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Review

Carbon Nanodots-Based Sensors: A Promising Tool for Detecting and Monitoring Toxic Compounds

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Abstract: The increasing prevalence of toxic compounds in food, agriculture, and the environment presents a critical challenge to public health and ecological sustainability. Carbon nanodots (CNDs), with their excellent photoluminescence, biocompatibility, and ease of functionalization, have emerged as highly promising materials for developing advanced sensors that target hazardous substances. This review provides a comprehensive overview of the synthesis, functionalization, and sensing mechanisms of CND-based sensors, highlighting their versatile application in detecting toxic compounds such as heavy metals, pesticides, mycotoxins, and emerging contaminants. The article outlines recent advancements in fluorescence, electrochemical, and colorimetric detection strategies and presents key case studies that illustrate the successful application of CNDs in real-world monitoring scenarios. Furthermore, it addresses the challenges associated with reproducibility, scalability, selectivity, and sensor stability and explores future directions for integrating CNDs with smart and sustainable technologies. This review emphasizes the transformative potential of CNDs in achieving rapid, cost-effective, and environmentally friendly toxin detection solutions across multiple domains.

Keywords: rapid detection; carbon dots; probes; heavy metal; contaminants; ultrasensitive sensor devices

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1. Introduction

The widespread presence of toxic compounds in food, agricultural products, and the environment has emerged as a critical global concern. These contaminants present risks to human health and contribute to economic losses. For example, nutrient pollution in freshwater bodies across the United States leads to annual losses of at least USD 4 billion, mainly due to decreases in lakefront property values and recreational usage [1]. Between 1975 and 2020, the global economic impact of aquatic and semi-aquatic invasive plants surpassed USD 32 billion. The majority of these costs were attributed to damages within freshwater ecosystems [2]. Effective monitoring and mitigation strategies are urgently needed to address the widespread impact of toxic compounds on ecosystems and economies. These toxins—including pesticides, heavy metals, mycotoxins, and industrial pollutants—not only threaten human health but also compromise food safety, environmental integrity, and agricultural productivity [3,4]. While agrochemicals have significantly increased food production, their residues impact terrestrial and aquatic ecosystems, including coastal marine systems [5].

The need for environmental monitoring stems from several critical concerns. Exposure to pollutants like heavy metals and synthetic organic compounds has been linked to severe health effects, including neurotoxicity, endocrine disruption, and an increased risk of cancer [6,7]. Pollutants also disrupt biodiversity, harming aquatic organisms, terrestrial wildlife, and plant life, leading to long-term ecological imbalances [8,9]. Maintaining water quality is critical for safe drinking water, agricultural irrigation, and industrial processes. Reliable detection systems help enforce environmental safety standards and prevent contamination-related hazards [10,11].

Regulatory bodies worldwide mandate pollution monitoring to enforce environmental safety standards, highlighting the need for reliable detection techniques [12]. Early pollutant detection enables timely intervention, reducing the risk of large-scale contamination [13]. Accurate monitoring data also play a key role in public awareness, informed decision making, and sustainable environmental management [14].

Carbon nanodots (CNDs) have gained attention for their diverse sensing applications due to their water solubility, low toxicity, biocompatibility, and tunable photoluminescence [15,16]. These nanomaterials can be customized through heteroatom doping, composite formation, and metal complexation to enhance selectivity and sensitivity toward specific toxins [15]. CND-based sensors offer advantages such as simplicity, affordability, and high detection accuracy [15], making them strong candidates for biosensing, drug delivery, bioimaging, and environmental monitoring [17].

This review explores advancements in CND-based sensors for detecting toxic compounds in food, agriculture, and the environment. It discusses synthesis and functionalization strategies, outlines key sensing mechanisms, and highlights practical applications. Additionally, challenges related to stability, reproducibility, and selectivity are examined, with future directions aimed at integrating CNDs into next-generation environmental monitoring systems.

2. Fundamentals of Carbon Nanodots (CNDs) in Sensing

Carbon nanodots (CNDs) are carbon-based nanomaterials, typically under 10 nm in size, characterized by water solubility, tunable photoluminescence, and biocompatibility [18,19]. Structurally, they possess a carbon core with various surface functional groups and exhibit either crystalline or amorphous forms depending on the synthesis method [18]. CNDs can be synthesized via top–down or bottom–up approaches using methods like arc discharge, laser ablation, hydrothermal, microwave-assisted techniques, and pyrolysis [20,21]. The most commonly used synthesis methods for CNDs are presented in Table 1, including their advantages, limitations, and key references. Their optical and electronic properties—such as strong photoluminescence, high stability, and excitation-dependent emission—make CNDs highly suitable for diverse applications, including biosensing, bioimaging, drug delivery, nano-farming, and energy conversion [19,20,22]. These properties also contribute to their eco-friendliness and cost effectiveness, enhancing their appeal across disciplines.

The structural and functional characteristics of CNDs are crucial to their sensing performance (Figure 1). Their fluorescence and electrochemiluminescence properties are particularly valuable in detecting contaminants and environmental changes [16]. Characterization tools like TEM, FT-IR, and XPS are used to evaluate their morphology and surface chemistry [23]. Functionalization or doping of CNDs further enhances their selectivity and sensitivity toward specific analytes [24]. For instance, incorporating molecularly imprinted polymers (MIPs) creates hybrid materials capable of targeting specific pollutants with improved reliability [25]. Their fluorescence behavior, influenced by solvent polarity and environmental factors, enables real-time chemical sensing [23].

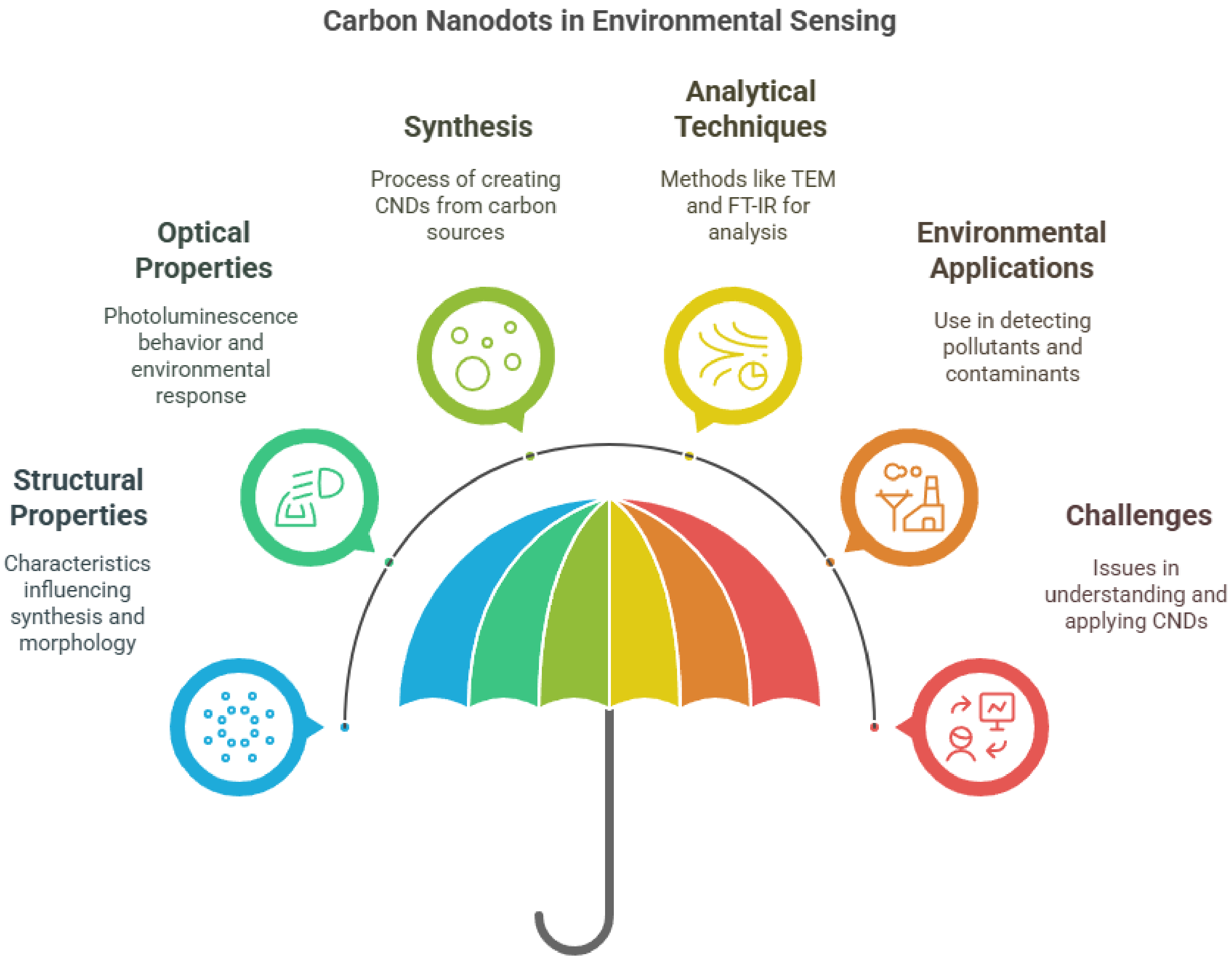

Figure 1. Primary aspects of carbon nanodots (CNDs) for sensing applications.

Due to these unique attributes, CNDs have become a preferred platform for fluorescence-based sensing systems. The integration of CNDs with MIPs has further refined detection capabilities in complex matrices [25]. Despite their promise, continued research is needed to fully understand and optimize the structural mechanisms influencing their performance and long-term stability in real-world conditions.

Table 1. Comparative overview of carbon nanodot (CND) synthesis methods.

Method	Advantages	Limitations	References
Arc discharge	• Produces high-quality nanostructures with fewer defects • Simple and cost-effective equipment setup	• Difficult to control size distribution and purity • High temperatures can limit material types	[26]
Laser ablation	• Generates high-purity nanoparticles with controlled size and shape • Suitable for various nanocarbons	• High energy input required • Limited scalability due to small laser-irradiating area	[26,27]
Hydrothermal	• Ability to synthesize substances unstable at melting point • Produces large, high-quality crystals	• Requires expensive autoclaves • Inability to observe crystal growth in steel vessels	[28]
Microwave assisted	• Rapid and energy-efficient synthesis • Facilitates surface modification and defect engineering	• Potential for uneven heating • Limited to materials that can absorb microwave radiation	[29]
Pyrolysis	• Simple and scalable process • Applicable to a wide range of carbon-rich precursors	• Requires high temperatures • Risk of aggregation or structural collapse if poorly controlled	[30]

3. Carbon Nanodot-Based Sensors: Design and Mechanisms

CNDs have garnered significant attention due to their unique optical and physicochemical properties, including strong photoluminescence, excellent biocompatibility, low toxicity, and ease of surface functionalization, which make them highly suitable for a wide range of sensing applications in food safety, environmental monitoring, and biomedicine [31,32].

3.1. Sensor Design and Synthesis

CND-based sensors are developed using various synthesis methods, such as hydrothermal, solvothermal, and microwave-assisted techniques [33]. The properties of the resulting CNDs—including their size, surface chemistry, and emission wavelength—are highly tunable depending on the precursors and synthesis conditions [34]. These sensors are typically designed to detect analytes through changes in fluorescence, electrochemical signals, or colorimetric properties upon interaction with the target compound [35,36].

To enhance selectivity and performance, CNDs can be functionalized with molecularly imprinted polymers (MIPs), aptamers, or antibodies, which improve the binding affinity and specificity for target pollutants [37].

3.2. Fluorescence-Based Detection Mechanisms

The most common detection strategy involves changes in the fluorescence behavior of CNDs upon interaction with analytes. This includes both fluorescence quenching (turn-off sensors) and fluorescence enhancement (turn-on sensors).

Fluorescence Quenching Mechanisms

Fluorescence quenching occurs when the fluorescence intensity of CNDs is reduced due to their interaction with specific analytes. Various mechanisms explain this phenomenon:

- Static quenching: This involves the formation of non-fluorescent ground-state complexes between CNDs and analytes, often leading to altered absorption spectra. This type of quenching is sensitive to temperature changes [38]. For instance, ref. [39] used static quenching in the detection of chlortetracycline with nitrogen-doped CNDs.
- Dynamic quenching: This happens when excited-state CNDs collide with quencher molecules, transferring energy or electrons. It affects the fluorescence lifetime but not the absorption spectrum. Increasing the temperature enhances this quenching type [40,41]. Researchers applied dynamic quenching to detect malachite green in food matrices.
- Förster resonance energy transfer (FRET): In FRET-based systems, energy transfers from an excited donor (CNDs) to a nearby acceptor within ~10 nm. This leads to decreased donor fluorescence and enhanced acceptor emission. The presence of an analyte can reverse quenching by displacing the quencher and restoring CND fluorescence [42,43]. Ref. [44] demonstrated this mechanism for detecting Aflatoxin B1. Additionally, bicolor fluorescent molecular sensors offer promising capabilities for detecting cations through various mechanisms, including intramolecular charge transfer, excimer/exciplex formation, and FRET [45] to sense ultralow hazardous elemental traces [46].
- Inner filter effect (IFE): An IFE occurs when excitation or emission light is absorbed by another species in the system. This requires overlap between the absorber's absorption spectrum and the CND's excitation/emission wavelengths [47]. Refs. [48,49] used IFE to detect tinidazole in milk using N-doped CNDs.
- Photoinduced electron transfer (PET): PET involves electron transfer between CNDs and an analyte after photoexcitation, influencing the fluorescence output [50]. This often accompanies or overlaps with other quenching mechanisms.

3.3. Electrochemical Detection

CNDs possess excellent redox properties and can be integrated into electrochemical sensors. These systems detect changes in current or potential as CNDs interact with analytes. Incorporating conductive materials like graphene or metal nanoparticles enhances the sensitivity [36]. This approach is particularly useful for detecting pesticides, heavy metals, and pharmaceuticals.

3.4. Colorimetric Detection

CND-based colorimetric sensors rely on visible color changes upon analyte interaction, often due to the following:

- Aggregation-induced changes: Target analytes cause CND aggregation, altering their optical properties.
- Enzyme-mimicking activity: CNDs can mimic peroxidase activity, catalyzing oxidation reactions that produce colorimetric signals (e.g., in H_2O_2 or pesticide detection).

3.5. Comparison with Other Carbon Nanomaterials

Compared to other carbon-based nanomaterials like graphene quantum dots (GQDs), carbon nanotubes (CNTs), and carbon nanofibers (CNFs), CNDs offer unique advantages in sensing:

- GQDs: Although they provide high sensitivity, their synthesis is more complex and less scalable [51].
- CNTs: These are known for their high conductivity and strength, so they are better suited for electrochemical sensing but raise environmental and health concerns due to their fibrous morphology [52].
- CNFs: CNFs have a high aspect ratio and provide good mechanical properties, similar to CNTs, making them useful for various sensor applications, particularly in electrochemical devices. However, unlike CNDs, CNFs generally lack significant photoluminescence, which limits their use in optical sensors. CNFs also require energy-intensive synthesis methods, which can be a disadvantage in terms of cost effectiveness and scalability [53].

CNDs strike a balance between safety, tunability, and optical performance, making them ideal for a broad range of optical and electrochemical sensing platforms [54,55].

4. Toxic Compounds in Food, Agriculture, and the Environment

4.1. Heavy Metal Contaminants

Toxic compounds such as heavy metals pose serious threats to ecosystems, human health, and agriculture [56]. Originating from industrial discharge, mining, wastewater irrigation, and agrochemical overuse, heavy metals persist in the environment and agriculture, leading to bioaccumulation in crops and health risks through the food chain [57–59]. These chemicals can persist and accumulate over time, leading to long-term contamination that impacts not only the local agricultural areas but also distant ecosystems through runoff and atmospheric deposition [60]. Identifying heavy metals is essential due to their profound environmental and health effects. Metals like lead, mercury, arsenic, cadmium, chromium, copper, and nickel can cause serious health problems [61]. Exposure to these metals can result in both acute and chronic conditions, including neurological disorders, developmental issues, and cancers [62]. Heavy metals do not degrade and can accumulate in the environment, leading to soil and water pollution. This pollution can harm plants, animals, and aquatic life, disrupting ecosystems and biodiversity [63]. Heavy metals can build up in living organisms and become more concentrated up the food chain. Even low environmental concentrations can become highly concentrated in top predators, including humans, posing significant health risks [64]. These pollutants alter soil pH, reduce microbial diversity, and impair nutrient cycling, ultimately degrading soil fertility [58,65,66]. In plants, metals like Pb, Cd, and As cause chlorosis, stunted growth, and diminished yields, threatening food security [57]. Early detection of heavy metals enables timely intervention and remediation [67], preventing further contamination and reducing long-term health and environmental impacts [68]. Carbon nanodots (CNDs) have emerged as a promising tool for this purpose due to their unique properties, such as high photoluminescence, biocompatibility, and ease of functionalization [69].

4.2. Organic Pollutants

Persistent Organic Pollutants (POPs), such as pesticides, PCBs, and PAHs, pose serious health and environmental risks due to their stability, bioaccumulation, and toxicity [70]. Originating from industrial waste, pesticides, and fossil fuel combustion, they persist in air, water, and soil, leading to widespread contamination [71]. POP exposure is linked to cancer, endocrine disruption, neurotoxicity, immune suppression, and cardiovascular and developmental disorders via oxidative stress and DNA damage [72,73]. These pollutants also accumulate in ecosystems, disrupting biodiversity and contaminating food webs. Agriculture heavily depends on various chemical substances to boost crop yields and protect plants from pests and diseases. These common substances, known as agrochemicals, include pesticides, herbicides, fungicides, and fertilizers (Figure 2) [3,74]. Although they are essential in modern farming, their widespread use poses significant risks to human health and the environment [75]. Fertilizers are nutrient-rich compounds that promote plant growth [76]. Overusing nitrogen-based fertilizers can lead to water contamination and eutrophication [77]. Organochlorine pesticides degrade soil health, PCBs are linked to neurological and reproductive issues [78], and PAHs pose ecotoxicological risks in aquatic environments [79,80]. Bioremediation methods like microbial and enzymatic degradation show promise but are limited by site-specific conditions [81]. While effective in crop protection, pesticides can remain in the environment, contaminating soil, water, and air [82]. Herbicides are used to control unwanted plants [83]. Fungicides prevent or eliminate fungal infections [84]. Nitrogen- and phosphorus-based fertilizers are commonly used to enhance plant growth, but excessive use can cause nutrient runoff into water bodies, leading to eutrophication and harmful algal blooms [85]. The accumulation of toxic compounds in soil can reduce soil fertility, disrupt microbial communities, and lead to biodiversity loss [77]. Agrochemicals can leach into groundwater or run off into surface water, contaminating drinking water sources and aquatic ecosystems [86]. Exposure to toxic compounds in agriculture can occur through inhalation, ingestion, or skin contact, leading to health effects such as endocrine disruption, carcinogenicity, reproductive disorders, and neurological issues [87].

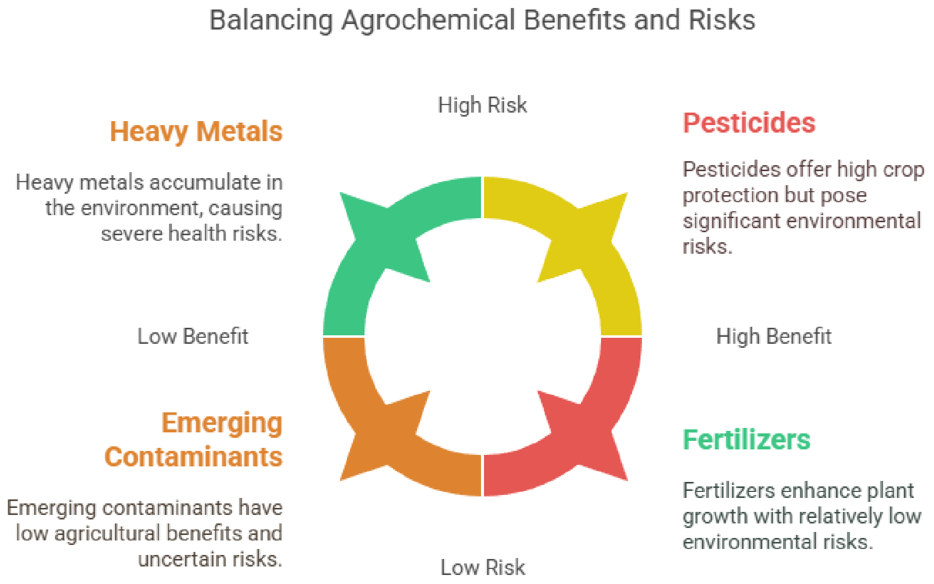

Figure 2. Benefits and risks of agrochemicals, including heavy metals, pesticides, emerging contaminants, and fertilizers.

Another common class of POPs in environments, particularly in food, is mycotoxins, which are extremely harmful substances created by different fungi that can accumulate in crops during growing and after harvesting. A specific type of mycotoxin, aflatoxins (AFs), is produced by specific *Aspergillus* sp., including *A. flavus*, *A. nomius*, and *A. parasiticus* [88,89]. Environmental factors, including food composition, high temperatures, extended periods of drought, prolonged storage, and poor storage conditions, significantly influence the proliferation of these fungi and the subsequent production of AFs [90,91]. Among the twenty aflatoxins (AFs), four are particularly notable: AFG2 (aflatoxin G2), AFG1 (aflatoxin G1), AFB2 (aflatoxin B2), and AFB1 (aflatoxin B1) [92]. The IARC identifies AFB1 as the most hazardous variant, known for its hepatotoxic, carcinogenic, and mutagenic properties [93,94]. Extended exposure to this toxic mycotoxin can accumulate in the body, possibly resulting in chronic health issues, especially liver cancer [95]. The European Union (EU) has set aflatoxin (AF) limits at 2 μg kg^{-1} for AFB1, the most toxic mycotoxin, and 4 μg kg^{-1} for the combined total of all classes of aflatoxin in cereals and related products [96].

Biogenic amines (BAs) are low-molecular-weight bioactive nitrogen compounds present in microorganisms, animals, and plants. They have various chemical structures and are classified into three primary categories: aliphatic polyamines, aliphatic diamines, and aromatic amines [97]. BAs are formed in food mainly by three factors: (1) lactic acid bacteria with decarboxylation activity; (2) the quality and characteristics of the raw material, including ionic strength, composition, and pH; and (3) processing and storage conditions, such as refrigeration, curing, or fermentation [98]. Many studies indicate that eating seafood with more than 500 mg kg^{-1} of histamine can lead to food poisoning [99]. The FDA (Food and Drug Administration) establishes 100 mg kg^{-1} for tyramine and histamine at 50 mg kg^{-1} in fish as admissible limits [100].

Polycyclic aromatic hydrocarbons (PAHs) are recognized as chemical pollutants due to their lipophilic and hydrophobic properties; these compounds primarily consist of aromatic rings containing carbon and hydrogen [101]. They typically arise or accumulate in food during thermal processing from the pyrolysis of organic materials or incomplete combustion [102]. Notably, benzo(a)pyrene (BaP), a specific type of PAH, has been linked to harmful effects on the human body. Prolonged exposure to PAHs from breathing, smoking, and eating contaminated food and water can accumulate in different organs, causing DNA damage, tumor formation, and a higher risk of lung, colon, and breast cancers. [103]. The EFSA reported a concentration higher than 1600 mg kg^{-1} for PAHs as a potential acute toxicity risk [104].

4.3. Emerging Contaminants

Emerging contaminants (ECs)—including pharmaceuticals, microplastics, and personal care products—are increasingly found in ecosystems due to wastewater, industrial discharge, and runoff [105]. Pharmaceuticals (e.g., trimethoprim and diclofenac) contribute to antimicrobial resistance and endocrine disruption [106,107]. Microplastics act as pollutant carriers and enter food chains [108–110]. Personal care product residues, such as phthalates and surfactants, disrupt hormonal functions and harm aquatic life [107,111]. These contaminants are not traditionally regulated but have recently been recognized as potential environmental pollutants [112]. In the case of food safety, contaminants are divided into intentional additives, which enhance food quality, and incidental contaminants, which arise unintentionally during food processing [113]. Eight compounds with significant toxic effects on human health in trace amounts include aflatoxin, HMF (hydroxymethylfurfural), BAs (biogenic amines), AA (acrylamide), furfural, PAHs (polycyclic aromatic hydrocarbons), BPA (bisphenol A), NAs (nitrosamines) [114].

The Maillard and caramelization reactions involve a series of chain reactions that produce appealing flavors and aromas in foods during various high-temperature cooking processes [115]. Hydroxymethylfurfural (HMF) and furfural (F) are cyclic aldehydes resulting from the breakdown of hexoses in caramelization and the Maillard reaction, acting as toxic byproducts [116]. HMF levels serve as a key quality indicator for assessing the intensity of heat treatment and the storage duration in a variety of food products [117]. Few studies have pinpointed distinct clinical symptoms related to F and HMF consumption. Nonetheless, specific research suggests that increased HMF concentrations may cause cytotoxic effects, irritating the skin, mucous membranes, and eyes [118]. The Codex Alimentarius states that the ADI value for furfural is 0.5 mg kg^{-1}. Additionally, a level of HMF exceeding 40 mg kg^{-1} is considered toxic to humans [119].

Acrylamide (AA) is a polar, low-volatile, and hydrophilic unsaturated amide [120]. AA is an unavoidable toxic byproduct of the Maillard reaction, resulting from the formation of desirable aromas, colors, and flavors. Its production occurs through the chemical interaction of reducing sugars, such as glucose and fructose, with asparagine, a free amino acid, during heating processes like roasting, frying, and baking at temperatures exceeding 120 °C [121–123]. Carbohydrate-rich items, particularly plant-based foods, are significant contributors to acrylamide formation. AA is categorized as a neurotoxic, genotoxic, mutagenic, and carcinogenic contaminant. It can gradually affect different body parts, particularly the cardiovascular and renal systems, thereby impacting human health [124,125]. An intake per day of AA above 40 μg kg^{-1} is being reported for neurotoxic effects and 2.6 μg kg^{-1} for carcinogenic effects [126].

Bisphenol A (BPA) serves as the monomer for polycarbonate (PC), a material commonly found in the plastic industry, especially in food and beverage packaging [127]. The increasing number of ready-to-eat meals and canned goods on a global level signifies a higher demand for BPA in these packaging. BPA leaches into food and subsequently enters the human body. Typically, the primary pathway for human exposure to BPA correlates with the consumption of canned foods [128,129]. Factors such as the storage duration and heating or freezing processes influence the amount of BPA that migrates from bottles or cans into the food [130]. BPA is known to have toxic effects on the human genome, reproductive capabilities, and the neurological, immune, and cardiovascular systems, also acting as a potential carcinogen [131,132]. The European Commission (EC) has proposed a TDI for BPA at 50 μg kg^{-1}, along with food-specific migration limits set at 0.6 mg kg^{-1} [133]. N-nitrosamine is a harmful compound generated from nitrates and nitrites, which are commonly added to certain foods, especially meat products. These substances not only enhance the quality of meat by acting as antibacterial preservatives and colouing agents but also contribute to its desirable flavor [134,135]. The primary way that N-nitrosamines (NAs) are formed is through the reaction of nitrates and nitrites with secondary amines found in food. Various factors affect the development of NAs in food, including acidity, cooking techniques, the duration, the alkalinity of secondary amines, nitrite levels, and the presence of catalysts or inhibitors [136,137]. Epidemiological studies classify NAs as food toxins that can lead to uncontrolled cell growth, consequently resulting in tumors in various organs, including the bladder, lungs, liver, pancreas, and esophagus [138,139]. In the USA, there is a daily maximum limit of 10 μg kg^{-1} per body weight in retail food products [140].

5. Applications of CND-Based Sensors for Detecting Toxic Compounds

5.1. Applications of CND-Based Sensors for Detecting Heavy Metals

Carbon nanodots (CNDs) have significantly attracted their usage in the food industry, which is mainly due to their fluorescence under UV light. This fluorescence emitted either increases or quenches with specific types of ions/molecule or substances [141,142]. Within certain limits, the quencher's concentration is equal to the fluorescence intensity emitted [143,144]. CNDs marks their potential usage as efficient and sensitive probes for the detection of different types of analytes in food systems [145]. Table 2 summaries the different CND synthesis methods, including hydrothermal and microwave assisted with various precursors, such as gallic acid, citric acid, and o-phenylenediamine. CNDs are typically characterized using spectroscopic techniques such as FT-IR, UV-Vis, and FS; microscopic techniques (TEM, HR-TEM, SEM, and AFM); and surface analysis techniques (XPS, Zeta potential, DLS, XRD, and EDX), ensuring detailed evaluation of their morphology, structure, and surface functionality. For example, CNDs have been effectively used to detect heavy metal ions such as As^{5+}, Fe^{2+}, Hg^{2+}, and Fe^{3+}, with limits of detection (LOD) reported at 31.50 μM, 122.4 μM, 96.40 μM, and 161.9 μM, respectively (Table 3 [146]). Their strong linearity ($R^2 > 0.99$) further supports their potential in food safety monitoring. Sensors based on CNDs have shown significant potential in detecting various toxic substances, including heavy metals, in agricultural environments (Table 4). CNDs can detect heavy metals through mechanisms such as fluorescence quenching and electrochemical sensing (Figure 2; [147]). When CNDs interact with heavy metal ions, changes in their photoluminescence properties are observed, which can be used to determine the presence and concentration of metals like lead, cadmium, and mercury [148,149]. This makes CND-based sensors highly effective for detecting heavy metal contamination in soil and water, providing a fast, sensitive, and cost-effective method for monitoring agricultural environments.

5.2. Applications of CND-Based Sensors for Detecting Organic Pollutants

In addition to heavy metals, CNDs have shown excellent performance in detecting organic pollutants in food systems. CNDs can be used as active ingredients in smart packaging materials to improve packaging quality and detect microbial deterioration [150]. Traditional detection methods like spectroscopy and chromatography [151,152] offer high accuracy but require costly equipment, complex sample preparation, and skilled personnel. In contrast, CND-based fluorescent probes provide a cheap, simple, rapid, and eco-friendly alternative. CNDs have been successfully applied for the detection of food additives and toxins such as melamine and acrylamide, achieving nanomolar sensitivity with low detection limits and strong linear relationships ($R^2 > 0.99$). Their biocompatibility, low toxicity, and flexibility in fabrication methods enhance their suitability for widespread applications in detecting various organic food pollutants [153].

Furthermore, these sensors can identify even trace amounts of pesticides in soil and water, offering a quick and sensitive method for monitoring pesticide residues [154]. The fluorescence properties of CNDs allow them to be functionalized selectively to bind with organic pollutants, facilitating efficient detection and improving environmental monitoring practices. This is particularly important in agriculture, where the safe and controlled use of pesticides is crucial to prevent contamination of food and the environment.

5.3. Applications of CND-Based Sensors for Detecting Emerging Contaminants

Emerging contaminants like toxic polymer compounds, endocrine-disrupting chemicals, and allergens have also become a focus for CND-based sensor applications. Various fabrication methods—such as hydrothermal, microwave-assisted, solvothermal, gamma irradiation, and sol–gel techniques (Table 2, [50,155])—allow for tuning the properties of CNDs, impacting their sensitivity and selectivity [156]. CNDs have demonstrated strong potential in detecting contaminants like Aflatoxin M1, with LODs reported between 0.02 and 0.07 $\mu g\ L^{-1}$ [157,158]. Moreover, CNDs offer an eco-friendly and low-cost option compared to conventional fluorescent probes made from expensive and toxic materials. Despite these advances, challenges remain regarding the cytotoxicity, bioaccumulation, and regulatory approval of CNDs. Future research must focus on sustainable large-scale production, ensuring stability, specificity, and safety for broader food industry applications. CND-based sensors can be used to monitor the presence and concentration of emerging contaminants in agricultural settings, ensuring safer practices and better management of environmental pollution [159]. CNDs have emerged as powerful tools in detecting antibiotic resistance. Their versatility, cost-effectiveness, and adaptability make them promising candidates for advancing diagnostic and therapeutic strategies in antibiotic resistance management which is summarized in Table 5.

Table 2. Comprehensive summary of different CND synthesis methods with various precursors and their characterization techniques.

Method of Synthesis	Precursors Used	Characterization Techniques Used	References
Hydrothermal	Gallic acid and DMF	FT-IR, DLS, HR-TEM, XRD, XPS, and FS	[160]
	Tea bag waste	UV–Vis, PSA, Zeta potential, HR-TEM, AFM, FT-IR, DSC, and FS	[161]
	o-phenylenediamine, dipicolinic acid	HR-TEM, DLS, FT-IR, XPS, and FS	[162]
	o-phenylenediamine	FT-IR, DLS, TEM, XRD, SEM, and XPS	[163]
	Salvadora persica powder and m-phenylenediamine	TEM, Zeta potential, UV-Vis, FT-IR, XPS, TRPL, and FS	[164]
	Citric acid and polyethyleneimine	HR-TEM, EDX, FT-IR, UV-Vis, and FS	[158]
	Citric acid and ethylenediamine	TEM, XPS, FT-IR, UV-Vis, and FS	[157]
	Ethylene glycol and sodium hydroxide	UV-Vis, TEM, FT-IR, and FS	[165]
	Citric acid, arginine, and ethane diamine	TEM, FT-IR, Zeta potential, XPS, UV-Vis, and FS	[166]
Microwave assisted	Citric acid, urea, and trisodium citrate	FT-IR, UV-Vis, XRD, FS, HR-TEM, and RS	[167]
	Cerium nitrate, dopamine hydrochloride, and citric acid	FT-IR, XPS, XRD, TEM, RS, UV-Vis, EPR, and Zeta potential	[168]
Solvothermal	Neutral red, sulfuric acid and glutathione	HR-TEM, SEM, FT-IR, XPS, PXRD, and DSC	[40]
Gamma irradiation	Sucrose and ammonia	Zeta potential, FT-IR, UV-Vis, XRD, XPS, TEM, and FS	[146]
Pyrolysis, sol–gel, and electrodeposition	Titanium oxide and citric acid	FT-IR, EM, Zeta analysis, UV–Vis, and XRD	[169]
Oil bath	Sucrose and urea	UV-Vis, FS, TEM, FT-IR, XRD, and XPS	[170]

Table 3. Application of CNDs for the detection of toxic compounds in food systems.

	Analyte Detected	LOD	Calibration Range	References
Metal ions	As^{5+}, Fe^{2+}, Hg^{2+}, and Fe^{3+}	As^{5+}—31.50 μM, Fe^{2+}—122.4 μM, Hg^{2+}—96.40 μM, and Fe^{3+}—161.9 μM	As^{5+}—0.09–0.19 mM (R^2 = 0.9969), Fe^{2+}—0.01–0.8 mM (R^2 = 0.9966), Hg^{2+}—0.04–0.9 mM (R^2 = 0.9962), and Fe^{3+}—0.01–0.9 mM (R^2 = 0.9967)	[146]
	Pb^{2+}	0.715 μM	30–130 μM (R^2 = 0.9902)	[160]
	Fe^{3+} and Ag^{+}	Fe^{3+}—0.250 μM; Ag^{1+}—0.140 μM	Fe^{3+}—1–100 μM (R^2 = 0.9952); Ag^{1+}—1–200 μM (R^2 = 0.9985)	[167]
	Hg^{2+}	0.147 μg L^{-1}	0.625–90 μg L^{-1} (R^2 = 0.9960)	[168]

Table 3. *Cont.*

	Analyte Detected	LOD	Calibration Range	References
Polymer	Melamine	30 nM	0–20 µM (R^2 = 0.9940)	[165]
	Melamine	0.67 µM	2.0 to 290 µM (R^2 = 0.9981)	[166]
	Acrylamide	0.354 µg L^{-1}	0.5–10 µg L^{-1} (R^2 = 0.9991)	[161]
	Acrylamide	0.670 nM	10–200 nM (R^2 = 0.9876)	[169]
	L-asparagine	0.31 µM	1.0–50.0 µM (R^2 = 0.9984)	[170]
Food Additives	Erythrosine	1.210 nM	4–20 µM (R^2 = 0.9970)	[164]
	Malachite green	1.200 nM	0.014–300 µM (R^2 = 0.9964)	[40]
Mycotoxin	Aflatoxin M1	0.07 µg L^{-1}	0.2–0.8 µg L^{-1} (R^2 = 0.9552)	[158]
Gamma irradiation	Aflatoxin M1	0.0186 µg kg^{-1}	0.003–0.81 µg kg^{-1} (R^2 = 0.9940)	[157]
Insecticide	Imidacloprid	1.870 µg kg^{-1}	0.037–0.2 mg kg^{-1} (R^2 = 0.9700)	[163]
Allergen	Histamine	6.96 µM	25–1000 µM (R^2 = 0.9978)	[162]

Table 4. Application of carbon nanodots (CNDs) in detecting and monitoring pesticide residues.

Source of Carbon Dots	Studied Pesticides	References
Green-fluorescent C-dots from vegetables/fruits	Pesticide parathion methyl can be detected through the reliable and sensitive technique in real food samples	[171]
Porphyrinic Zr metal–organic framework (PCN-224@CDs)	Organo-phosphorus pesticides via carbon dots supported Zr-based metal organic framework	[172]
Producing carbon quantum dots from tea residue	Using $Al_2(SO_4)_3$/CQDs composite in photocatalytic degradation of pesticide Fipronil ($C_{12}H_4C_{l2}F_6N_4OS$)	[173]
Using carbon dots from *Boerhavia diffusa* leaves	Nanocomposite of CDs/cobalt ferrite and boehmite for photo-degradation via sensing of pesticide methyl parathion	[174]
Producing carbon dots using gallic acid	Detecting the “organophosphate pesticide” chlorpyrifos in wastewater as fluorescent probe	[175]
Producing carbon dots using *Grewia asiatica* fruit via microwave	Detecting the organo-phosphorus pesticide of quinalphos by forming red emissive carbon dots in vegetable, water, and soil samples	[176]
Bio-producing CeO_2@C-dots from agrowaste (chestnut peels)	Active catalyst for degradation of Rhodamine B dye and detecting 4-Nitrophenol in aqueous solutions	[177]
Nitrogen-doped carbon dots using hydrothermal method	Detecting imidacloprid as an effective neonicotinoid insecticide in real foods	[178]
Boron-nitrogen doped carbon dots (BN-C-dots) using hydrothermal protocol	Rapid detection of insecticide acephate using BN-C-dots in vegetables and water	[179]
Producing TiO_2/ZnO-CQDs from spent coffee using hydrothermal method	Detecting carbaryl ($C_{12}H_{11}NO_2$) in carbamate pesticides via photocatalytic degradation in water for environmental remediation approach	[180]
Producing graphene carbon dots in corn stalk pith as green sorbent	Using the studied green sorbent in detecting triazole fungicide residues in different types of rice samples	[181]
Nitrogen- and phosphorus-doped carbon quantum dots (NP-CQDs) via hydrothermal method	Using fluorescent NP-CQDs in detecting pesticides of chlorpyrifos in miscellaneous beans and their residues in different kinds of foods	[41]
Nitrogen-doped carbon dots (N-CDs)	Using N-CD-based fluorescent sensor for detecting glyphosate in organo-phosphorus pesticides	[182]

Table 5. Application of carbon nanodots (CNDs) in detecting or combating antibiotic resistance.

Source of Carbon Dots	Studied Antibiotics	Ref.
Producing N- and S-doped blue-fluorescent carbon dots via a one-step solvothermal protocol	Detecting chloramphenicol in environmental and food safety contexts as portable fluorescence-based sensor for several analytical purposes	[183]
Producing N-doped C-quantum dots via microwave-assisted hydrothermal protocol	Detecting the antibiotic meropenem using a sensor of N-CQDs-AuNPs in pharmaceuticals and plasma	[184]
Producing N-doped carbon quantum dots using hydrothermal protocol	N-CQDs are more effective than antibiotic levofloxacin in treating bacterial keratitis caused by multidrug-resistant *Staphylococcus aureus*, combating its resistance	[185]
Producing Curcumin-derived C-dots via hydrothermal protocol	Cur-CDs exhibit significant antibacterial effects against strains such as *Escherichia coli*, and *Staphylococcus aureus* comparing with antibiotic chloramphenicol	[186]
Producing fluorescent C-quantum dots from disposable water bottles	Using Polyethylene Terephthalate plastic (PET) fluorescent C-quantum dots for removing antibiotic ciprofloxacin	[187]
Producing N and S co-doped C-quantum dots using hydrothermal protocol	On-site detection of antibiotics (i.e., moxifloxacin, gatifloxacin, and ofloxacin) in milk using N, S co-doped CQNs in combination with a smartphone	[188]
Producing N-doped C-quantum dots from the peels of *Citrus limetta*	Detecting β-Lactam antibiotics (ampicillin) in milk and water depending on the N-CQDs by forming a greenish-blue fluorescent color	[189]
Producing highly water-soluble Curcumin carbon dots using the hydrothermal protocol	Studied Cur-CDs exhibited a higher antimicrobial efficacy against *Escherichia coli* and *Staphylococcus aureus* and combating drug-resistant bacterial infections	[190]
Producing N-doped green-fluorescent C-dots using the hydrothermal protocol	A cost-effective, reliable approach, using high-fluorescence CDs for detecting the antibiotic chlortetracycline in real samples	[191]
Producing stable red-fluorescent nitrogen-doped carbon dots via solvothermal method	Studying N-CDs as a fluorescent probe to detect ceftazidime antibiotic in real samples	[192]
Producing CDs via hydrothermal method using different quaternary ammonium salts	Detecting tetracycline antibiotics in real milk using CDs as a cost-effective approach for providing insights into food safety testing methodologies	[193]
Producing magnetic molecular nanomaterials coupled with CDs via hydrothermal method	Detecting doxycycline antibiotics using CDs in food matrices through fluorescence quenching mechanism and inner filter effect (IFE)	[194]

6. Sensitivity, Selectivity, and Performance of CND-Based Sensors

The development of sensors based on carbon nanodots (CNDs) marks a significant leap in nanotechnology, providing high sensitivity, selectivity, and performance for detecting various analytes (Figure 3; [17,195]. These parameters are essential for applications in biosensing, environmental monitoring, and food safety [196]. Sensitivity, defined as the ratio of the change in sensor output to the change in input signal, reflects how responsive the sensor is to low concentrations of analytes [197]. High sensitivity in CND-based sensors can be attributed to their strong fluorescence, high surface area, and efficient interaction with target molecules [198]. Several factors influence the sensitivity, including synthesis methods (e.g., hydrothermal, solvothermal, microwave assisted, and electrochemical), which determine the size, shape, and surface properties of the CNDs [199]. Smaller, uniformly distributed CNDs often offer higher sensitivity due to a larger surface area-to-volume ratio [200]. Surface functionalization, such as with carboxyl, hydroxyl, or amine groups, enhances sensitivity by facilitating stronger interactions with analytes [201]. Environmental parameters, like the pH, temperature, and ionic strength, also affect the performance of the sensor and must be optimized for consistent detection [202]. The choice of detection mechanism—fluorescence quenching, electrochemical response, or colorimetric changes—also influences the sensitivity, with fluorescence-based detection being particularly popular due to its simplicity and real-time response [203].

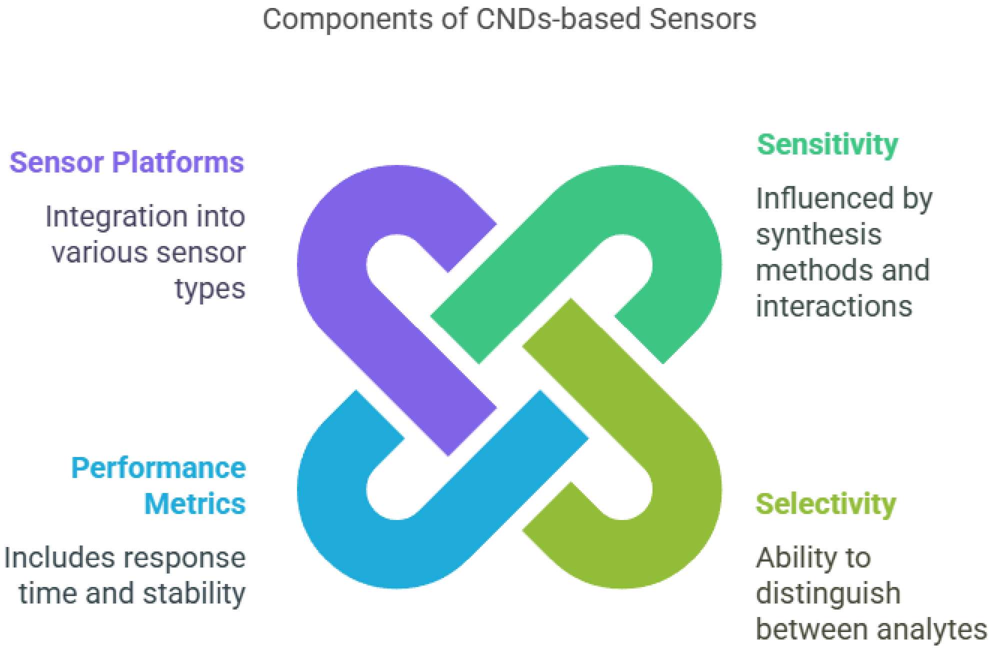

Figure 3. The main components of CND-based sensors.

Selectivity, which is the ability of a sensor to distinguish a specific analyte in the presence of other substances, is crucial in complex environments like biological fluids or food matrices [204]. It can be significantly enhanced through the surface modification of CNDs with recognition elements such as antibodies, enzymes, or molecularly imprinted polymers [205]. These modifications create specific binding sites that improve their interaction with target analytes. The synthesis method and environmental conditions (e.g., pH and ionic strength) also affect the selectivity by altering the binding affinity and specificity [206]. Furthermore, the detection mechanism can influence the selectivity: for example, electrochemical sensors may be more selective for redox-active compounds, while fluorescence sensors may be designed to respond only to specific fluorophore-target interactions [207].

The performance of CND-based sensors also depends on other factors, such as the response time, stability, reproducibility, and detection limit [208]. A fast response time is critical for real-time monitoring, while long-term stability ensures consistent performance under varying environmental conditions [209]. Reproducibility, or the sensor's ability to deliver consistent results across multiple measurements or batches, is essential for reliable use [210]. The detection limit, which indicates the lowest concentration of analyte the sensor can detect, is particularly important for applications requiring high precision, such as medical diagnostics or trace contaminant detection in food and water [211,212].

To enhance sensitivity and selectivity, researchers have developed various functionalization strategies (Figure 4). Bio-functionalization with antibodies, aptamers, or peptides is a promising approach, as these biomolecules provide high binding affinity and specificity toward target analytes. For instance, CNDs conjugated with horseradish peroxidase (HRP)-linked antibodies showed enhanced sensitivity for detecting carcinoembryonic antigen

(CEA) [213–215]. Selective peptides have also improved the detection of specific pollutants and biomolecules [216]. Doping CNDs with heteroatoms such as nitrogen or sulfur can modulate their electronic structure and enhance their photoluminescence, thereby increasing sensor sensitivity and stability [217]. Chemical modification techniques like click chemistry enable site-specific functionalization for targeted applications [218]. Both covalent and non-covalent approaches are used to introduce functional groups or recognition elements to the CND surface. However, challenges remain in achieving uniform functionalization and maintaining reproducibility across batches [201]. Developing standardized protocols for functionalization will be crucial for advancing CND-based sensors into scalable, real-world applications in biomedical diagnostics, environmental monitoring, and food safety [156].

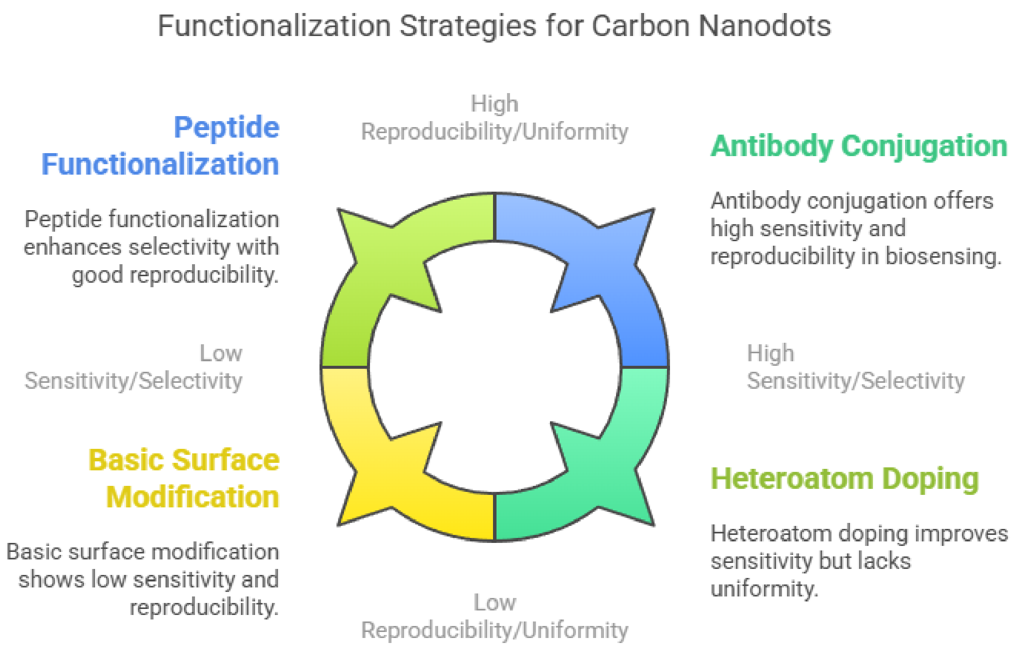

Figure 4. Functionalization strategies of carbon nanodots (CNDs).

7. Challenges and Future Perspectives

Despite the promising potential of carbon nanodot (CND)-based sensors, several limitations continue to hinder their widespread application in real-world scenarios. These challenges span across material synthesis, performance stability, functional complexity, and scalability, all of which impact the sensors' consistency, cost effectiveness, and reliability in diverse environments (Figure 5). One of the most persistent issues lies in the synthesis and purification of CNDs. Like other carbon-based nanomaterials such as graphene quantum dots (GQDs) and carbon nanotubes (CNTs), the production of CNDs often results in impure products containing small molecules and aggregates, which significantly alter their physicochemical properties and interfere with sensor performance [219]. The purification methods currently available are insufficient to eliminate these impurities entirely, leading to inconsistencies in reproducibility and sensitivity [219].

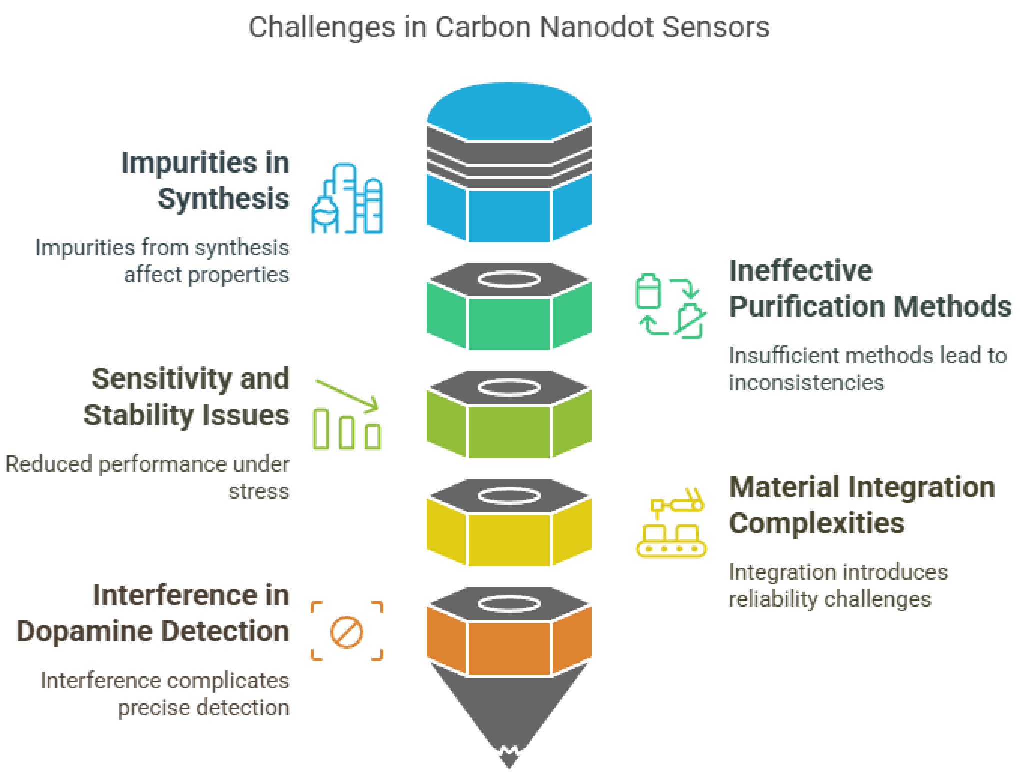

Figure 5. Challenges in carbon nanodot-based sensors.

Performance-related limitations are also a concern. CND-based sensors may exhibit reduced sensitivity and stability, particularly in flexible or wearable applications, where they are subject to mechanical stress [220]. Although integrating CNDs with other materials, such as polyaniline, can enhance overall sensor capabilities, it often introduces structural and functional complexities that complicate sensor fabrication and may compromise stability [220]. Furthermore, certain applications—such as dopamine detection—face challenges due to the potential for interference from similar biomolecules, making precise quantification difficult [221]. In addition, the intricate surface functionalization required for improving selectivity and target specificity increases production costs and reduces practicality for commercial deployment [222].

Comparatively, CND-based sensors share both advantages and limitations with other carbon nanomaterial sensors and traditional analytical techniques (Figure 6). They offer rapid detection, high sensitivity, and low detection limits, making them attractive for real-time environmental monitoring. For instance, compared to techniques like inductively coupled plasma mass spectrometry (ICP-MS) and high-performance liquid chromatography (HPLC), CND-based sensors can deliver near-instantaneous results with minimal sample preparation [223]. Their lower production and operational costs also make them suitable for deployment in resource-limited settings [110]. However, selectivity remains a common limitation among carbon nanomaterial-based sensors, often leading to cross-reactivity and false positives when detecting analytes in complex matrices [224]. Additionally, the fabrication of stable and reproducible CND-based sensor platforms typically requires advanced nanofabrication techniques, which limits their scalability [225]. Long-term stability is another issue, as environmental factors such as humidity, temperature changes, and chemical interference can degrade sensor performance over time [226].

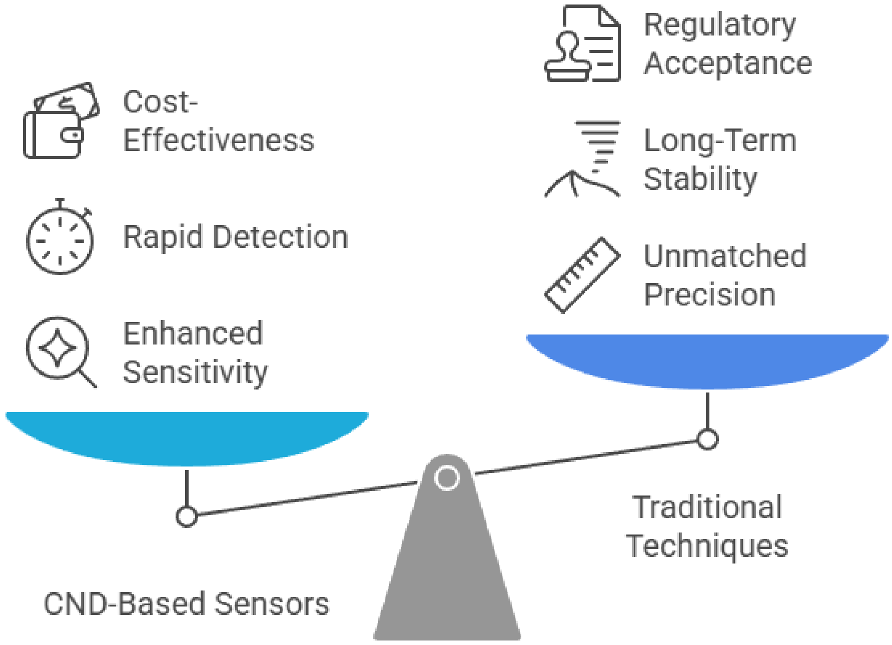

Figure 6. Balancing innovation and tradition in carbon nanodot-based sensors.

Looking ahead, future research should focus on overcoming these challenges through the development of multifunctional sensors, advanced hybrid materials, and novel synthesis and purification techniques. Incorporating artificial intelligence (AI)-assisted data processing may also improve signal interpretation and enhance sensor accuracy in complex environments. Moreover, the integration of CND-based sensors into smart, portable devices opens new avenues for real-time diagnostics and environmental surveillance. While traditional methods like ICP-MS and HPLC remain the gold standard for precision and regulatory approval, the ongoing evolution of carbon nanomaterials holds significant promise for expanding the practical utility and commercial scalability of CND-based sensing technologies.

8. Conclusions

Carbon nanodot-based sensors represent a significant advancement in the field of analytical detection technologies, offering unique advantages in sensitivity, selectivity, and environmental compatibility. Their successful application in identifying toxic compounds across food, agricultural, and environmental matrices demonstrates their versatility and efficacy. With customizable surface functionalities, tunable optical properties, and compatibility with diverse detection platforms, CNDs provide a foundation for next-generation sensing devices. However, challenges such as inconsistent synthesis, limited scalability, and long-term stability must be addressed to fully harness their potential. Future innovations should focus on refining green synthesis methods, improving functionalization strategies, and developing integrated portable sensor systems for real-time, on-site monitoring. The continued convergence of nanotechnology, materials science, and environmental engineering will pave the way for deploying CND-based sensors as essential tools in ensuring public health, food security, and ecological resilience.

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