

Review

Illuminating Pollutants: The Role of Carbon Dots in Environmental Sensing

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Abstract

The pursuit of cleaner environments and healthier ecosystems has driven the development of innovative strategies for detecting and mitigating toxic pollutants. Among emerging nanomaterials, carbon dots (CDs) have gained prominence due to their low toxicity, excellent biocompatibility, high fluorescence efficiency, and environmental sustainability. This review critically analyzes the transformative role of CDs in environmental sensing and remediation. Highlighting their versatile applications, including bioimaging, photocatalysis, and sensitive biochemical sensing, we examine how CDs support the next generation of pollutant detection and degradation technologies, such as contaminant adsorption, membrane filtration, and photocatalytic breakdown. Furthermore, we discuss advances in sensor architectures integrating CDs and outline pathways for their expanded use in environmental monitoring. By mapping the intersection of nanotechnology, environmental science, and sensor innovation, this review anticipates future developments that could redefine pollution control through the strategic deployment of carbon dots.

Keywords: carbon dots; environmental sensing; pollutant remediation; nanotechnology; photocatalysis; sensor technologies



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1. Introduction

The rapid rate of urbanization has increased environmental issues, raising urgent concerns regarding the escalation of atmospheric hazardous pollutants [1]. In response, global initiatives are increasingly focused on mitigating pollution and safeguarding human health [2]. Addressing these complex issues demands innovative strategies, among which nanomaterials have emerged as attractive alternatives owing to their distinctive physicochemical features and multifunctional capabilities [3]. A broad array of nanomaterials, such as metallic nanoparticles, transition metal dichalcogenides, metal–organic frameworks, and carbon-based nanomaterials have demonstrated notable success in addressing environmental pollution, remediation initiatives, and energy-related challenges [4,5]. Among these, carbon-based nanomaterials, including graphene oxide, pristine graphene, carbon nanotubes, and fullerene, have garnered particular attention for their exceptional features, including elevated specific surface area, remarkable water stability, and considerable pore volume, making them highly attractive for environmental applications [6]. These materials have been extensively utilized in diverse domains such as environmental sensing, adsorptive pollutant removal, energy conversion and storage, catalytic degradation, and membrane-assisted separation. In recent years, carbon dots (CDs), a novel category of

carbon-based nanomaterials, have emerged as a primary objective in environmental research due to their unique structural, optical, and surface properties [7]. CDs exhibit a wide range of advantageous characteristics, including diverse optical properties such as broad absorption spectra, strong and stable fluorescence, tunable photoluminescence, and outstanding optoelectronic performance [8]; versatile physicochemical features stemming from diverse synthesis methods and precursors, characterized by abundant surface functional groups, excellent aqueous dispersibility, enhanced electron donor-acceptor behavior, and high surface-to-volume ratio; and intrinsic attributes of low toxicity, high biocompatibility, environmental sustainability, and economic efficiency [9]. These multifaceted qualities empower CDs to act as highly effective agents in environmental applications, including pollutant sensing, contaminant extraction, integration into water treatment membranes, and antimicrobial activity against pathogenic bacteria [10].

Moreover, CDs have emerged as pivotal players in both the photodegradation of persistent organic contaminants and the ultra-sensitive detection of heavy metal ions—broadening their impact across wastewater treatment and biomedical diagnostics. As nanotechnology continues to evolve and converge across disciplines, the role of CDs is poised to expand dramatically, potentially reshaping the future of environmental monitoring and remediation [11]. This review offers a critical exploration of the expanding frontier of CD-based technologies, unveiling their unique physicochemical properties and versatile functionalities. From trace contaminant detection and adsorptive removal to membrane-assisted separations, catalytic degradation, and antimicrobial action, we chart the multifaceted applications of CDs while addressing key technological challenges and research frontiers. By offering a comprehensive synthesis, this review aspires to illuminate transformative pathways for the strategic integration of CDs driving forward the next generation of sustainable environmental solutions.

2. Importance of Pollutant Sensing in the Present Scenario

The accelerating pace of development and industrialization has profoundly reshaped our environment, thrusting pollution control into the heart of global sustainability efforts (Figure 1). As urban populations swell and resource demands intensify, emissions into the air, water, and soil have surged, fueling a cascade of environmental and public health crises, including infectious outbreaks, respiratory illnesses, and long-term chronic conditions [12]. Among the array of environmental pollutants, heavy metals stand out as particularly insidious threats. Their persistence, high toxicity, and tendency to biomagnify through food chains pose grave risks to both ecological integrity and human well-being [13]. In this rapidly evolving and increasingly complex environmental landscape, the ability to detect pollutants early, sensitively, and accurately is no longer optional; it is an imperative for planetary health and human survival. From industrial discharge and vehicular emissions to domestic waste, a myriad of sources fuel environmental degradation, manifesting in phenomena such as acid rain, intensified greenhouse gas effects, and ozone depletion [14]. These disruptions not only destabilize vital natural systems but also elevate global health vulnerabilities and jeopardize food security on an unprecedented scale.

Therefore, the development and deployment of effective pollutant-sensing technologies are indispensable for real-time environmental monitoring, predictive risk assessment, and the timely initiation of remediation strategies. Robust sensing systems not only facilitate a deeper understanding of pollutant dynamics but also empower policymakers, researchers, and communities to implement evidence-based interventions for a sustainable future. Recent technological innovations have dramatically enhanced pollutant detection capabilities, offering unprecedented sensitivity, selectivity, and adaptability across diverse environmental matrices. In air quality monitoring, the development of solid electrolyte

sensors has enabled the precise detection of critical pollutants such as CO_2 , NO_2 , NO , and SO_2 at trace concentrations [15]. These gases are closely associated with respiratory illnesses, cardiovascular diseases, and ecosystem degradation, emphasizing the urgent need for their early detection to inform public health strategies and policy interventions [16]. In parallel, substantial advancements have been made in the sensing of heavy metals, where sophisticated sensors now permit the detection of ions like Cu^{2+} , Co^{2+} , and Ni^{2+} at exceptionally low levels [17]. The monitoring of toxic metals such as Pb^{2+} and Cr^{2+} in drinking water is of particular concern, given their potent neurotoxic and carcinogenic effects even at minute concentrations [18]. These capabilities are crucial, especially in regions increasingly vulnerable to groundwater contamination driven by industrial effluents, mining operations, and intensive agricultural practices.

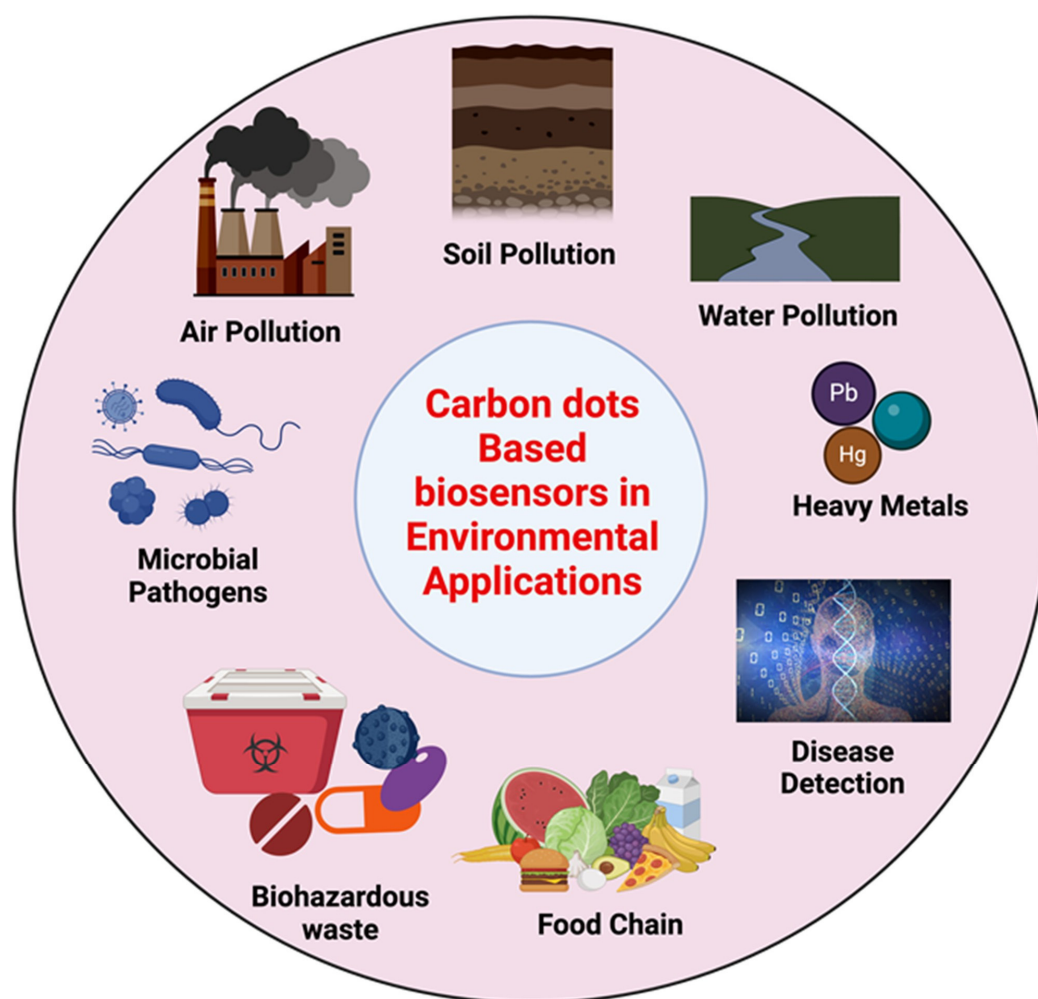


Figure 1. Schematic representation of CD-based biosensors for environmental pollutant detection and monitoring.

Nanotechnology has revolutionized water pollutant sensing, offering transformative tools for real-time and cost-effective environmental monitoring. Gold nanoparticles (AuNPs), for instance, have been effectively incorporated into colorimetric assays for the detection of metallic ions, enabling rapid, visual, and low-cost analysis. Functionalization with biomolecules such as cysteine has further broadened their applications, allowing the sensitive detection of hazardous explosives like trinitrotoluene (TNT), thus enhancing efforts to maintain drinking water safety and preserve aquatic ecosystem integrity (Kasonga, et al.) [19]. Beyond freshwater systems, escalating anthropogenic pressures on marine environments have necessitated the deployment of advanced sensing technologies.

Pollution from agricultural runoff, industrial discharge, and maritime activities has led to significant biodiversity losses and ecosystem imbalances [20]. Industrial contaminants have been implicated in developmental abnormalities, reproductive failures, and neurotoxic effects among marine organisms, with cascading consequences for food security and human health via seafood consumption. Alarming, bioaccumulation of marine toxins can induce severe neurological impairments in humans, including memory loss and paralysis [21].

In the face of mounting environmental threats, the emergence of innovative biosensor platforms and advanced chemical sensing technologies marks a transformative leap in our ability to detect and respond to pollutants with unprecedented speed and accuracy. Designed for real-time, on-site deployment in complex environmental matrices, these next-generation sensing systems overcome the limitations of traditional monitoring tools through their enhanced sensitivity, portability, and operational simplicity [22]. Beyond mere detection, they serve as the backbone of early warning systems, empowering proactive environmental risk assessment, rapid response, and informed decision making. As such, pollutant sensing has evolved far beyond a laboratory pursuit, establishing itself as a strategic instrument for driving sustainable development, fortifying ecological resilience, and safeguarding the health of both current and future generations.

3. Existing Sensors in Pollutant Sensing and Their Limitations

The creation of unique, sensitive, and fast-detection sensors is essential in various domains, including industry, medicine, space exploration, and environmental monitoring [23]. Harmful gases such as SO₂, CH₄, NH₃, and CO pose significant risks to both ecosystem and human health, necessitating their detection at parts-per-million (ppm) levels, often below established exposure limits. In response, various types of sensors have been engineered to detect specific atmospheric gases with enhanced precision and reliability [24]. For practical deployment, these sensors must exhibit rapid responsiveness, high stability, and selective specificity for target analytes, making them indispensable tools for ensuring safety and sustainability across sectors.

3.1. Metal-Based Sensors

Metal-based sensors are predominantly designed for methane detection, which is critically important because methane can become explosive when its concentration in air reaches 5–15% by volume [25]. However, traditional metal-based sensors often suffer from high energy consumption and the need for elevated operational temperatures, rendering them less practical for certain portable or low-energy applications [26]. Recent advances in nanoscale semiconducting metal oxides (SMOs) have led to sensors functionalized with dopants to finely tune their chemiresistive behavior and crystalline properties. These next-generation sensors offer several benefits, such as portability and ease of handling, and effectively detect pollutants at lower temperatures with remarkable sensitivity, selectivity, and durability. Hybrid SMO sensors, like CuO-ZnO networks at a 4:1 ratio, exhibit enhanced gas-sensing responses with sensitivity threefold greater than pure CuO and sixfold greater than pure ZnO for H₂S detection [27]. Similarly, nanostructured metal oxide semiconductors (NMOs) exhibit enhanced structural and morphological features, yielding high reliability and precision in detecting gases like NO₂ [28]. Tin oxide (SnO₂) remains a material of choice for air pollutant detection due to its enhanced sensitivity at low operational temperatures and economic efficiency [29]. ZnO nanorods have also shown impressive sensitivity toward NH₃ across a wide temperature range, rendering them strong candidates for environmental monitoring applications [30].

3.2. Carbon Nanotube (CNT)-Based Sensors

Carbon nanotube (CNT)-based sensors represent another revolutionary advancement in pollutant detection technologies. Operating efficiently at room temperature, these sensors are esteemed for their remarkably high surface-area-to-volume ratios, which enhance molecular interactions and improve sensing precision [31]. Gas molecules interacting with CNTs induce charge transfer processes that alter the electrical conductivity of the nanotubes, thus enabling highly sensitive and fast detection [32]. Polyaniline-based composites utilizing multi-walled carbon nanotubes (MWCNTs) have demonstrated remarkable success in identifying a diverse range of hazardous gases with high sensitivity and specificity [33]. Functionalized MWCNTs have also been implemented in the development of thin-film sensors for detecting bisphenol A (BPA), achieving extremely low detection limits and showcasing their versatility in environmental sensing [34].

Single-walled (SWCNTs) and multi-walled (MWCNTs) carbon nanotubes have unique benefits: SWCNTs provide higher pore volume and electrical conductivity, while MWCNTs offer better dispersibility [35]. Notably, CNTs can be directly employed in sensor fabrication, such as in nano-Cox sensors for volatile organic compound (VOC) detection, eliminating the need for extensive surface modifications [34]. The biocompatibility of CNTs with biological entities such as DNA, aptamers, and proteins significantly expands their potential across various biosensing platforms [36]. Moreover, incorporating single-walled carbon nanotubes (SWCNTs) into structures like mesoporous silica enhances electrical conductivity, thereby improving their performance in advanced sensing devices [37]. Additionally, innovative screen-printed CNT-based chemical sensors have been developed that can identify NH_3 concentrations as minimal as 5 ppm with high reliability. Wang and colleagues synthesized MWCNTs using plasma-enhanced microwave chemical vapor deposition (CVD), employing Ni as a catalyst, and developed detectors able to sense ammonia gas in the range of 5–200 ppm. Overall, carbon nanotubes offer distinctive multifunctional characteristics including superior chemical stability, enhanced electrical properties, and a high surface-to-volume ratio that make them ideal for monitoring environmental and human health hazards (Figure 2).

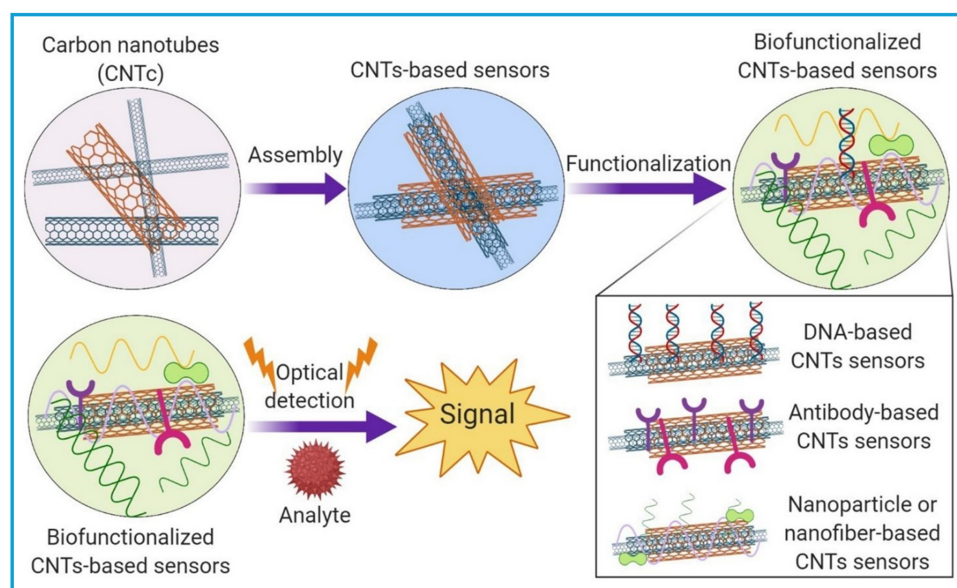


Figure 2. Schematic illustration of biofunctionalized carbon-nanotube-based sensors to monitor human and environmental health. Reprinted from Ref. [38]. Copyright (2019) with permission from Elsevier.

3.3. Chemical Sensors: Advancements

At the intersection of nanoscience and innovation, chemical nanosensors have ignited a transformative shift in detection technologies. By tapping into the extraordinary chemical reactivity and quantum-scale phenomena unique to the nanoscale, these sensors transcend conventional limitations, delivering remarkable sensitivity, unparalleled selectivity, and adaptability across environmental, biomedical, and industrial domains. Whether monitoring toxins in water, tracking pathogens in clinical settings, or detecting trace chemicals in the atmosphere, nanosensors stand as sentinels of a smarter, safer, and more sustainable future [39].

3.4. Electrochemical-Based Sensors

Electrochemical sensors function by translating chemical information (such as concentration of a specific analyte) into an electrical signal. The construction of these sensors involves a variety of electrode materials, such as gold electrodes (AuE), glassy carbon electrodes (GCE), indium tin oxide electrodes (ITO), reduced graphene oxide electrodes (ERGO), screen-printed electrodes (SPE), and sensors utilizing gallium oxide nanoparticles [40,41]. Their high sensitivity, low detection limits, and real-time detection capabilities make them widely used across disciplines.

3.5. Voltammetric Sensors

Among electrochemical sensors, voltammetric sensors are extensively employed. They quantify the current response as a function of an applied potential and are pivotal in environmental pollutant detection [42,43]. Frequently used techniques include differential pulse voltammetry (DPV) and cyclic voltammetry (CV) [44]. Glassy carbon electrodes (GCEs) serve as a highly modifiable platform, often enhanced with nanomaterials for improved performance [45]. Recent innovations include the development of nanocomposite-modified electrodes, such as porous graphene (PGR) calcium lignosulfonate (CLS) composites, enabling the simultaneous and highly sensitive detection of multiple heavy metals. For instance, Keerthana, et al. [46] fabricated a sensor based on a composite of aminothiazole (AT) and carbon quantum dots (CQDs) coated onto carbon fiber paper (CQD-AT/C*FP), achieving extremely low limits of detection (LOD) for Pb(II) and Hg(II) at 3.0 pM and 6.2 pM, respectively, across a wide linear detection range (0.6×10^{-11} – 160×10^{-6} M), and absorbing hazardous organic chemicals [47,48]. Moreover, enhancements using ferrocene-derivative composites and hydrophilic ionic liquids have expanded the electrochemical sensing capabilities, offering greater stability and electrocatalytic activity [49,50].

3.6. Amperometric Sensors

Amperometric sensors quantify the current generated from the electrochemical oxidation or reduction of an analyte at an appropriate potential [51,52]. Typically, these systems employ Ag/AgCl as the reference electrode and platinum as the working electrode. The resulting current, when plotted against time, is directly proportional to the concentration of the analyte [53]. Amperometric biosensors have demonstrated high efficacy in pathogen detection. For instance, Altintas et al. [54] developed an amperometric sensor for *E. coli* detection by immobilizing biorecognition elements on screen-printed interdigitated microelectrodes. Similarly, Kumar et al. [55] enhanced biosensing platforms by integrating bifunctional glucose oxidase polydopamine-based nanocomposites with Prussian-blue-modified electrodes. Another exemplary system, a TiO₂-CNT-Pt nanohybrid sensor, exhibited outstanding H₂O₂ detection sensitivity ($120 \mu\text{A mM}^{-1} \text{cm}^{-2}$) and a low LOD (<5 μM).

3.7. Potentiometric Sensors

These sensors determine analyte concentration by measuring the potential difference between a reference and a working electrode without drawing significant current. These include coated wire electrodes, ion-selective electrodes, and ion-selective field-effect transistors [56]. Potentiometric systems are crucial for detecting ions such as H^+ , NH_4^+ , and OH^- , as well as biomolecules and pollutants [57]. Advances include the integration of carboxylated multiwalled carbon nanotubes for enhanced selectivity [58] and novel sensing techniques such as the layer-by-layer assembly of poly (diallyldimethylammonium chloride) and aptamers for bisphenol A (BPA) detection [59]. Furthermore, potentiometric gas sensors, capable of operating at high temperatures (450–900 °C), have been deployed to monitor pollutants like NO_x , CO, and H_2 from vehicular emissions. A notable innovation involved a hydrogen sensor with a proton-conducting graphene oxide membrane and a $WO_3@rGO$ composite, demonstrating an impressive response at ambient conditions with an LOD of ~11 ppm for H_2 [60].

3.8. Optical Sensors

Optical sensors provide non-invasive, highly sensitive, and real-time approaches to chemical detection by monitoring changes in light properties such as intensity, phase, polarization, or wavelength when an analyte interacts with a sensing element [61]. These sensors are particularly valued for their ability to deliver rapid, label-free, and remote measurements with minimal sample disturbance, making them ideal for multiple applications ranging from environmental monitoring to biomedical diagnostics. Optical sensing technologies encompass several modalities, including fluorescence-based sensors, surface plasmon resonance sensors, fiber-optic sensors, and colorimetric sensors, each offering unique benefits depending on the specific analyte and detection environment.

3.9. Fluorescence Sensors

Fluorescence sensors utilize the emission properties of fluorophores to detect target molecules. Enzyme-based systems, such as glucose-oxidase-mediated glucose sensors, offer high selectivity [62], while non-enzymatic strategies using boronic acid groups and fluorescence resonance energy transfer (FRET) mechanisms have broadened sensor designs. Gold nanoparticles (AuNPs) are often employed as fluorescence quenchers due to their strong extinction properties [63].

3.10. Surface Plasmon Resonance (SPR) Sensors

SPR sensors detect refractive index changes at a metal surface due to analyte binding, providing real-time kinetic data on molecular interactions [64]. They have been employed for biomolecular analysis, including human IgG detection using silver nanocubes and carboxyl-functionalized graphene oxide, and for pollutant detection, such as diclofenac, using imprinted polymer films [65]. SPR-based methods have also extended into food quality monitoring, e.g., detecting spoilage-related microbial populations in meat [66].

3.11. CD-Based Antigen–Antibody Biosensors

CDs offer promising platforms for antigen–antibody biosensing, with rich surface functionalities enabling controlled antibody immobilization. CDs have been incorporated into both electrochemical and optical biosensors for detecting vitamins, tumor markers (alpha-fetoprotein, carcinoembryonic antigen), and infectious disease biomarkers [67]. Notably, CD-based biosensors have demonstrated applicability in the detection of viruses such as Japanese encephalitis, Zika, dengue, and HSV-1 [68]. Examples include an FL-IRA dual-mode biosensor for carcinoembryonic antigen (CEA) that provides high sensitivity

and excellent recovery in serum samples. Similarly, Pourmadadi et al. [69] developed an aptamer-based electrochemical sensor using Au/carbon quantum dots for prostate-specific antigen (PSA) detection, achieving promising results. Existing sensor technologies, spanning electrochemical (voltammetric, amperometric, and potentiometric) and optical platforms (fluorescence, SPR, CD-based systems), play indispensable roles in pollutant monitoring, pathogen detection, and clinical diagnostics. Each sensor type brings distinct strengths: high sensitivity, selectivity, portability, or real-time analysis. Despite the promising potential of advanced sensors, challenges such as sensor fouling, limited operational stability, and matrix interferences persist, driving ongoing research efforts to address these issues. Future advancements in sensor technology are expected to focus on several key areas to fix these limitations. The integration of nanomaterials is anticipated to enhance selectivity and stability, enabling more reliable sensor performance.

Additionally, the development of multiplexed detection capabilities will allow for the simultaneous analysis of multiple analytes, increasing the efficiency and scope of sensor applications. Advances in point-of-care and in situ deployment are also a priority, aiming to simplify the sensor process with minimal sample preparation, which is crucial for real-time environmental monitoring and disease detection. Furthermore, the integration of artificial intelligence and machine learning is set to transform the interpretation of sensor data, making it smarter and more intuitive. These innovations are essential for improving environmental monitoring, enabling early disease detection, and ultimately ensuring global health and safety.

4. Modern Nanotechnologies for Sensing Pollutants

In the current environment, where industries and manufacturing processes have become highly modernized and technologically advanced, our environment faces unprecedented levels of contamination [70]. Pollutants are often found simultaneously in water, air, and soil at varying concentrations, creating complex environmental challenges [71]. Addressing these challenges demands sophisticated technologies capable of not only detecting and tracking pollutants but also facilitating their removal or neutralization. In this regard, nanotechnology offers transformative solutions, significantly enhancing our ability to monitor, manage, and restore environmental quality [72].

4.1. Nanotechnology for Clean Water

Water pollution remains one of the most pressing global issues, affecting around 1.1 billion people who do not have access to safe drinking water [73]. Although water covers around 71% of the Earth's surface, only about 0.3% is available as accessible freshwater for human consumption [74]. Growing demands, pollution, and climate change have further compounded the scarcity of clean water, making its provision an increasingly critical challenge [75]. Nanotechnology presents promising avenues for improving water quality through innovative applications such as separation and filtration, bioremediation, and disinfection [76]. Remediation, or the process of removing, reducing, or neutralizing harmful contaminants, is traditionally achieved through thermal, physicochemical, or biological methods [77]. However, conventional methods like chemical extraction, adsorption, and oxidation often prove costly, time consuming, and less efficient. Biological degradation, although environmentally friendly and cost-effective, tends to require extended periods to achieve the desired outcomes. Nanomaterials provide a cutting-edge alternative, offering upgraded affinity, selectivity, and capacity for binding heavy metals and various organic and inorganic pollutants. Their high surface-area-to-volume ratio, elevated reactivity, and efficient disposal potential make them highly effective in water treatment processes [78]. Various nanomaterials including carbon nanotubes, zeolites self-assembled monolayers on

mesoporous supports, biopolymers, and single-enzyme and zero-valent iron nanoparticles have demonstrated considerable potential for advanced water remediation [79].

Nanomaterials used in water treatment can be classified into three main functional groups, each playing a distinct role in addressing water pollution. First, nano-adsorbents are employed for capturing and removing pollutants from water, offering a highly efficient means of pollutant removal. Second, nanocatalysts are used to promote the chemical breakdown and degradation of contaminants, accelerating the purification process through enhanced catalytic reactions [80]. Lastly, nanomembranes are integral to wastewater treatment, providing efficient filtration and selective separation capabilities that help ensure cleaner water by targeting specific contaminants. The various functional roles highlight the adaptability and efficiency of nanomaterials in enhancing water treatment processes [81]. Figure 3 showcases different nanoparticles and their mechanisms for water purification. Nanomaterials disrupt bacterial membranes for water disinfection [82], while Fe_3O_4 /PMA-g-PVA magnetic nanocomposites enhance heavy metal ion adsorption by five times [83]. Graphene oxide–polysulfone composite membranes effectively separate dyes from contaminated water (Figure 4). Additionally, TiO_2 nanoparticles, activated by UV light, generate reactive free radicals to degrade organic pollutants and microorganisms in drinking water [84,85]. These nanoparticles offer diverse strategies, including membrane disruption, adsorption, filtration, and photocatalysis, for improving water purification.

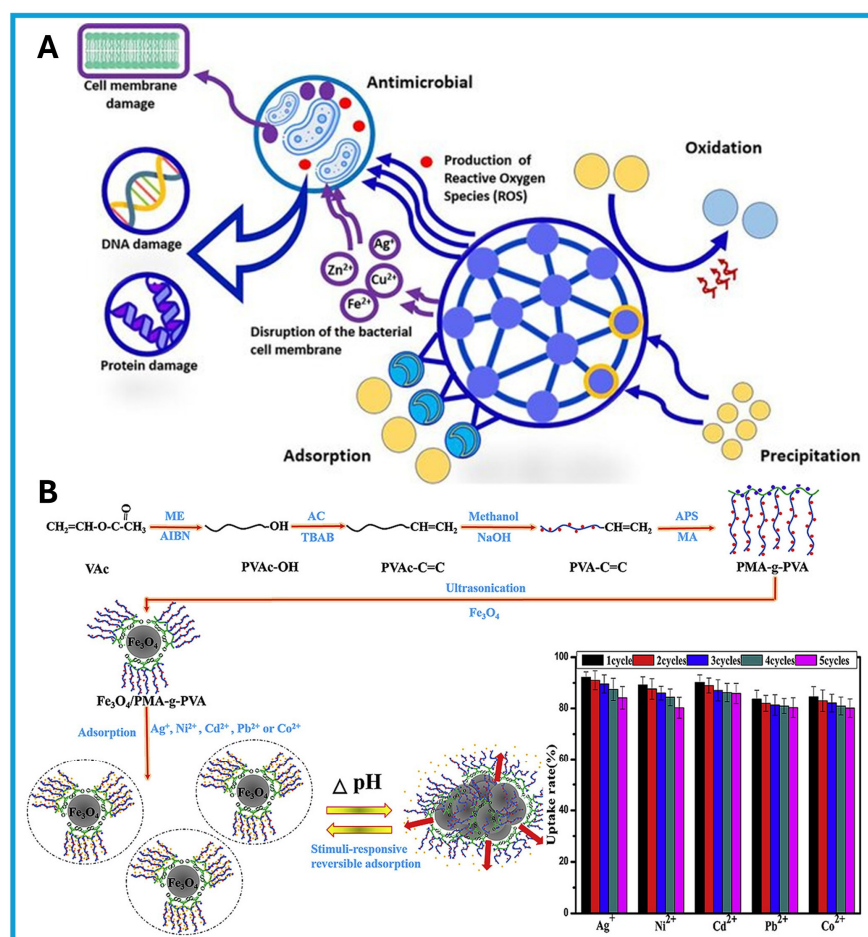


Figure 3. Different types of nanoparticles and their mechanisms for water purification: (A) disruption of bacterial membranes by nanomaterials for water disinfection; (B) linear polymer Fe_3O_4 /PMA-g-PVA nanocomposite-functionalized magnetic nanoparticles showing fivefold-enhanced adsorption of heavy metal ions ((A) reprinted from Ref. [82], Copyright (2022) with permission from Springer; (B) reprinted from Ref. [83], Copyright (2020) with permission from Elsevier).

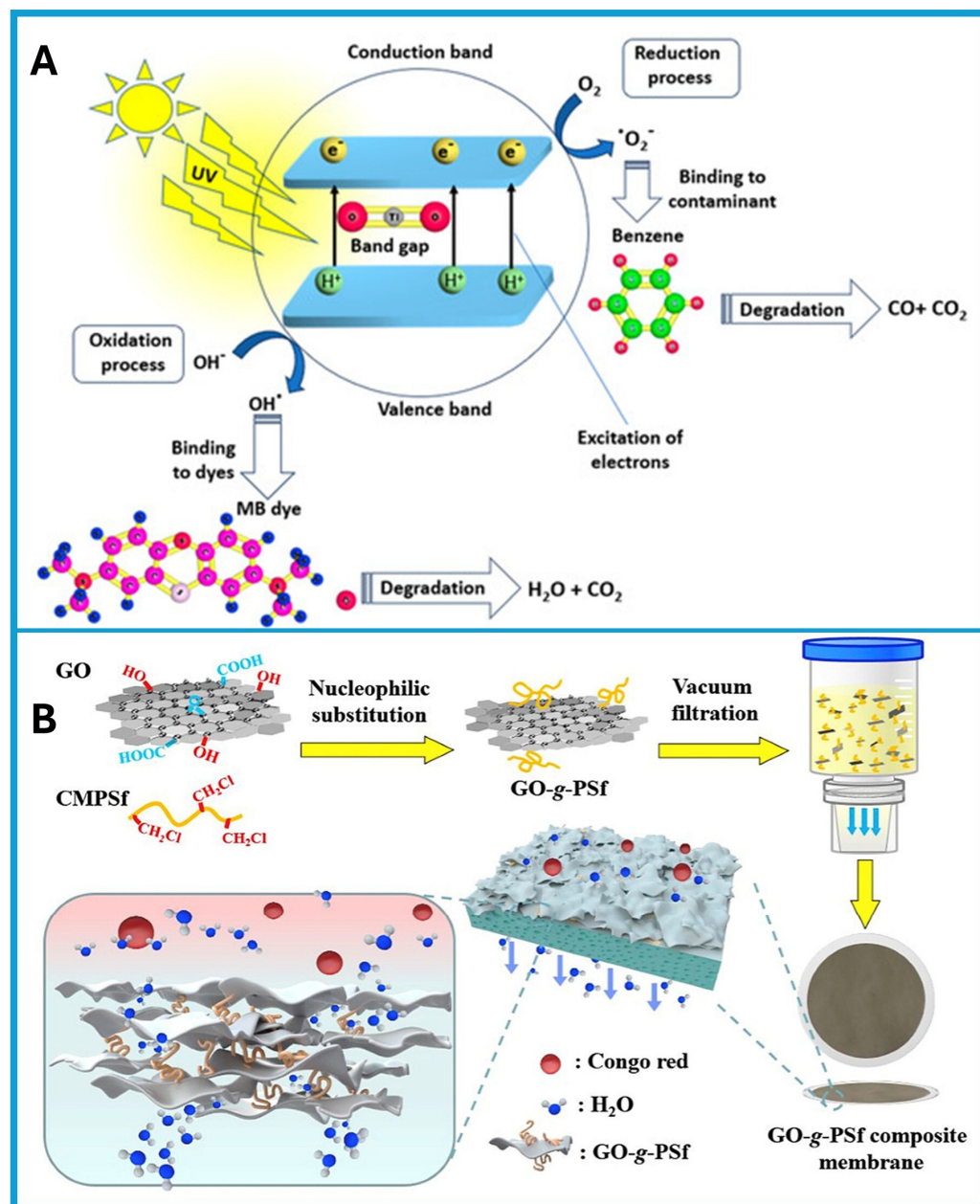


Figure 4. Mechanisms for water purification: (A) TiO₂ nanoparticles activated under ultraviolet (UV) light to generate reactive free radicals that degrade organic pollutants, microorganisms, and inorganic contaminants in drinking water; (B) polysulfone-grafted graphene oxide nanosheet composite membranes achieving effective dye separation from contaminated water ((A) reprinted from Ref. [84]; (B) reprinted from [85], Copyright (2020) with permission from Elsevier).

4.2. Nanoscale Zerovalent Iron (nZVI)

Nanoscale zerovalent iron has emerged as one of the most widely used agents for in situ environmental remediation due to its non-toxic nature, cost-effectiveness, ease of production, and strong reductive potential [86]. For over two decades, nZVI nanoparticles (10–100 nm in diameter) have been successfully deployed for the remediation of groundwater and wastewater contaminated with a wide range of organic and inorganic pollutants [87]. Structurally, nZVI consists of a metallic iron core surrounded by an oxide/hydroxide shell formed via surface oxidation. The iron core acts as the primary reducing agent, facilitating pollutant transformation through redox reactions that generate reactive species such as Fe(II), hydrogen, and iron oxides/hydroxides [88]. The mechanisms involved in pollu-

tant removal include adsorption, coprecipitation, complexation, and surface-mediated chemical reduction.

pH significantly influences the interfacial reactions and degradation kinetics. At acidic pH (~4), enhanced corrosion and dissolution of the passivation layer accelerate contaminant degradation, whereas at higher pH levels, the formation of ferrous hydroxide precipitates on the nZVI surface inhibits electron transfer and slows the reaction [89]. The reductive capacity of nZVI is attributed to its high standard reduction potential ($E^\circ \text{Fe}/\text{Fe}^{2+} \approx -0.447 \text{ V}$) [90], facilitating rapid electron transfer to pollutants, thereby stabilizing and immobilizing them within the aqueous system [91]. However, particle aggregation and limited mobility present challenges. Strategies such as clay-supported nZVI have been developed to enhance dispersibility and pollutant removal, for instance, in decolorizing dyes like methyl orange. Recently, oxidic-shell-free nZVI has demonstrated improved reactivity under anoxic conditions by effectively reducing arsenite III and arsenate V to elemental arsenic [90].

4.3. Bioactive Nanoparticles for Water Disinfection

Bioactive nanoparticles are at the forefront of next-generation water disinfection technologies, unleashing powerful antimicrobial effects through a symphony of synergistic mechanisms. Under photocatalytic activation, materials like titanium dioxide, zinc oxide, and fullerenes become dynamic agents of purification, generating reactive oxygen species that target, disrupt, and dismantle microbial cells and viral structures with extraordinary precision. This approach not only neutralizes biological threats but also paves the way for safer, cleaner, and more resilient water systems [92]. Additionally, many nanoparticles, including peptides, chitosan, carboxy fullerenes, carbon nanotubes, ZnO, and silver nanoparticles, directly disrupt bacterial cell membranes, compromising structural integrity and leading to cell death. Some nanoparticles, like chitosan, go further by inhibiting key enzymatic activities and obstructing DNA replication, thereby effectively neutralizing pathogenic threats. Moreover, silver and aqueous fullerene nanoparticles interfere with cellular energy transduction processes, further crippling microbial survival and proliferation [93].

Among the diverse spectrum of bioactive nanoparticles, TiO_2 nanoparticles stand out as particularly promising candidates for water disinfection applications. Their appeal lies in a combination of factors: exceptional chemical stability, inherent nontoxicity to humans, cost-effectiveness, and remarkable disinfection performance when activated under UV irradiation. TiO_2 nanoparticles not only facilitate rapid microbial inactivation but also degrade a broad spectrum of organic contaminants, offering dual benefits for comprehensive water purification. Their versatility and eco-friendly nature position TiO_2 -based nanomaterials at the forefront of next-generation water treatment technologies, addressing global challenges related to safe and sustainable water access [94].

4.4. Bimetallic Nanoparticles (BNPs) for Remediation

Bimetallic nanoparticles have emerged as effective tools for environmental remediation, owing to their superior catalytic and redox capabilities driven by the synergistic interactions between two distinct metals [95]. Typically composed of a reactive base metal, such as iron, paired with a noble metal catalyst like palladium, platinum, gold, or nickel, BNPs exhibit enhanced properties including improved magnetism, accelerated reduction and oxidation rates, and increased stability. A notable example is palladium–iron nanoparticles, which demonstrate remarkable efficiency in degrading soil and groundwater contaminants through dehalogenation reactions. The versatility and high reactivity of BNPs have positioned them as efficient, commercially viable solutions for pollutant re-

removal from aquatic environments, reflecting a promising advancement toward sustainable environmental cleanup technologies [96].

4.5. Semiconductor Nanoparticles for Remediation

Semiconductor nanoparticles, particularly titanium dioxide (TiO_2), have been extensively investigated for their ability to break down various organic pollutants, including plastics such as polystyrene and polyethylene, as well as agrochemicals like insecticides, herbicides, and pesticides [97]. Among these, TiO_2 nanotubes have shown significant promise in the photodegradation of persistent chlorinated organic compounds, offering an effective route for environmental detoxification. Recent innovations have shifted toward developing visible-light-active photocatalysts, such as nitrogen–fluorine co-doped TiO_2 , which exhibit superior degradation efficiency against endocrine-disrupting compounds like bisphenol A (BPA). These advancements not only expand the operational range of TiO_2 -based photocatalysts beyond ultraviolet light but also highlight their strong potential for practical, in situ environmental remediation applications [98].

4.6. Nanoadsorbents

Adsorption is an essential technique for fine removing organic and inorganic pollutants from water, and nanoadsorbents offer several advantages over conventional materials, including abundant active sites, high surface-to-volume ratio and enhanced reactivity [99]. Various classes of nanoadsorbents have been developed to address different types of contaminants, such as carbon materials (e.g., carbon nanotubes, graphene), polymeric nanoadsorbents, magnetic and non-magnetic metal oxide nanoparticles, and modified compounds like oxide composites and zeolites [100,101]. To maximize their sustainability and practical utility, nanoadsorbents should ideally be nontoxic, highly selective even at low pollutant concentrations, and regenerable for multiple reuse cycles [102]. According to Baruah, et al. [103], nanoadsorbents can be broadly classified into four major categories: (a) carbon nanoadsorbents, (b) metal nanoadsorbents, (c) polymer nanoadsorbents, and (d) zeolite nanoadsorbents, each offering unique benefits tailored to specific environmental remediation needs.

4.7. Nanomembranes

Nanomembranes have revolutionized water and wastewater treatment by offering major advantages over traditional reverse osmosis techniques, including reduced energy consumption and lower operational costs [104]. These advanced membranes are primarily divided into two main categories: thin-film nanocomposite and mixed-matrix membranes. Typically, nanomembranes are manufactured through interfacial polymerization over ultra-filtration substrates, a process that allows for fine-tuning of their structural and functional properties. The incorporation of nanoparticles such as nano-zeolites, nano-Ag, nano- TiO_2 , and carbon nanotubes (CNTs) significantly enhances the performance of these membranes by improving their permeability, selectivity, mechanical strength, and antimicrobial activity. Among these additives, nano-zeolites are particularly valued for their role in boosting membrane permeability without compromising rejection efficiency [105], making them a critical component in the advancement of next-generation water purification technologies.

4.8. Nanocatalyst

Nanocatalysts, a type of nanomaterial, are extensively used in several applications due to their significantly enhanced catalytic properties compared to their bulk counterparts. They have gained particular attention for water treatment and organic contaminant degradation. For instance, Fe_2O_3 nanoparticles (NPs) have been employed for methylene blue dye degradation, nano-nickel zinc ferrite catalysts for the degradation of 4-chlorophenol,

and platinum-nickel nanoalloys for catalytic water purification [106]. Among the various nanocatalysts, TiO_2 and ZnO nanoparticles exhibit strong photocatalytic activity, attributed to their wide bandgap energy of approximately 3.2 eV. Upon exposure to UV light, electrons in the valence band are excited to the conduction band, generating energized “holes” in the valence band that react with water or surface pollutants to produce highly reactive hydroxyl radicals, leading to pollutant degradation. However, a major limitation of TiO_2 is that its photocatalytic activity is restricted to UV light. This drawback can be overcome by doping TiO_2 with metals or nonmetals, which enhances its light absorption capabilities. Among dopants, anions like nitrogen are preferred for industrial applications due to their cost-effectiveness and feasibility. Moreover, doped TiO_2 nanoparticles have demonstrated potential in effectively inactivating bacteria in wastewater [107].

4.9. Nanotechnology for the Adsorption of Toxic Gases

Nanotechnology has emerged as a transformative approach for the adsorption and removal of toxic gases, leveraging the distinctive structural and physicochemical properties of nanomaterials to enhance adsorption, catalysis, and sensor performance. Materials such as carbon nanotubes (CNTs), graphene oxide (GO), ordered mesoporous carbons (OMCs), nanostructured boron-doped diamond (BDD), and cellulose acetate (CA) composites have been widely explored for these applications. For instance, CNTs decorated with gold nanoparticles have shown great promise in toxic gas remediation [108]. Structurally, CNTs are composed of graphene sheets rolled into cylindrical forms with a hexagonal carbon arrangement, enabling strong interactions with organic pollutants like dioxins, particularly through the robust binding between the dioxin’s benzene rings and the CNT surface [109]. Both single-walled and multi-walled carbon nanotubes demonstrate remarkable chemical stability and thermal resilience, making them ideal candidates for capturing a wide range of organic and inorganic contaminants [110].

The adsorption capacity of CNTs is largely determined by their pore structure and the density of surface functional groups, which can be further optimized through chemical or thermal modifications to enhance their performance. Advances in graphene-based nanomaterials have also provided new opportunities: for example, graphene oxide nanosheets (GONSs) offer multiple adsorption mechanisms due to their high surface area and abundant functional groups [111,112], while graphene oxide nanoparticles have been shown to significantly improve CO_2 adsorption by providing additional reactive sites on the GO framework [113]. These innovations illustrate how nanotechnology is paving the way for efficient, scalable, and selective gas adsorption strategies crucial for environmental protection. Figure 5 illustrates the diverse applications and mechanisms of graphene oxide (GO) nanoparticles in adsorption processes. The adsorption mechanisms of graphene oxide nanosheets (GONSs) highlight their ability to interact with contaminants through various physical and chemical interactions, essential for the effective removal of pollutants, as shown by Zhang et al. [112]. Additionally, the enhancement of CO_2 adsorption by graphene oxide nanoparticles is demonstrated, where the GO framework provides additional reactive sites, significantly improving the material’s capacity for carbon dioxide capture. This capability of GO, as discussed by Khumalo et al. [113], opens promising avenues for mitigating CO_2 emissions and addressing environmental challenges. Both studies underscore the versatility of graphene-oxide-based materials in advanced environmental applications, particularly in pollution control and carbon capture.

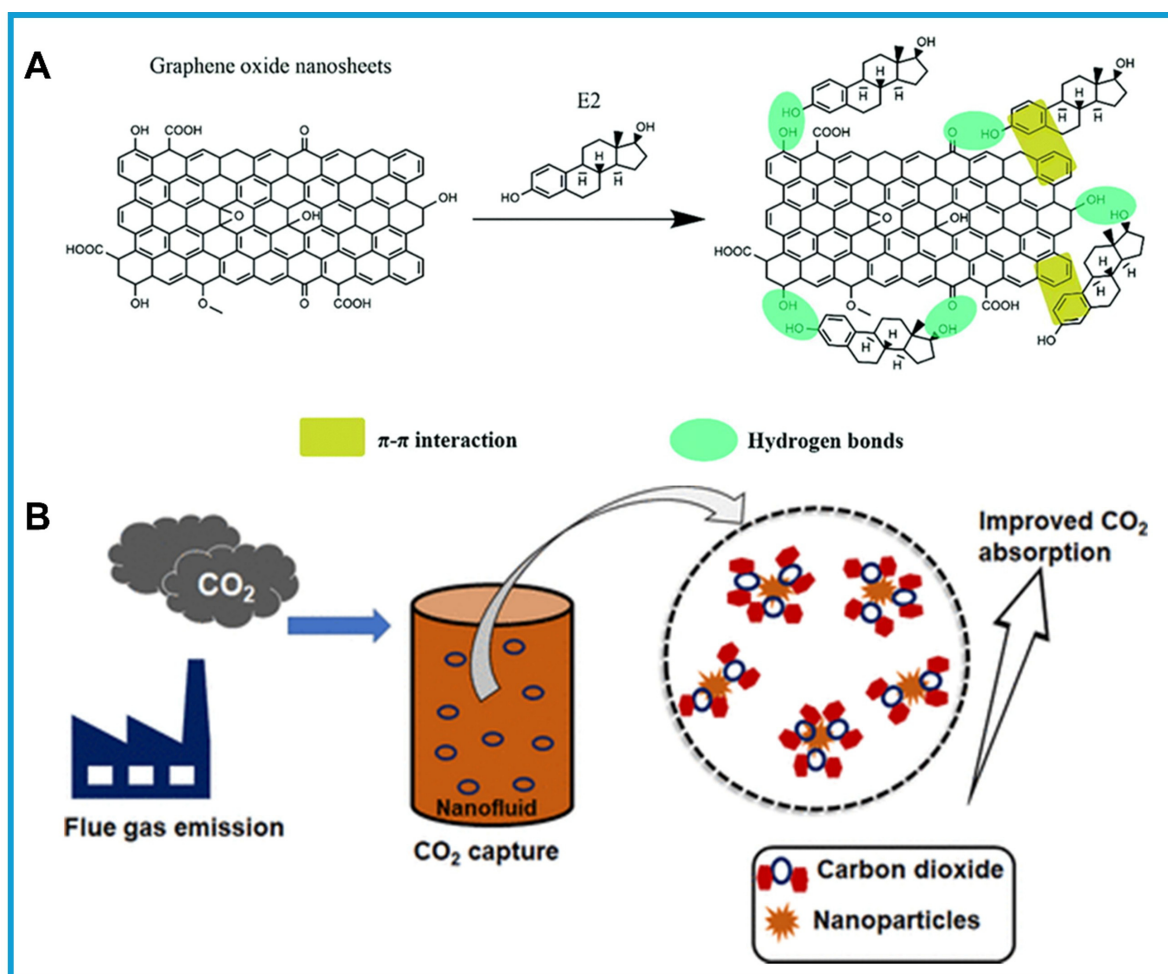


Figure 5. (A) Illustration of adsorption mechanisms of graphene oxide nanosheets (GONSs); (B) graphene oxide nanoparticles enhancing CO₂ adsorption by providing additional reactive sites on the GO framework ((A) reprinted from Ref. [114]. Copyright (2016) with permission from Elsevier; (B) reprinted from [113]).

4.10. Adsorption of Dioxin

Dioxins, a class of highly volatile and toxic polyhalogenated aromatic hydrocarbons, are structurally characterized by two benzene rings linked through two oxygen atoms. Their toxicity is heavily influenced by the degree of chlorination, with higher numbers of chlorine atoms generally correlating with increased harmful effects [115]. Among various dioxins, tetrachlorodibenzo-p-dioxin (TCDD) is particularly notorious for its severe impacts on human health, including immunotoxicity, endocrine disruption, and impaired fetal development [116]. Effective removal of dioxins from the environment is critical, and activated carbon has traditionally been exploited as an effective adsorbent due to its high bond energy when interacting with dioxin molecules, outperforming other materials like clay, alumina (α -Al₂O₃), and zeolites [117]. Recent advancements have revealed that carbon nanotubes (CNTs) present even greater potential for dioxin adsorption. Studies show that the interaction between dioxins and CNTs is almost three times stronger than with activated carbon [118]. This enhanced performance is primarily attributed to the unique curvature of CNT surfaces, which amplifies the contact forces between the dioxin molecules and the nanotube structure. The combination of high surface area, strong π - π interactions, and customizable surface properties positions CNTs as a highly promising material for the efficient capture and removal of persistent organic pollutants like dioxins from contaminated environments.

4.11. Adsorption of Nitrogen Oxides

The adsorption of nitrogen oxides (NO_x) plays a pivotal role in mitigating air pollution and protecting environmental and human health. Traditional adsorbents such as ion-exchanged zeolites, activated carbon, and FeOOH dispersed on activated carbon fibers have been widely utilized for NO_x removal, especially at low temperatures [119]. Among these, activated carbon stands out due to the presence of surface functional groups that significantly enhance its affinity for nitric oxide (NO) molecules [55]. More recently, carbon nanotubes have emerged as highly promising NO adsorbents, offering distinct advantages attributed to their unique structural features, tunable surface chemistry, and exceptional electronic properties [70]. When nitrogen oxide (NO) and oxygen (O_2) pass over CNT surfaces, NO undergoes oxidation to form nitrogen dioxide (NO_2), which is subsequently captured as nitrate species on the nanotube surface. This multi-step adsorption and oxidation process highlights the catalytic potential of CNTs in environmental remediation strategies. Interestingly, while CNTs also exhibit some adsorption capacity for sulfur dioxide (SO_2), their efficiency is significantly lower compared to NO_x , and their interaction with carbon dioxide (CO_2) remains minimal. These findings underline the selective affinity of CNTs for nitrogen oxides, positioning them as advanced materials for next-generation air purification technologies.

5. Importance of CDs in Pollutant Sensing

CDs, a novel class of carbon-based nanomaterials, have emerged as highly promising agents for environmental protection due to their unique optical, electronic, and surface-active properties [120]. Their tunable photoluminescence, abundant functional groups, high aqueous stability, and biocompatibility distinguish them from conventional nanomaterials [121]. Rather than merely reiterating the threats posed by pollutants, this section focuses on how CDs are transforming pollutant-sensing strategies, particularly for detecting trace levels of hazardous substances in complex environments [122].

CDs offer several practical advantages, such as simple, low-cost synthesis from a diverse range of precursors and flexible fabrication techniques, including electrochemical deposition, microwave-assisted synthesis, hydrothermal/solvothermal methods, and pyrolysis. Their surfaces are rich in functional groups like carbonyl, carboxyl, and amine groups, which enhance their interaction with biological molecules and environmental pollutants. Consequently, CDs are being increasingly applied in pollutant detection, environmental remediation, and water purification systems [123].

Beyond environmental applications, the versatile surface chemistry of CDs allows easy functionalization for a wide range of biomedical uses, including drug and gene delivery, biosensing, bioimaging, and bacterial labeling. Furthermore, their integration with molecularly imprinted polymers has significantly enhanced their sensitivity and selectivity toward specific contaminants, broadening their potential for next-generation pollutant-sensing technologies [11].

5.1. Unique Optical and Physicochemical Properties of Carbon Dots (CDs) Relevant to Pollutant Sensing

CDs exhibit unique optical and physicochemical properties that make them highly effective for pollutant sensing and environmental applications. They show strong absorption in the 260–320 nm range, with shifts in absorption between 280–390 nm often indicating structural changes. This fluorescence capability is the cornerstone of their utility in sensing and imaging, allowing for sensitive detection of environmental pollutants [9]. Furthermore, the presence of oxygen-containing functional groups ($-\text{O}$, $-\text{OH}$) enhances their charge transfer ability, which, combined with their semiconductor-like behavior, promotes the

photocatalytic degradation of pollutants [124]. These attributes make CDs valuable for a range of environmental monitoring applications.

In addition to their optical and charge transfer properties, CDs demonstrate remarkable chemical stability, strong electrocatalytic activity, and high photoluminescent quantum yields. Their excellent aqueous stability and chemical inertness further contribute to their versatility across various nanotechnological and environmental platforms. The unique properties of CDs simplify the detection and interaction with a diverse range of environmental pollutants, such as pathogens, heavy metal ions, pesticides, and small organic molecules [125,126]. Their ability to efficiently sense and degrade contaminants positions CDs as a promising tool in environmental protection and pollution control.

5.2. Detection of Pathogens Using CDs

The efficient and rapid identification of foodborne bacterial pathogens is crucial for reducing the global health burden of foodborne diseases, particularly in regions plagued by poor sanitation, improper food storage, and weak regulatory frameworks. With these challenges in mind, there is an urgent need for effective and rapid biosensors to ensure food safety and public health [127]. CDs have shown great potential in pathogen detection due to their distinctive characteristics and adaptability as biosensing agents. For instance, antibody-labeled CDs have been successfully incorporated into amperometric immunosensors for the detection of pathogens like *Salmonella* [128].

Moreover, CDs have demonstrated strong interactions with bacteria such as *Escherichia coli* and *Staphylococcus aureus*, resulting in fluorescence quenching signals that provide an effective means for pathogen detection [129]. Additionally, functionalized CQD sensor arrays, when integrated with machine learning algorithms, offer a sophisticated and highly sensitive alternative to traditional diagnostic methods. This combination allows for rapid and accurate pathogen detection, marking a significant advancement in biosensing technology and paving the way for more efficient and accessible diagnostic tools [130]. While CDs are extensively explored for their fluorescence-based sensing capabilities, their multifunctionality also extends to pollutant remediation, particularly through photocatalytic degradation. Although sensing and remediation serve distinct objectives—detection versus elimination—they are interconnected within an integrated environmental strategy. In the subsequent section, we shift focus from pollutant detection to pollutant degradation, highlighting the photocatalytic potential of CDs in breaking down environmental contaminants.

5.3. CDs for Pollutant Degradation

In addition to their sensing applications, CDs have gained recognition in environmental remediation, owing to their remarkable photocatalytic activity. Their performance often exceeds conventional photocatalysts such as zinc oxide and titanium dioxide. Attributes such as high aqueous solubility, excellent chemical stability, strong photoluminescence, and cost efficiency collectively render CDs highly suitable for sustainable pollutant degradation strategies [131]. The unique optoelectronic behavior of CDs enables them to serve diverse photocatalytic roles—ranging from electron shuttling and spectral conversion to acting as standalone catalysts, photosensitizers, and core catalytic centers. These functionalities collectively allow CDs to engage with and degrade a broad spectrum of chemical contaminants in air and water.

Experimental studies further demonstrate enhanced degradation efficacy when CDs are hybridized with other nanomaterials. For example, nitrogen-doped CDs (NCDs) embedded in zinc oxide nanoparticles (ZnO NPs) achieved nearly 95% degradation of methyl orange dye under UV light within 50 min [132]. This remediation-oriented use of CDs

complements their sensing capabilities, suggesting their dual applicability in smart environmental systems capable of both detecting and neutralizing pollutants. Additionally, nickel oxide (NiO) nanocomposites demonstrated efficient degradation of phenolic pollutants like 3-aminophenol and Safranin-O dye. Furthermore, CDs combined with tungsten trioxide (WO_3) exhibited near-complete degradation ($\sim 98\%$) of dyes such as methylene blue and malachite green, along with enhanced antibacterial activity in water [133]. These findings illustrate the versatility of CDs in addressing both pollutant degradation and microbial contamination, positioning them as key materials in the development of next-generation photocatalysts and sustainable environmental remediation technologies. Their unique properties and adaptability for functionalization make them indispensable tools for advancing eco-friendly solutions in environmental management. Figure 6 illustrates the synthesis of N-CQDs and the CQDs@NiO nanocomposite, along with its photocatalytic mechanism for degrading SO/3-AP dye under sunlight. While the degradative abilities of CDs highlight their role in active remediation, their application in pollutant detection remains equally critical. The following section explores recent advancements in CD-based sensor design for trace pollutant detection.

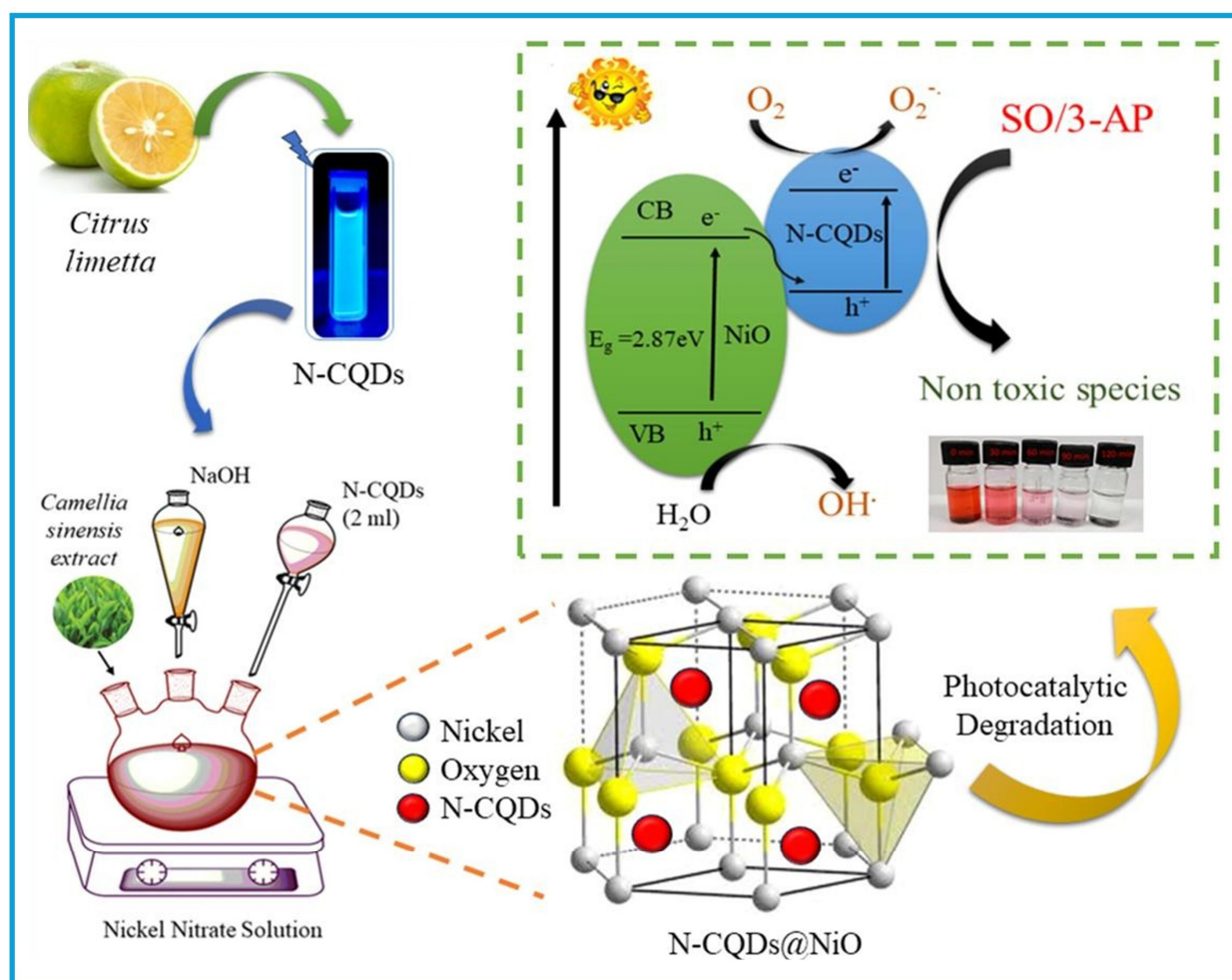


Figure 6. Synthesis of N-CQDs, and CQDs@NiO nanocomposite with photocatalytic mechanism for degrading SO/3-AP dye under sunlight (reproduced from Ref. [134], Copyright (2024) with permission from Elsevier).

Detection of heavy metals: Heavy metal detection has become a major need due to the high toxicity and lengthy persistence of these metals in the environment [135]. Metals are detected with the help of a biosensor made of CDs. Due to their high sensitivity, yeast

biosensors are widely used for heavy metal detection, with advantages such as time and cost effectiveness, sensitivity, reproducibility [136], and scalability to high-throughput formats. Since yeasts have less demanding growth conditions than humans, yeast biosensors may be adaptable to portable devices for in-field research [137].

6. Recent Trends in Developing Pollutant-Sensing CDs

Certain heavy metals such as iron, copper, lead, manganese, and zinc are nutritionally essential for a healthy life, but only in limited amounts [11,138]. Heavy metal, on the other hand, has a strong proclivity for forming complexes [139]. Particularly with nitrogen-containing ligands from biological matter, sulfur, as well as oxygen [140]. Consequently, improvements in the molecular structure of proteins, hydrogen bond breaking, or inhibition of enzyme activity are possible [141]. These phenomena, as well as others, may explain how heavy metals have carcinogenic and toxicological effects, such as those that impact the central nervous system (Hg^{2+} , Pb^{2+} , etc.).

There is an ongoing effort to establish trace heavy metal sensing strategies for early emission detection in a variety of environments [142]. As a result, the current aim is to provide a comprehensive overview of detectors and detection of heavy metals. The various synthetic methods for preparing CDs can be categorized into two main approaches: top-down and bottom-up. Techniques such as electrochemical oxidation, laser ablation, hydrothermal, solvothermal, ultrasonication, microwave, and other techniques are available [143]. Similarly, CDs can be made from a variety of sources, including bulk carbonaceous materials, organic molecules, and nanoparticles occurring in the synthetic phase using a top-down approach [144]. In contrast, bottom-up synthesis of CDs is also possible through the carbonization or pyrolysis of small organic compounds [145]. The bottom-up method is greener, cleaner, quicker, and easier to make at a large scale at a low cost [146]. A wide variety of renewable and natural materials have been explored as sources for CDs, marking a significant shift toward greener, more sustainable alternatives to fossil-based resources. Among these, CDs derived from natural biomass materials have garnered significant attention due to their non-toxic and biocompatible properties, which align with the principles of green chemistry. Liu et al. [147] describe the preparation of biomass-derived CDs and their promising applications in chemical and biological research. Similarly, Feng and Qian [148] detailed the synthesis of CDs from various natural sources, emphasizing their use in chemosensors and biosensors. A notable advancement in recent years has been the development of CD-based sensors for detecting heavy metals in water, as highlighted by Xu et al. [149]. Their work, spanning from 2017 to the present, illustrates the growing application of CDs in sensing technologies (Table 1).

Table 1. Plant-part-derived CDs and their sensing applications.

S. No.	Compounds	Source	Sensing Application	LOD	References
1	CDs	Radish	Cu^{2+} and acetic acid vapors in water samples	0.16 μM and 6.8 μM	[150]
2	CDs	Rice residue	Fe^{3+} and Tetracyclines	0.073 μM	[151]
3	CDs	<i>Pongamia pinnata</i>	Ag^{2+}	0.758 μM and 0.340 μM	[152]
4	CDs	Lychee Waste	Fe^{3+}	2.36 nM	[153]
5	Nitrogen-doped CDs	<i>Lantana camara</i> berries	Pb^{2+}	9.64 nM	[154]
6	CDs	<i>Prosopis juliflora</i>	Hg^{2+}	1.26 ng mL^{-1}	[155]

Table 1. Cont.

S. No.	Compounds	Source	Sensing Application	LOD	References
7	CDs	<i>Hibiscus sabdariffa</i>	Cr^{6+}	-	[156]
8	CDs	<i>Catharanthus roseus</i> leaves	Al^{3+} and Fe^{3+}	0.5 and 0.3 μM	[157]
9	Nitrogen-doped CDs	Rice residue	Fe^{3+} and Tetracycline	0.7462 μM	[158]
10	CDs	<i>Tulasi leaves</i>	Cr^{6+}	229 nM	[159]
11	Au NCs-CDs	Nanocomposite test paper and polyvinyl alcohol film	H_2S	4.20 nM	[160]
12	Fluorescent CDs	Discarded cigarette butts	Fe^{3+}	0.5–800 μM	[161]

CDs are typically synthesized using hydrothermal or microwave methods from a variety of natural materials. These nanomaterials are primarily composed of carbon and oxygen, with carbon forming a sp^2/sp^3 hybridized structure. The surface of CDs contains oxygen-containing functional groups such as hydroxyl (OH), carboxyl (COOH), and others, which significantly influence their chemical reactivity and compatibility in various applications [162]. The chemical composition and functional properties of CDs depend largely on the type of precursor material used. Biomass and other natural sources serve as carbon precursors, providing functional groups like OH and COOH. Additionally, certain precursors may introduce heteroatoms, such as nitrogen or sulfur, into the structure of CDs, further modifying their properties. The variety of natural materials used to synthesize CDs leads to different types of CDs, each with distinct characteristics, as illustrated in Figure 7 [163].

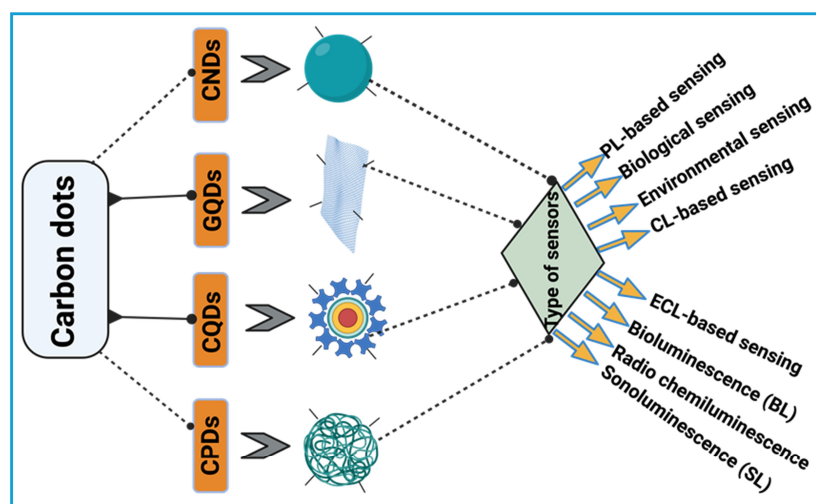


Figure 7. Image representing the classification of CDs and the different types of sensors that are based on CDs.

N/S/P-Doped CDs: Nitrogen-doped carbon dots (N-CDs) or carbon quantum dots (N-CQDs) could be easily synthesized from a nitrogen-rich precursor that contains amino functional groups [164]. Normal sources of nitrogen-containing organic molecules will result in N-doping and improved CD properties. Citric acid and carbohydrates were widely used as carbon sources for the synthesis of CDs in bottom-up synthesis due to efficient carbonization, low costs, and a large number of precursors. CDs, for example,

can be produced by refluxing high-temperature carbohydrates such as glucose, sucrose, or starch. Similarly, high-temperature thermal decomposition of citric acid results in intensely luminescent COOH-capped CDs [147]. To prepare the nitrogen (N)-doping source, several organic molecules were added, including diethylenetriamine, ethylenediamine, triethylamine, and urea [165]. Nitrogen-containing functional groups, among others, are needed for the formation of CDs and have a strong influence on their fluorescence strength [166]. Nitrogen doping is responsible for CDs' peculiar properties, such as longer wavelength absorption and fluorescence, higher fluorescence quantum yield, favorable optoelectronic properties, and so on [167]. N-CQDs are highly sensitive, selective, and stable carbon-based compounds beneficial for environmental sensing applications, particularly for detecting hazardous metals in environmental and biological samples. A wide range of CQD-based sensors have been reported for detecting toxic metal ions, including lead, chromium, iron, aluminum, arsenic, cobalt, cadmium, copper, gold, silver, and mercury. Additionally, N-CQD-based sensors have successfully detected and monitored Hg^{2+} ions in tap water and natural lake water, as well as accurately identified Pb^{2+} , Fe^{3+} , Ag^+ , and Cu^{2+} ions in human urine and serum [168].

For the preparation of sulfur (S)-doped CDs, thiol-containing biomolecules such as l-cysteine, glutathione, and cysteamine along with inorganic sources like sodium sulfite, sodium thiosulfate, and ammonium persulfate have been identified as suitable sources along with a carbon source [169]. As compared to non-doped CDs, the prepared S-doped CDs exhibited stable blue fluorescence, a high fluorescence quantum yield (21.1%), and excellent photobleaching resistance and stability [151]. Furthermore, additional doping of N may increase the quantum yield of S-doped CDs. Additional doping of N could increase the quantum yield of S-doped CDs [170]. Nitrogen/sulfur co-doped fluorescent carbon quantum dots (NS-CQDs) exhibit significant quantum confinement. The enhanced fluorescence efficiencies of these CDs are particularly advantageous as highly sensitive sensing materials, demonstrating robust blue emission under UV light [171]. These composite CD sensors have been successfully applied as selective and sensitive nanoprobe for detecting the hazardous explosive picric acid (PA) in analytical, environmental, and pathological applications. The sensing mechanism of NS-CQDs was investigated, indicating that detection occurs through fluorescence resonance energy transfer (FRET) and the formation of non-fluorescent complexes (Figure 8).

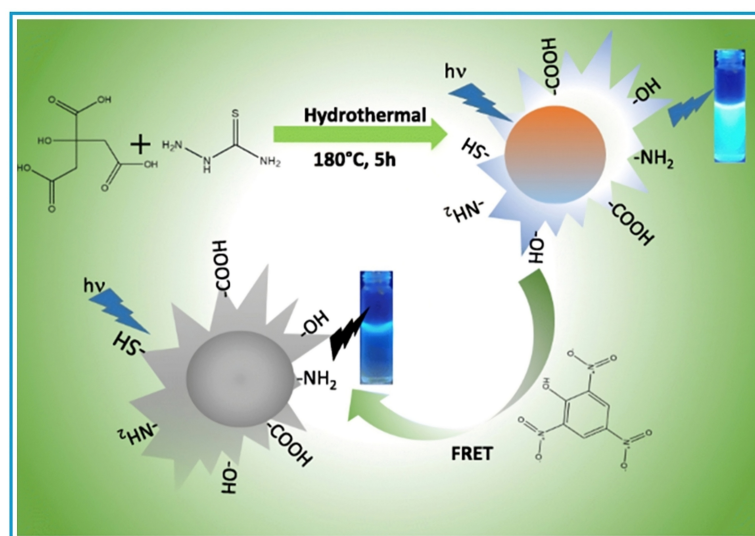


Figure 8. Image representing nitrogen/sulfur-co-doped fluorescent carbon quantum dots nanoprobe successfully monitoring environmentally hazardous explosive picric acid (PA) (reproduced from Ref. [172], Copyright (2020) with permission from Springer).

Similarly, phosphorus-doped CDs can be prepared by using phosphorus and phosphorus derivatives. Adenosine (A), adenosine monophosphate (AMP), adenosine diphosphate (ADP), and adenosine triphosphate (ATP) were utilized as nitrogen and phosphorus sources to develop a series of adenosine-derived N/P-doped CDs. Because of the presence of the P factor, N/P co-doped CDs have a higher fluorescence than N-doped CDs. In comparison to other adenosine derivatives, CDs prepared from AMP have the highest quantum yield (33.81%) [173]. Consequently, these combination CDs are highly effective in detecting lower concentrations of chromium (Cr) 4-nitrophenol (4-NP) and Ag(I) in water and soil samples [174,175]. Similarly, phosphorus-doped CQDs (P-CQDs) are highly effective in detecting lower concentrations of Fe^{3+} ions in blood, urine, and various industrial waste samples [176].

6.1. Transition-Metal-Doped CDs

Some transition metals, such as Co, Mn, Cu, Au, and Ag, can dope CDs to improve their properties, similar to how N, S, and P elements can be doped. Most of the metal-doped CDs are used to monitor and degrade water pollutants [177]. CDs were recently doped with Co using the hydrothermal method and 1-(2-pyridylazo)-2-naphthol. Because of the intraparticle fluorescence resonance energy transfer, the cobalt-doped CDs (Co/CDs) exhibited two emission peaks (FRET) [178]. Similarly, manganese-doped CDs show a high quantum yield of 54% because of the metal charge transfer and high quantum yield. Since valence electrons promote charge electron transfer, the radiative recombination of electrons and holes is improved, resulting in a higher QY [179]. Cu-doped graphitic carbon nitride composite sensors exhibit high reliability, selectivity, and reproducibility, making them suitable for environmental monitoring applications targeting cadmium ions (Cd^{2+}), with a detection limit as low as 0.098 nM [180]. Transition-metal-doped CD sensors have also been developed for gas-sensing applications. For instance, sensors doped with nitrobenzene, Rh, Pd, and Pt can detect hydrogen selenide (H_2Se) gas in various sensing environments [181,182]. In contrast, manganese-doped cadmium oxide (Mn-doped CdO) thin-film sensors successfully detect ethanol vapor at ambient temperature [183]. Nitro aromatic compounds and silver-doped Ag-NPs show reduced fluorescence properties due to FRET between CDs and Ag NPs; CDs' fluorescence efficiency decreased after they developed a complex with them. Because of the reducing activity of functional groups, especially the hydroxyl group, CDs can act as a reducing agent in general. CDs have been used as a reducing and binding agent in preparing Ag NPs to form a CDs–Ag NPs nanocomposite [166,184].

6.2. Nanohybrid-Based CDs

Encapsulating CDs in host materials to create a new fluorescent probe with special properties is another important functionalization of CDs. MOFs are chemosensors because of their intrinsic fluorescence [185]. The lower quantum yield of MOFs, on the other hand, can restrict the use of sensors due to low selectivity and sensitivity. CDs' emergent fluorescent material encapsulates in MOFs, forming a CDs@MOFs hybrid composite with both MOF and CD properties. MOFs' porous nature provides a high specific surface, which increases the contact area between the sensor and analyte, and CDs' strong fluorescence can improve the sensitivity [186]. Meanwhile, nanohybrid sensors have high sensitivity and good accuracy, for example, AuNCs/CDs-based sensors were successfully used to detect cefodizime sodium (CDZM) applied in urine sample detection (Figure 9). Interestingly, nanostructured metals, carbon-based materials, CDs, and quantum-dot-conjugated nanohybrids exhibit significant detection by using sensing and inhibitory effects against bacteria, fungi, and various viruses, including HIV, SARS-CoV-2, AIV-HV7, ZIKV, JEV, and HSV-

1 [187]. Novel protein–carbon dot nanohybrids exhibit minimal biotoxicity and superior thrombolytic capabilities and can be integrated with targeting ligands for site-specific recognition. They provide multicolor emission for cellular and in vivo bioimaging, facilitating disease diagnosis while enhancing therapeutic efficacy in ischemic brain tissue [188].

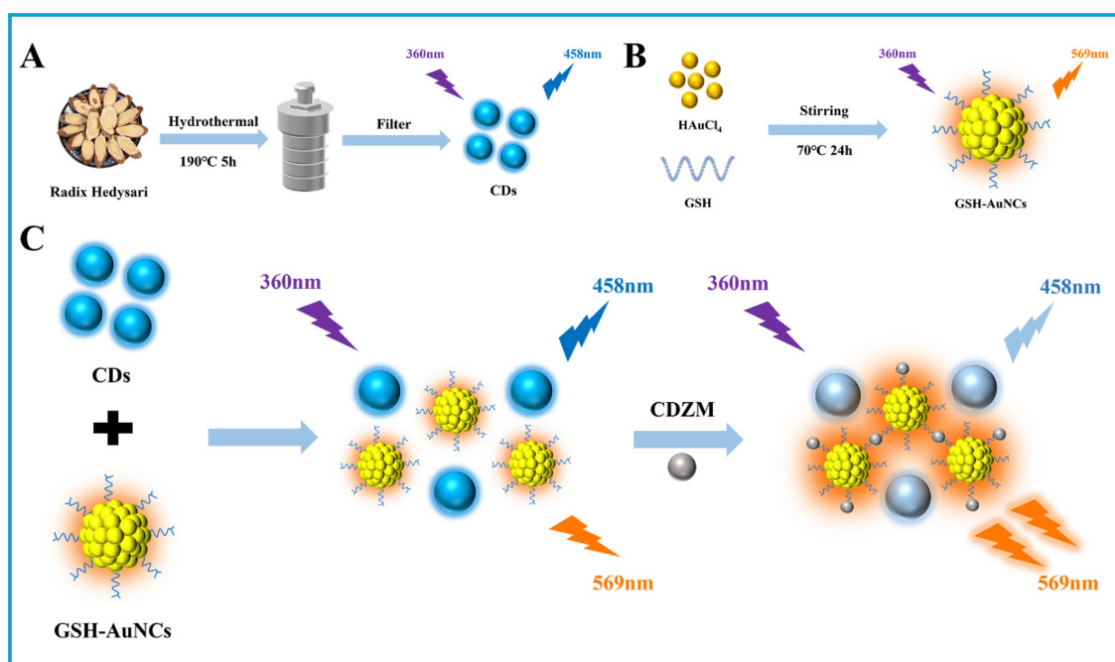


Figure 9. Image illustrating (A) the synthesis of the CDs and (B) GSH-AuNCs, (C) the creation of the GSH-AuNCs/CDs nanohybrid, and the principle for detecting CDZM (reproduced from [189]).

7. Limitations and Future Perspectives

In the past decade, substantial progress has been made in utilizing CDs and CD-based nanocomposites for addressing critical environmental challenges. Despite the tremendous advances in the design and deployment of CD-based systems for pollutant detection and remediation, several critical challenges remain unresolved, posing barriers to their widespread adoption in real-world environmental applications. One of the foremost limitations lies in the lack of standardized synthesis protocols [190,191]. Variability in precursor materials, reaction conditions, and purification strategies often leads to heterogeneity in particle size, surface chemistry, and quantum yield [192]. This inconsistency undermines reproducibility and complicates cross-comparison of results among research groups. To address this, future work must prioritize the development of universally accepted synthesis frameworks, potentially exploiting automated microfluidic platforms and AI-assisted optimization to produce CDs with predictable and tunable properties [193]. Another pressing challenge is the susceptibility of CD-based sensors to matrix interferences, especially in complex environmental samples, where competing ions, pH fluctuations, or organic matter can distort sensor signals [194]. To overcome this, there is a compelling need for surface engineering approaches that integrate zwitterionic coatings, molecularly imprinted polymers, or robust bio-conjugation techniques to enhance selectivity and minimize background noise without compromising sensitivity. The mass-scale production of CDs, particularly with controlled doping and multi-functionality, remains a bottleneck. Advanced synthetic routes such as continuous flow reactors, green microwave-assisted carbonization, and biomass valorization offer promising alternatives for achieving scalability while maintaining eco-compatibility [195]. Coupling these strategies with in-line real-time characterization tools like in situ spectroscopy and dynamic light scattering could facilitate better quality control.

Moreover, while CDs have shown excellent photophysical properties, their spectral responsiveness is often confined to the visible range [196]. Expanding emission into the near-infrared (NIR) domain would open doors for deeper tissue penetration in biomedical applications and enhance detection in turbid environmental matrices. Recent studies exploring co-doping with transition metals or heteroatoms have demonstrated promise in red-shifting emission wavelengths, offering a tangible direction for further exploration [197,198]. A major gap in the current research is the limited understanding of the mechanistic basis of adsorption and photocatalysis by CDs. Bridging this knowledge gap demands a multidisciplinary approach that combines density functional theory (DFT), time-resolved spectroscopy, and advanced electron microscopy to decode surface interactions at the molecular level. Such insights are pivotal for rational material design and functional tailoring. Importantly, the lifecycle fate, ecotoxicity, and long-term environmental persistence of CDs are still underexplored. Integrating life-cycle assessment (LCA), bioaccumulation studies, and environmental risk modeling into future investigations will ensure the safe and responsible integration of CDs into ecological systems. Finally, the integration of CD-based sensors with Internet-of-Things (IoT) platforms, cloud computing, and AI-driven data analytics could revolutionize environmental monitoring [199]. Such convergence would enable real-time pollutant tracking, predictive modeling of contamination hotspots, and intelligent decision-making frameworks, transforming CDs from static detectors into dynamic environmental sentinels.

8. Conclusions

This review highlights the rapidly evolving landscape of nanotechnology and its potential to generate innovative materials with significant societal impacts. CDs stand out as promising candidates due to their unique properties, low toxicity, eco-friendliness, and exceptional optical characteristics. However, while these advancements hold immense promise for resolving global environmental issues, they also raise critical questions about the long-term effects of nanomaterials on human health and the environment. The application of CDs for pollutant detection is particularly notable, given their ability to sense and degrade pollutants in the environment. By delving into the diverse array of sensors designed for pollutant detection, this review illuminates the unique strengths and challenges of each technology, unveiling a rich landscape of possibilities for their strategic deployment in environmental remediation. Through this lens, we highlight how innovation in sensing paves the way for smarter, more responsive, and sustainable solutions to global pollution challenges. Among the various sensor technologies, carbonaceous electrochemical biosensors are especially compelling due to their high conductivity and sensitivity, making them suitable for both catalytic and affinity-based applications. The bottom-up synthesis method for CDs, being cleaner, greener, and more cost effective, stands out as an efficient approach for large-scale production, offering a sustainable pathway for widespread implementation. Notably, CDs prepared using this method exhibit excellent biocompatibility and stability, expanding their potential for use in fields ranging from biomedical applications to pollutant sensing. Furthermore, doping CDs with metals or conductive materials enhances their fluorescent properties, broadening their utility across various domains. As the field continues to evolve, it is crucial to not only explore the vast applications of CDs but also to address the underlying challenges, such as their environmental and health impacts, to ensure their safe and responsible integration into society.

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