the fluorescence of N-CQDs decreased more significantly, as illustrated in Fig. 5B. Building upon previous research[141,142] demonstrating the interaction between tetracycline (TC) derivatives and metal ions, Ca^{2+} ions were added to solutions containing different TC derivatives. The formation of a stable six-membered ring complex between Ca^{2+} and DC, facilitated by the intramolecular oxygen of the ketone and hydroxyl groups, weakened the intramolecular vibration of DC, thereby increasing its radiation energy.[143,144] This unique interaction enabled the selective detection of DC among the other TC derivatives, as depicted in Fig. 5C. By leveraging the high selectivity and sensitivity of N-CQDs towards DC, the study successfully evaluated real-world environmental samples, including pharmaceutical waste. Fluorescence measurements were conducted both with and without the addition of Ca^{2+} ions to accurately determine the presence and concentration of DC in these samples. The results unequivocally demonstrated the N-CQDs' capability to detect and quantify DC in real-world scenarios (Fig. 5D).

6.5. Ciprofloxacin

Liu *et al.*[145] studied the selective and sensitive assay of CIP and used TiO_2/CDs/CdTe QDs as a photocatalyst for the degradation of CIP. Highly fluorescent CDs were synthesized through hydrothermal treatment of *Osmanthus fragrans* leaves as a carbon source and polyethyleneimine as a nitrogen source. This novel strategy presented an excellent linear CIP assay range of 0–60 nM with a detection limit as low as 0.0127 nM. Significant findings emerged from the investigation of the CIP recognition capabilities of MIPs@CdTe/CDs@SiO_2 fluorescence sensors. Upon excitation at 340 nm in the presence of CIP, the fluorescence emission spectra of both MIPs@CdTe/CDs@SiO_2 and NIPs@CdTe/CDs@SiO_2 were analyzed, revealing a prominent emission peak at 465 nm and a relatively moderate peak at 647 nm (Fig. 6A). The MIPs demonstrated an exceptional recognition ability, evidenced by a slight decrease in fluorescence at 465 nm following the removal of CIP, alongside a rapid recovery of the emission at 647 nm, which paralleled the behavior of NIPs. Additionally, the suspension color shifted from light blue to magenta when exposed to UV light, providing a visually discernible indicator of the sensor's effectiveness. Overall, MIPs@CdTe/CDs@SiO_2 serves as a robust method for the visual detection of CIP, enhancing its applicability in monitoring antibiotic presence. In complicated mixtures, selectivity was shown to be essential for reducing interference from other substances while isolating a particular analyte.[146] The researchers added 30 nM of different metal cations to MIPs@CdTe/CDs@SiO_2 in order to assess its recognition capabilities. This method made it possible to evaluate the material's selectivity for CIP detection. As seen in Fig. 6B, the results showed that although some ions, such mercury, slightly reduced fluorescence, the overall detection rate of CIP was essentially unaffected. This emphasizes how crucial it is to keep

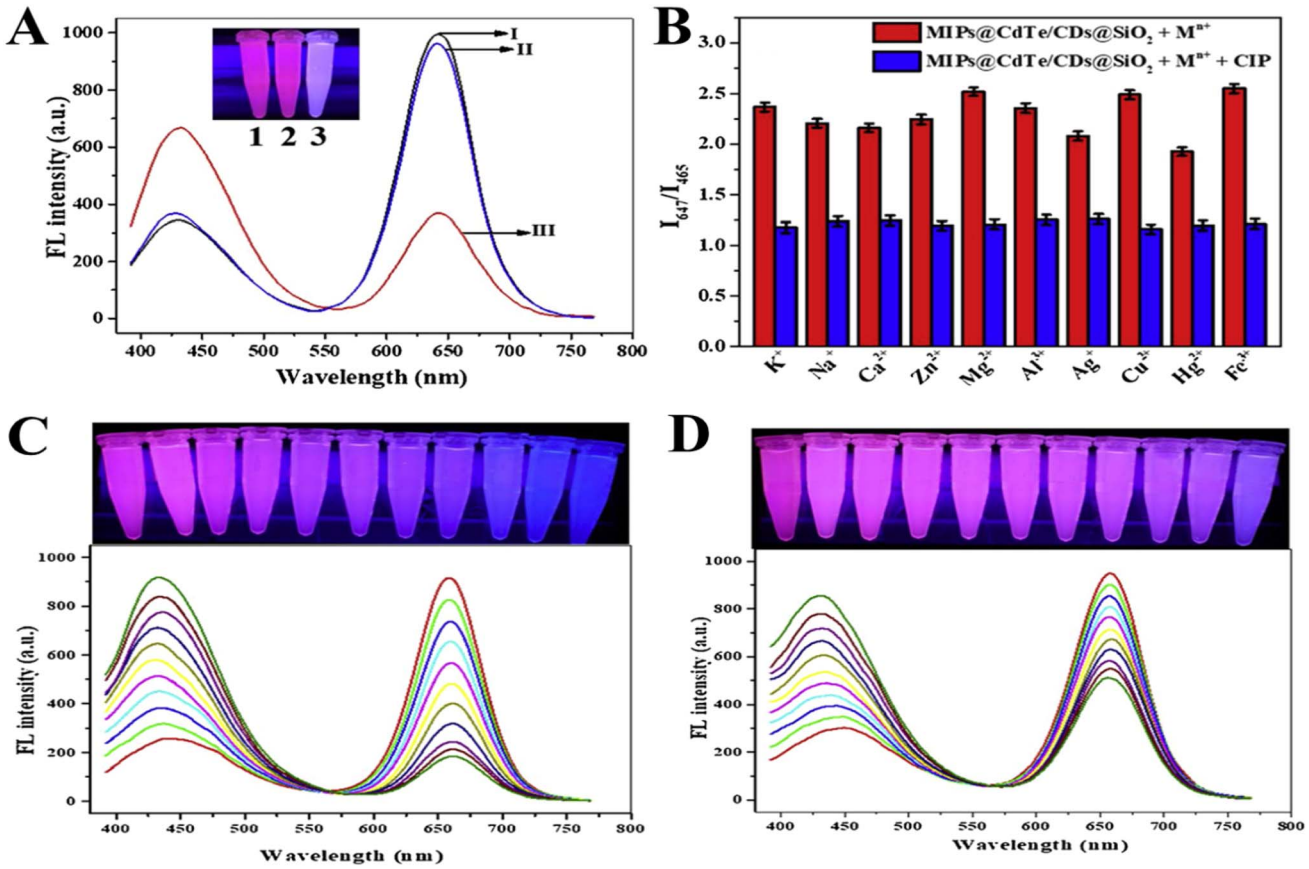


Fig. 6 (A) The fluorescence spectra and accompanying picture of NIPs@CdTe/CDs@SiO_2 (curve I, 1), MIPs@CdTe/CDs@SiO_2 (curve II, 2), and MIPs@CdTe/CDs@SiO_2@CIP (curve III, 3), seen under a UV light. (B) The impact of 30 nM distinct metal ions on MIPs@CdTe/CDs@SiO_2 to identify CIP (24 nM). (C) MIPs@CdTe/CDs@SiO_2 fluorescence spectra and photos that correspond with them. (D) NIPs@CdTe/CDs@SiO_2 fluorescence spectra and photos that correlate with them. Adapted/reproduced from ref. 145 with permission from Elsevier, copyright 2026.

a reference signal in order to reduce outside interference and improve detection precision. In this study, the sensitivity of the ratiometric fluorescence sensor was evaluated by adding varying concentrations of CIP to MIPs@CdTe/CDs@SiO_2 and NIPs@CdTe/CDs@SiO_2 solutions under ideal conditions. With CIP concentrations ranging from 0 to 60 nM, the fluorescence intensity of MIPs@CdTe/CDs@SiO_2 showed a gradual increase at around 465 nm, while at 657 nm, it showed a steady fall, as shown in Fig. 6C. Conversely, NIPs@CdTe/CDs@SiO_2 had a sustained drop in fluorescence intensity at 657 nm, followed by a slight increase at 465 nm (Fig. 6D). Interestingly, MIPs@CdTe/CDs@SiO_2 showed more noticeable red to blue alterations in their relative fluorescence response under UV light than did NIPs@CdTe/CDs@SiO_2. The number of recognition sites in MIPs@CdTe/CDs@SiO_2 is responsible for this observation since it allows for quick and accurate interactions with CIP.[145]

7. Different mechanisms of CDs for sensing antibiotics

The sensing mechanism of CDs relies on the chemical interactions of the fluorescent probe. Several mechanisms are utilized by CDs for antibiotic detection, including Förster resonance energy transfer (FRET), photoinduced electron transfer (PET), static quenching, and inner filter effect (IFF) (AIE).

7.1. Förster resonance energy transfer (FRET)

FRET is an electrodynamic phenomenon that can be explained by both quantum and classical physics. Dipole–dipole energy transfer that is non-radiative causes acceptor enhancement and donor fluorescence quenching. Long-range dipole–dipole interactions enable FRET between CDs in the excited state and a quencher in the ground state in this process when the donor's emission spectrum overlaps with the quencher's absorption spectrum.[147,148] When the distance is less than 10 nm, this energy transfer occurs without a photon being released.[149,150] Because of their better qualities over fluorescent proteins and chemical dyes, CDs are especially useful as fluorescent donors in FRET-based systems.[151,152] Carbon-based FRET-based probes show promise in multiplexed analysis and can be customized for uses such as the detection of antibiotics by using several linking sites with quenching species. Reduced fluorescence lifetime of CDs, increased acceptor fluorescence, and spectrum overlap between CD fluorescence and quencher absorption are

all signs of a FRET mechanism.[153] Qu *et al.*,[69] using ethylene glycol and ascorbic acid as precursors, created dual-emission carbon nanodots by a hydrothermal procedure. The blue emitters on these CDs peaked at 385 nm when excited at 315 nm, while the yellow emitters peaked at 530 nm when excited at 365 nm. Through a FRET mechanism, TC could extinguish the fluorescence of these CDs.

7.2. Photoinduced electron transfer (PET)

The detection of analytes *via* the PET quenching mechanism of CDs encompasses both inorganic and organic substances. PET is a process in which electrons are transferred between CDs and the quencher, with both potentially acting as either electron donors or acceptors.[153,154] This transfer results in the formation of cationic and anionic radicals. During the process, an interaction occurs between the electron donor and acceptor, leading to a complex that returns to its ground state without emitting a photon. Based on this mechanism, PET can be categorized into two types: reductive and oxidative. In reductive PET, CDs function as electron acceptors by receiving electrons from the quencher, which serves as an electron donor, ultimately forming an anionic radical. Conversely, in oxidative PET, CDs act as electron donors, transferring electrons to an acceptor, resulting in the formation of a cationic radical. The driving force behind PET is the energy gap between molecular orbitals. In oxidative PET, this driving force is determined by the energy difference between the LUMO of CDs and the LUMO of the quencher, whereas in reductive PET, it depends on the energy gap between the LUMO of the quencher and the HOMO of CDs.[153,155,156] Huang *et al.*[157] synthesized CDs using L-cystine and phosphoric acid as precursors through a one-step microwave-assisted method. These CDs, operating *via* the PET mechanism, utilize TC both as a target pollutant and as a natural electron transfer mediator. As a result, the CDs function effectively as sensors for TC detection and also demonstrate remarkable photocatalytic activity for the degradation of TC in aquatic environments.

7.3. Static quenching

Static quenching is another phenomenon that occurs between CDs and the quencher through their mutual interaction. In this mechanism, CDs form a non-fluorescent ground-state complex which, upon light absorption, rapidly returns to the ground state without emitting a photon.[158] The formation of this ground-state complex leads to changes in the absorption spectrum of CDs. Moreover, the extent of static quenching decreases as the stability of the ground-state complex diminishes with rising temperature.[159,160] Researchers have reported the development of rapid, low-cost, and highly sensitive strategies for the detection and degradation of DOX in water systems. Kaur *et al.*[161] used Fe-doped carbon dots (Fe-N@CDs) to synthesize iron oxide–carbon dot hybrid nanoparticles (Fe_3O_4-CDs) through a one-step hydrothermal carbonization process, employing $FeCl_2$ as the iron source and citric acid as the carbon precursor, with ethylenediamine as an additive. These functional nanomaterials exhibit excellent sensitivity for DOX detection, operating based on the static quenching effect (Table 3).

7.4. Inner filter effect (IFE)

The IFE is a phenomenon that influences the fluorescence behavior of CDs when their excitation and emission spectra overlap with the absorption spectrum of a quencher within the detection system. Unlike static quenching, IFE is a concentration-dependent optical process, where an excess of CDs or quencher molecules attenuates the excitation light or absorbs the emitted fluorescence, rather than causing true quenching through molecular interactions.[162] Notably, since IFE does not involve direct interactions between CDs and quenchers, it does not alter the fluorescence decay time of CDs but only leads to a reduction in fluorescence intensity. Furthermore, because no new substances are formed during this process, the absorption peaks of CDs remain unchanged. Importantly, IFE can still occur even when the distance between the emitter and the

Table 3 Summary of carbon-based fluorescence, target antibiotics, and the principal mechanisms utilized for antibiotic detection

Material	Target analyte	Mechanism of detection	LOD (nM)	Linear range (μM)	References
CDs	TC	IFF	0.5	0–16	165
CDs	TC, OTC, CTC, DOX	FRET	0.52	1–30	69
CDs	TC	PET			166
Fe-N@CDs	DOX	Static quenching	121.6	0–92, 100	167
CDs	CTC	IFF	6	0.02–0.2	168
CDs	OTC	IFF	20	0.02–2	169
CDs	TC	IFF	4000	0.004–6	169
R-CDs	TC	Static quenching	38.5	3–40	170
R-CDs	CTC	Static quenching	64.6	4–50	170
R-CDs	OTC	Static quenching	45.4	2–50	170
CDs	TC	Static quenching	3.3	0.01–100	171
N-CDs	TC	IFF	3.3	6.5–72.3	172
N-CDs	OTC	IFF	3.3	0.6–73.3	173
N-CDs	DC	IFF	3.3	0–95.2	173
CQDs	TC	FRET	0.355	0.001–0.1	174
RBP-CDs	TC	PET	360	30–90	175
CDs@SBA-15	CTC	PET	113	0–100	176

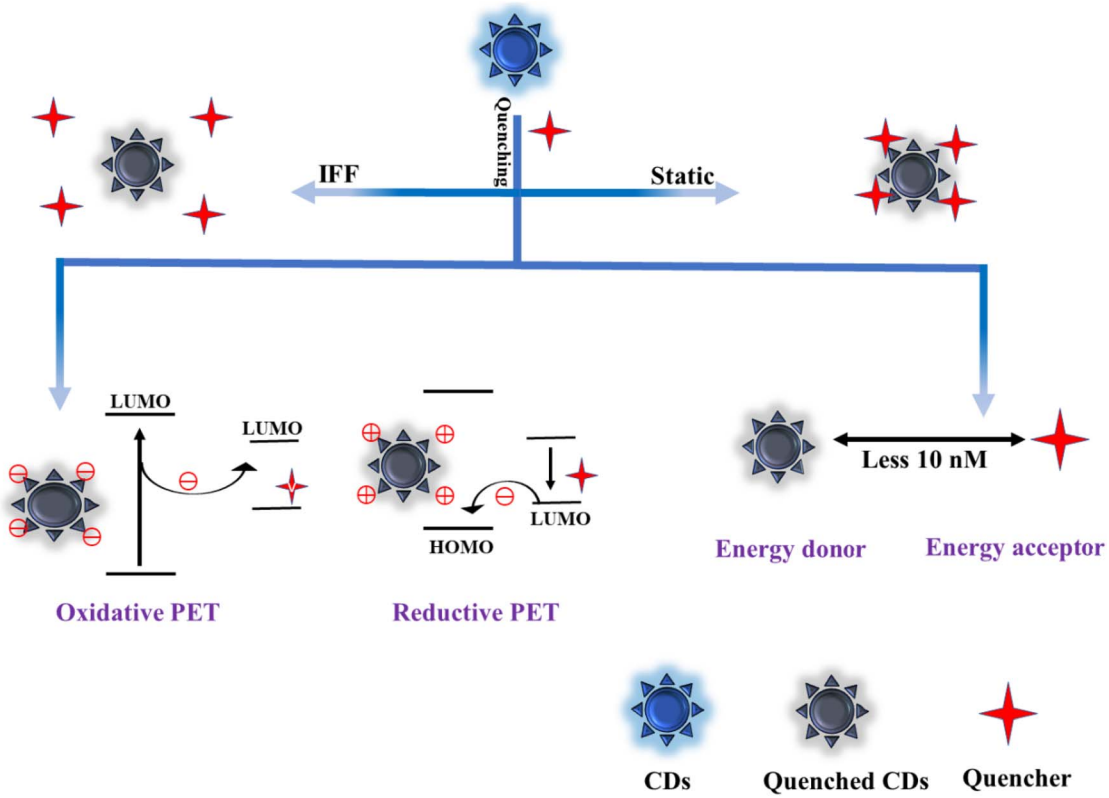


Fig. 7 Schematic illustration of the main fluorescence quenching pathways involved in carbon dot (CD)-based sensing of antibiotics, including photoinduced electron transfer (PET), inner filter effect (IFE), static quenching, and energy transfer interactions between CDs and quenching analytes. Reproduced from ref. 153 with permission from Springer, copyright 2026.

absorber exceeds 10 nm, distinguishing it from typical quenching mechanisms.[163] Korah *et al.*[164] reported, for the first time, the development of a CD-based sensor for TC detection, utilizing *Curcuma amada* as the carbon source through a straightforward hydrothermal synthesis method. The sensing mechanism relies on fluorescence quenching *via* the IFE in the presence of TC. This sensor demonstrated excellent sensitivity, selectivity, and reliability for TC detection in real sample analyses. The principal fluorescence quenching pathways (PET, IFE, static quenching and energy transfer) involved in carbon dot-based antibiotic sensing are summarized schematically in Fig. 7.

8. Design strategies for enhanced molecular recognition in complex matrices

Binding affinity in fluorescence sensing systems can be strengthened by incorporating selective recognition components such as molecularly imprinted polymers, which are designed to form specific binding cavities for target molecules and thereby improve sensing selectivity.[177,178] In some studies, hybrid designs that combine imprinting layers with aptamer recognition have been proposed as an additional route to enhance binding performance and stability.[179] Carbon dot-based sensors coated with MIPs have also been highlighted as promising platforms, since they merge the fluorescence advantages of carbon nanodots with the molecular selectivity provided by imprinting techniques.[180] However, even when binding appears satisfactory under controlled laboratory conditions, sensor recognition can become less reliable in real complex samples, mainly because coexisting substances may interfere with target interactions or contribute to non-specific adsorption effects.[181] Therefore, improving matrix tolerance and optimizing imprinting-based recognition strategies remain important steps toward more practical sensing applications.

9. Limitations of carbon-based nanomaterials and challenges for industrial transition

Although CDs have attracted considerable attention as promising fluorescence nanoprobes, several challenges still need to be addressed before they can be reliably applied in real industrial environments. One important issue is that the fundamental origin of carbon dot photoluminescence remains not completely clarified, which limits the ability to design materials with fully predictable optical behavior.[182] Similar concerns have also been raised for dual-emission systems, where the mechanisms responsible for stable emission outputs are still under discussion.[183] In addition, current synthesis approaches often suffer from insufficient control over structural features and

surface chemistry, leading to variability in optical properties and reproducibility between different batches.[184] From a practical perspective, scalability remains another major difficulty, since some reported procedures require multi-step preparation routes, and large-scale production is still considered a significant challenge for industrial translation.[182,183] Furthermore, fluorescence performance may be affected by aggregation-related quenching phenomena, particularly in hybrid or composite systems, which can reduce signal reliability.[183] Finally, when sensors are transferred from laboratory conditions to realistic samples, their response may become influenced by environmental factors such as ionic strength, pH variations, or competing substances present in complex matrices, highlighting the need for further validation in real-field applications.[185] At present, most carbon dot-based sensing systems remain at the proof-of-concept stage, and routine adoption by environmental monitoring agencies is still limited. This is mainly due to practical matrix effects and stability requirements in real samples, rather than limitations in the intrinsic potential of carbon dots. Nevertheless, carbon dots continue to represent highly promising nanomaterials with broad applicability in environmental sensing.[186]

10. Conclusion and future perspectives

Carbon nanodots (CDs) offer a promising approach for sensitive and selective antibiotic detection in wastewater. Their unique optical properties, versatile synthesis, and ability to interact with antibiotics at low concentrations make them ideal for monitoring antibiotic pollution. Traditional methods like HPLC, HPTLC, UV-Vis, and FT-IR face challenges related to sampling, preparation, analysis time, and cost. CDs overcome these issues by converting nonfluorescent substances into fluorescent ones, enabling an alternative sensing mechanism. This review highlights the potential of CD-based sensors for measuring a broad range of antibiotics, including TC, doxycycline and ciprofloxacin. Despite their considerable promise, CD-based detection methods require further refinement. Furthermore, this review has discussed the various mechanisms governing the interactions between CDs and quencher materials, including FRET, IFE, and static quenching, highlighting how these interactions lead to the attenuation of CD fluorescence. Future research should focus on improving their selectivity and specificity, particularly in distinguishing between structurally similar antibiotics. Additionally, exploring the integration of CD-based detection with other remediation techniques, such as photocatalysis or advanced oxidation processes, could enhance the overall approach to addressing antibiotic contamination. Overall, CD-based fluorescence detection shows significant potential as an effective tool for real-time monitoring and controlling antibiotic levels in aquatic environments. As research progresses, CD-based sensors could play a crucial role in protecting public health and the environment from the impacts of antibiotic contamination.

Conflicts of interest

The authors declare no conflict of interest.

Data availability

All data generated or analyzed during this study are included in this published article.

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