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Nitrogen-doped carbon dots in food sensing: a review of detection mechanisms and applications

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Ensuring food safety is an escalating global priority due to the rising risk of contamination and the necessity for meticulous monitoring of food quality. Fluorescent nanomaterials, specifically carbon dots (CDs), have garnered interest among new technologies for their potential in sensitive and speedy detection systems. Nitrogen doping has become a pivotal approach for augmenting the optical and electrical characteristics of carbon dots, owing to nitrogen's elevated electronegativity and its capacity to produce functional groups and trap states that enhance photoluminescence and sensor efficacy. Nitrogen-doped carbon dots (N-CDs) have exceptional biocompatibility, stability, and adjustable fluorescence, rendering them suitable for food safety applications. This review article presents an overview of the synthesis methods for N-CDs and their application in food sensing. Particular uses encompass the identification of heavy metals, antibiotics, food colourants, and spoilage indicators. The review addresses contemporary obstacles in synthesis, reproducibility, and practical integration, while delineating future directions for the advancement of N-CD-based sensing in food safety monitoring.

1. Introduction

Food quality and safety are global concerns that significantly impact human health, economic stability, and societal well-being. Intensive agricultural production coupled with the globalization of food supply chains and large-scale food processing has increased the risks of contamination, adulteration, and spoilage.[1] Foodborne illness outbreaks, which are caused by pathogenic microorganisms, chemical residues, and natural toxins, still pose serious health effects, and such practices as excessive use of antibiotics in animal production, pesticide residues and loss of nutritional value during storage make the safety management even more complicated.[2–4] Conventional methods of analysis such as chromatography, mass spectrometry and immunoassays offer high accuracy and dependability, yet are frequently limited by their expensive nature, time-consuming procedures and complex apparatus and expert operators. These limitations highlight the need for fast, sensitive, and economical sensing technologies that can be applied in real-time and on-site, which is generating increasing interest in nanotechnology-enabled solutions.[5,6]

Carbon-based nanostructures have emerged as the most prominent among the nanomaterials because of abundance, environmental compatibility, and versatile functionalization. CDs, a new class of quasi-spherical nanoparticles typically below 10 nm in size, exhibit unique optical and electronic properties, most notably strong and tunable photoluminescence.[7,8] They can broadly be grouped into graphene quantum dots (GQDs), carbon nanodots (CNDs), and polymer dots (PDs), which differ in terms of their structure and synthesis.[9–11] Although these advancements have occurred, pristine CDs tend to possess relatively low quantum yields, have restricted emission tunability, and lack the selectivity in complicated food matrices. Recent progress in CD-based fluorescent probes has demonstrated improved optical sensitivity and functional versatility through heteroatom modification and structural engineering.[12,13] To overcome these issues, heteroatom doping has been extensively embraced as one of the solutions to modify the physicochemical and optical characteristics of CDs.[14] There are a few broad groups of heteroatom-doped carbon dots (CDS) that are identified with respect to the type of dopant used: single-element doping, co-doping and multi-element or hybrid doping. Sulfur (S), phosphorus (P), boron (B) and nitrogen (N) atoms are added to the carbon lattice in single-element doping to adjust the electronic structure and surface properties. There are a few broad groups of heteroatom-doped carbon dots (CDS) that are identified with respect to the type of dopant used: single-element doping, co-doping and multi-element or hybrid doping. Sulfur (S), phosphorus (P), boron (B) and nitrogen (N) atoms are added to the carbon lattice in single-element doping to adjust the electronic structure and surface properties. Co-doping combines two elements, such as N,S- or N,P-doping, to achieve synergistic effects that enhance photoluminescence efficiency, charge transport, and targeting. Multi-element or hybrid doping incorporates three or more heteroatoms to further optimize optical, electronic, and

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chemical properties for advanced applications.[15–17] Among these approaches, nitrogen doping has attracted particular attention due to nitrogen's comparable atomic size to carbon, its higher electronegativity, and its ability to introduce electron-rich functional groups and active sites that boost both photoluminescence and electron-transfer efficiency.[18,19] Structurally, N-CDs have pyridinic, pyrrolic, and graphitic nitrogen species, which are synergistic in promoting their photoluminescence intensities and electron transfer kinetics,[20] as illustrated in Fig. 1. These nitrogen structures enhance radiative recombination, stabilize emissive traps and form active surface sites that facilitate more powerful and selective interactions with food-related analytes. Consequently, N-CDs have an improved performance of sensitivity, stability, and specificity compared to that of undoped carbon dots.[21] Recent reports evidence the wide versatility of N-CDs in food sensing.[22] They have been used effectively for the detection of antibiotic residues, toxic heavy metals, multi-functional additives and preservatives, dyes, and spoilage in food.

As illustrated in Fig. 2, a literature search on ScienceDirect using the keywords 'Nitrogen-Doped Carbon Dots (N-CDs)' in combination with 'Food Sensing' reveals a marked increase in publications from 2015 to 2025. This trend increases the importance of the study of N-CDs and their emerging uses as versatile and sensitive materials in food quality and safety monitoring. The data were retrieved in August 2025.

The sensing mechanisms of N-CDs are broadly classified into three catagories: photoluminescence (PL)-based mechanisms, electron and energy transfer-based mechanisms, and dual sensing mechanisms.[23] Here, 'Dual Sensing Mechanisms' refers to systems that combine a photoluminescence readout with a complementary detection mode, such as dual-mode optical platforms (*e.g.*, fluorescence–colorimetric) or hybrid optical-electrochemical systems (*e.g.*, photoluminescence–electrochemiluminescence), to enhance reliability and mitigate false positives. Notably, the processes are

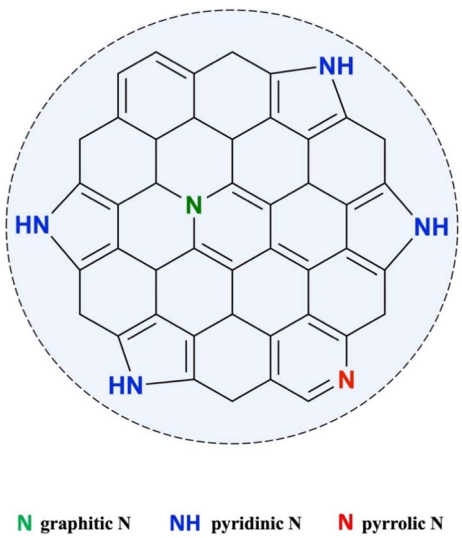


Fig. 1 Schematic representation of the structural configuration of N-CDs.

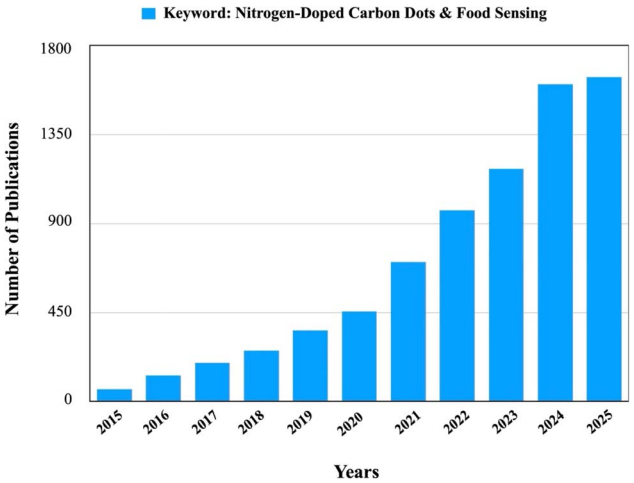


Fig. 2 A literature search on ScienceDirect reveals trends in the yearly release of N-CDs for food sensing from 2015 to 2025. The data indicate the growing research interest in N-CDs as multifunctional materials to monitor food quality and safety.

increased by nitrogen doping, which allows the transfer of electrons and establishes strong binding interactions between metal ions, organic molecules, and biomolecules. Moreover, N-CDs can be synthesized using biomass or in green conditions; thus, they can be made to fit in the ideals of green chemistry, which offer sustainable and environmentally friendly alternatives to food analysis. They are also biocompatible and less cytotoxic, which allows their safe integration into portable sensor devices, test strips and smartphone-based testing platforms.[24–28]

This review is a critical assessment of the use of nitrogen-doped carbon dots in food sensing, especially the mechanism and scope of use. The structural properties and synthesis schemes of N-CDs are discussed and much attention is paid to the effects of nitrogen introductions on their electronic and optical features. Subsequent sections address the fluorescence-based mechanisms that govern analyte recognition and signal transduction within food matrices. Recent application studies are then considered, including those on antibiotics, heavy metals, and spoilage markers, while also evaluating the device's performance in terms of analysis, integration, and real-life application. The article ends with a prospective outlook of the current issues, gaps in knowledge to be addressed, and opportunities in moving N-CDs as new-generation nanomaterials in monitoring food quality and safety.

1.1. Novelty of this review article

This review carves a distinct niche in the literature by providing the first dedicated, translational framework for Nitrogen-Doped Carbon Dots (N-CDs) in food safety monitoring, systematically bridging the gap between promising lab-scale research and practical field deployment. Its novelty lies in moving far beyond a simple summary of applications. I establish a rigorous "Synthesis, Structure, and Performance" paradigm (Sections 2–5.1), explicitly showing how specific nitrogen-doping configurations (graphitic, pyrrolic, pyridinic) dictate optical properties and

sensing mechanisms, a depth often missing in broader reviews. Uniquely, the review provides a three-tiered comparative analysis (Sections 5.2 and 5.3), quantitatively benchmarking N-CD sensors against both competing nanomaterials (*e.g.*, quantum dots, metal nanoclusters) and gold-standard conventional methods (*e.g.*, HPLC, ICP-MS), considering detection limits, response time, cost, and scalability. The core contribution lies in confronting the field's major translational bottlenecks: dedicated sections critically analyze matrix effect mitigation strategies (Section 5.4), biocompatibility and toxicity in food-contact applications (Section 7), and commercialization challenges such as reproducibility and device integration (Section 8). By integrating these elements with discussions on green synthesis, multiplex detection, and sensor arrays, this review provides a roadmap guiding researchers from fundamental material design to field-deployable food safety sensors. Furthermore, the review reframes the discussion of applications (Section 6) by organizing them not just by analyte, but by the design logic required for different food matrices. It highlights how sensing strategies must be tailored for distinct contaminants such as antibiotics, heavy metals, food additives, dyes, and spoilage indicators based on matrix complexity, target analyte properties, and N-CDs' doping chemistry and surface functionalization. This application-centric perspective moves beyond a catalog of successes, providing a practical framework for engineering N-CDs toward real-world detection scenarios. It also ties seamlessly to the critical discussions on matrix effects and selectivity challenges (Section 5.4), creating a cohesive narrative that connects material design to practical implementation.

2. Synthetic strategies

The synthesis of N-CDs is often classified into bottom-up and top-down approaches, as shown in Fig. 3, each providing unique benefits in regulating particle size, shape, surface chemistry, and doping efficacy.[29] The selection of a synthetic pathway is essential, since it directly influences the optical characteristics, electrical configuration, and functionalization capabilities of the resultant N-CDs.

2.1. Bottom-up approaches

N-CDs can be synthesized in a bottom-up approach through the molecular assembly and carbonization of nitrogen-containing organic precursors like citric acid, urea, or amino acids under the influence of thermal or microwave energy input. Particle size distribution, surface functionalities, and N-doping levels can be controlled within tight limits through this approach.[30,31]

2.1.1. Hydrothermal method. One of the frequently used methods to prepare N-CDs is *via* the hydrothermal method due to its simplicity, scalability, and ability to retain oxygen and nitrogen functional groups.[32] Organic precursors with high nitrogen contents, such as citric acid, urea, ethylenediamine, amino acids and lactic acids, are normally dissolved in aqueous solutions and are exposed to high temperature (120–250 °C) and a pressurized environment in a closed autoclave.[33,34] The functional properties of N-CDs are closely tied to their atomic and surface structure, which dictates photoluminescence and sensing performance. Insights from structural studies in other systems, such as yeast telomeric proteins, demonstrate how atomic-level organization can influence activity and specificity.[35] Several studies highlight the versatility of this approach. Monday *et al.*[36] presented the simple synthesis of N-CDs by the hydrothermal method using palm kernel shell biomass. In the study, the N-CDs were well dispersed in water and good blue fluorescence was observed. They were well spherically shaped and very dispersible in water and strong blue fluorescence was observed (Fig. 4).

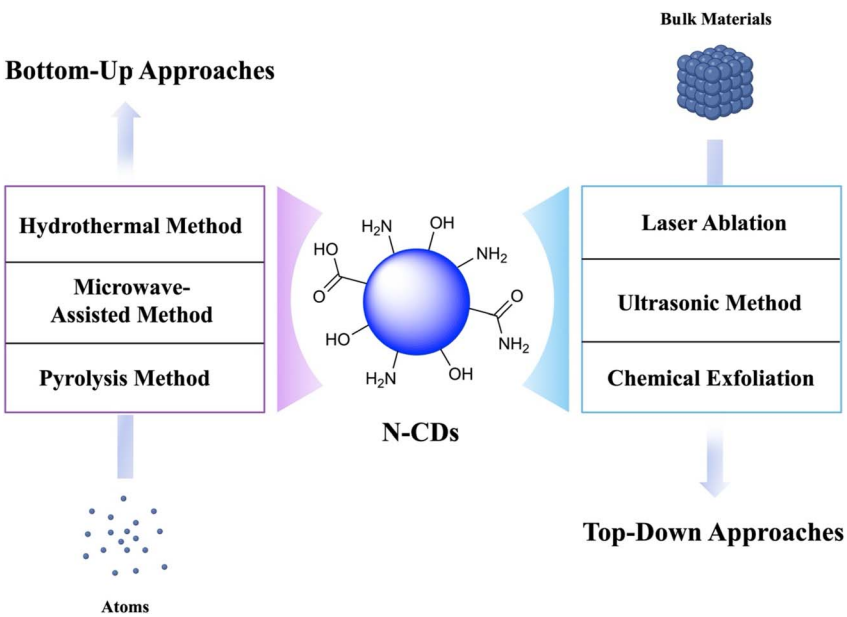


Fig. 3 Schematic representation of bottom-up and top-down approaches for synthesis of N-CDs.

In another study, Zhao *et al.*[37] synthesized N-CQDs *via* a carbon and nitrogen source composed of chitosan in a one-step synthesis process using the hydrothermal method. Similarly, Xie *et al.*[38] reported a green hydrothermal method for producing N-CDs using biomass highland barley as the starting material. These results are combined to create powerful and water-soluble N-CDs that have photostability benefits attached to them. Lastly, Wu *et al.*[39] reported a hydrothermal method to synthesize N-CQDs, using a biomass biosource, which consisted of microcrystalline cellulose. The process was a nitrogen-doped, controlled carbonization using acidic hydrothermal conditions and resulted in N-CQDs of uniform size distribution and spherical morphology with plentiful functional groups and high fluorescence.

2.1.2. Microwave-assisted method. Microwave-assisted synthesis is a volumetric heating method at a rapid rate and

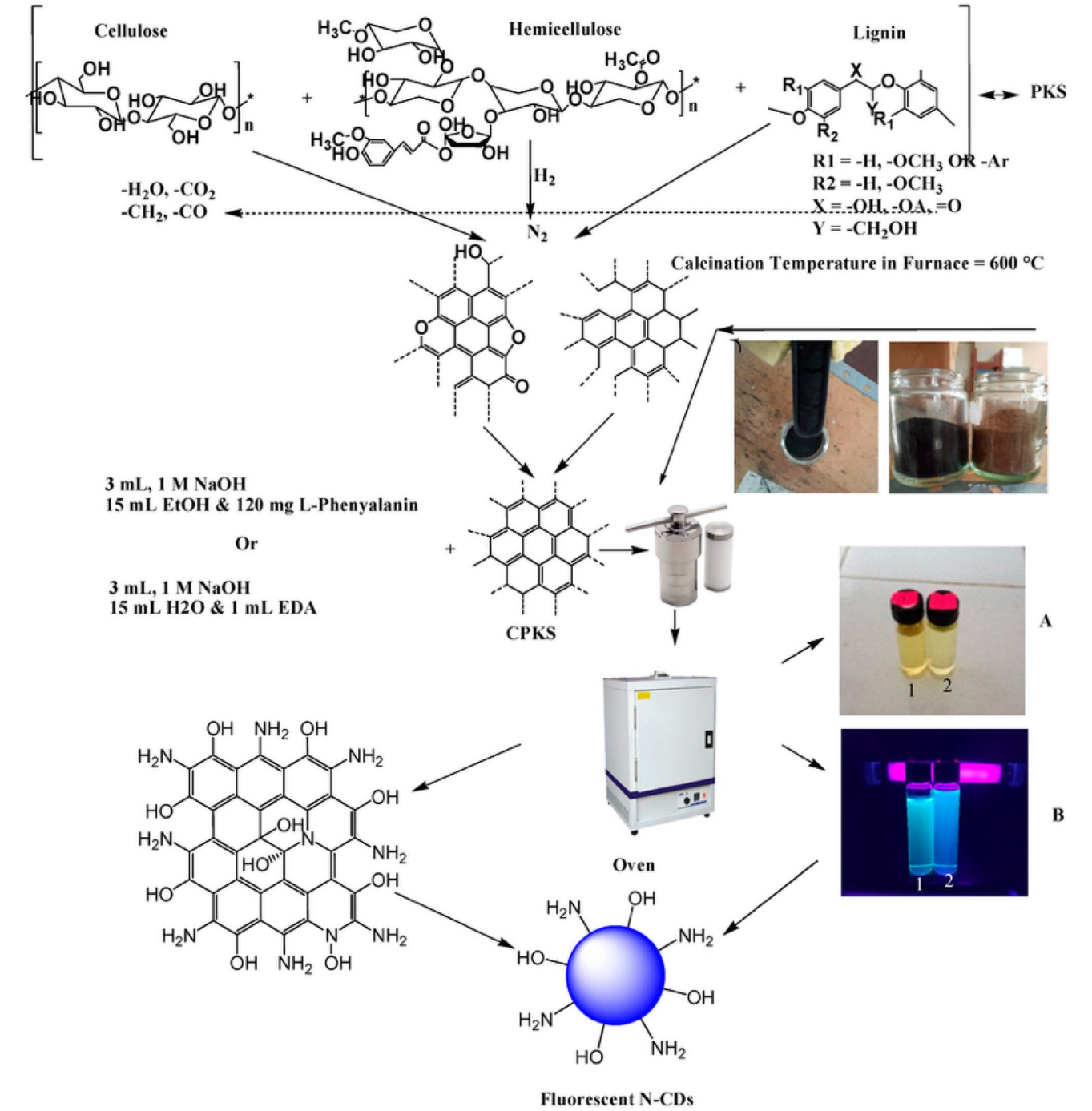


Fig. 4 Schematic representation of the synthesis of N-CDs using a one-pot hydrothermal synthesis method, this figure has been reproduced from ref. 36 with permission from MDPI, copyright 2021.

constant temperature; hence, it enables nucleation and growth of N-CDs within minutes. The technique is energy-sparing and can utilize a wide range of nitrogen-containing molecules, including those composed of biomass, small organic molecules, and polymers. The rapid heating makes the reaction proceed faster, thus producing an increased quantum yield and a narrow size dispersion. Additionally, microwave temperatures are potentially advantageous to the generation of some nitrogen functionalities, as they reduce the excessive heating degradation, thus enhancing the stability of fluorescence.[40–43] For instance, Bhatt *et al.*[44] have developed N-CDs in a single-step microwave-assisted reaction *via* nitrogenation/carbonization of prickly pear as the carbon source and *m*-xylylenediamine as the nitrogen source. Further, Magdy *et al.*[45] synthesized nitrogen-doped CQDs employing orange juice and urea through a microwave-assisted method. Lastly, Abdelaal *et al.*[46] reported a one-step, eco-friendly microwave-assisted synthesis of N-CDs using egg white as a glycoprotein-derived carbon source. The procedure, requiring just 3 minutes, accomplished concurrent carbonization and nitrogen doping. The resultant N-CDs had an average particle size of 2.98 ± 1.57 nm, pronounced blue fluorescence, and excitation-dependent emission characteristics.

2.1.3. Pyrolysis method. The pyrolysis synthesis method involves direct thermal degradation of solid or viscous nitrogen-rich precursors in reductive or inert atmospheres at very high temperatures, usually over 300 °C. This method produces very graphitic N-CDs with improved conductivity and chemical resistance and thus suitable for electrochemical and photocatalytic devices. Nevertheless, higher processing temperatures can lead to a partial loss of surface functional groups, which requires a subsequent passivation step of surface states when required in a high density of surface states.[47–51]

An example is the work by Ma *et al.*[52] describing an extremely efficient pyrolysis approach to fabricating N-CDs with superior stability and their photoluminescence strength. The fine-tuning of nitrogen doping and particle sizes was possible with the controlled pyrolytic method, allowing superior quantum yield, chemical robustness, and thermal stability of N-CDs (Fig. 5). Furthermore, Rong *et al.*[53] developed a one-pot solid-phase pyrolysis method of N-CDs. The giving method allowed the production of N-CDs with a homogeneous size distribution, a high fluorescence, and stable chemical properties. The reaction was both efficient and in scalable form, which offers a reliable way to produce N-CDs of high quality out of simple compounds. Finally, Thongsai *et al.*[54] developed multifunctional N-CDs through the pyrolytic method with the use of maleic anhydride and tetraethylenepentamine as starting materials. The one-step standard pyrolytic process produced N-CDs whose functionalization and high nitrogen content could be tuned accordingly.

2.2. Top-down approaches

The top-down approaches of N-CDs start with bulk carbon materials such as graphite, graphene oxide, carbon nanotubes, or soot, which are then fragmented into nanoscale particles. Nitrogen incorporation may occur either simultaneously during fragmentation or during a later doping phase.[55–57]

2.2.1. Laser ablation. A high-power pulsed laser irradiates a bulk carbon target immersed in a nitrogen-rich fluid or environment during laser ablation. The strong localized heating and plasma generation break the carbon material into nanometer-sized particles, while nitrogen atoms are assimilated from the surrounding environment. This technique produces extremely crystalline N-CDs with low defect density; however, it often requires careful regulation of laser settings and subsequent surface functionalization.[58–61]

Calabro *et al.*[62] developed a controlled laser ablation in liquid technique to synthesize N-GQDs using carbon nano-onions as the carbon source and nitrogen-containing aqueous solutions (ammonia, ethylenediamine, and pyridine) as dopant precursors. The method enabled accurate adjustment of nitrogen levels and surface functional groups, yielding N-GQDs with improved photoluminescence and electrocatalytic performance. The research illustrated the capabilities of these N-GQDs for bioimaging and oxygen reduction processes, emphasizing their multifunctional efficacy (Fig. 6). Furthermore, Santiago *et al.*[63] reported the synthesis of N-GQDs using pulsed laser ablation in the presence of diethylenetriamine (DETA). The resultant N-GQDs demonstrated strong photoluminescence, averaging around 3.4 nm in size and containing 26 at% nitrogen. Improved photoluminescence was ascribed to defect states caused by nitrogen. Temperature-dependent photoluminescence investigations demonstrated distinct carrier transfer processes. These results underscore the promise of laser-ablated N-GQDs for sophisticated optoelectronic applications.

2.2.2. Ultrasonic method. Ultrasonic-assisted synthesis is an effective top-down approach for synthesizing N-CDs, using high-frequency sound waves to create acoustic cavitation in a liquid medium including bulk carbon sources and nitrogen-rich precursors.[64–66] The rapid formation and implosive collapse of microbubbles produce localized hot spots with temporary temperatures reaching several thousand kelvin and pressures surpassing hundreds of atmospheres. These severe microenvironments concurrently disintegrate the carbon structure into nanoscale domains and activate nitrogen-containing compounds, facilitating their *in situ* integration into the carbon lattice. The resultant N-CDs demonstrate regulated particle sizes, tailored surface characteristics, and altered electronic band structures, which improve their photoluminescence, quantum yield, and efficacy in sensing, imaging, and catalytic applications.[67–69] A notable application of this method was demonstrated by Ma *et al.*[70] demonstrated a facile one-step ultrasonic synthesis technique to generate fluorescent N-CDs using glucose as both the carbon source and nitrogen dopant. Ultrasonic irradiation prompted acoustic cavitation, enabling carbonization and concurrent nitrogen incorporation into the carbon dot structure without the need for further chemical reagents or harsh conditions. The resultant N-CDs demonstrated strong blue fluorescence, a high quantum yield, and stable photoluminescence. In another study, Chong Qi *et al.*[71] developed an efficient ultrasonic-assisted hydrothermal

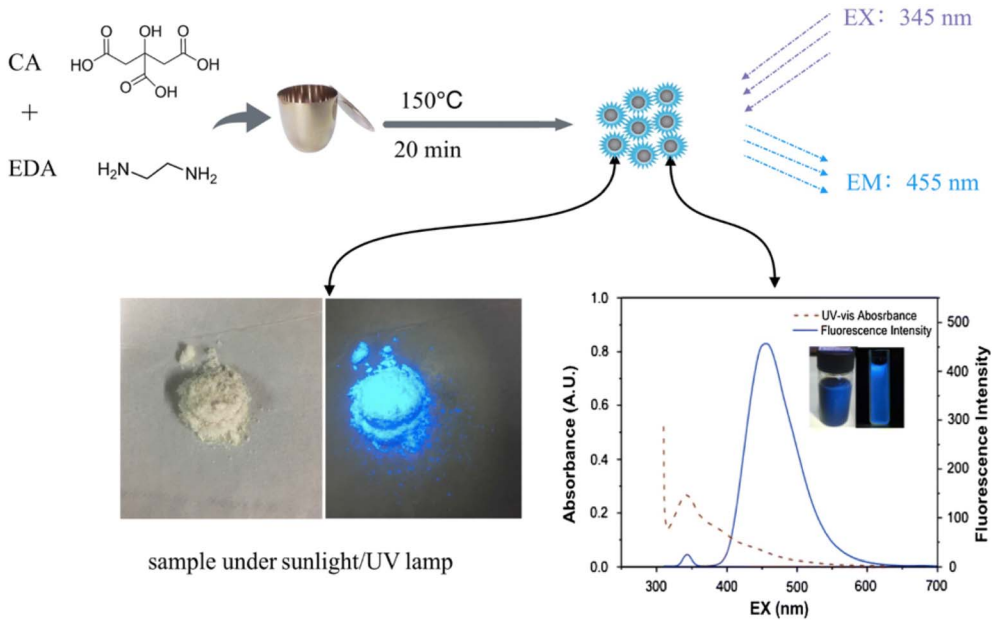


Fig. 5 Schematic diagram of the preparation of N-CDs by pyrolysis synthesis method, this figure has been reproduced from ref. 52 with permission from Springer Nature, copyright 2019.

synthesis of highly fluorescent nitrogen-doped carbon quantum dots (N-CQDs) using simple precursors under moderate circumstances.

2.2.3. Chemical exfoliation. The chemical exfoliation method produces nitrogen-doped carbon dots by decomposing layered carbon materials, such as graphite or graphene oxide, by intense oxidative or intercalation reactions involving nitrogen-containing compounds.[72–74] Reactive substances, such as acids, oxidants, or alkali intercalants, penetrate graphitic layers, reducing interlayer forces and facilitating the release of nano-scale carbon fragments. Nitrogen incorporation occurs either during exfoliation or by post-treatment with nitrogen-rich compounds. This technique could give N-CDs with adjustable surface properties and increased nitrogen content; however, the technique typically demands harsh reaction conditions and can necessitate significant purification to eliminate excess reagents and chemical by-products.[72,75,76] The versatility of this method is evident in several studies; Zhou *et al.*[77] successfully demonstrated a large-scale electrochemical exfoliation method to synthesize N-CQD employing ammonium bicarbonate as the source of nitrogen. This approach provided N-CQDs with high dispersibility and N-containing functional groups, exhibiting an effective scalable method to produce high-quality N-CQDs. In another study, Fu *et al.*[78] developed an electrochemical method to synthesize multicolour fluorescent N-GQDs through the direct exfoliation of a graphite rod in a nitrogen-rich electrolyte to produce N-GQDs with tunable optical properties and rich surface functional groups. Lastly, Chu *et al.*[79] synthesized N-GQDs by an electrochemical exfoliation approach utilizing nitrogen-containing electrolytes, allowing concurrent exfoliation and nitrogen doping. The approach yielded N-GQDs with precisely regulated dimensions, plentiful surface nitrogen functionalities, and distinctive electrogenerated chemiluminescence and electroluminescence characteristics.

2.3. Green synthesis of N-doped carbon dots from biomass precursors

The burgeoning environmental and safety issues surrounding the currently used synthesis pathways to N-CDs that frequently involve the use of chemical reagents and organic solvents have prompted the rising popularity of the sustainable, green synthesis approaches.[80] The strategies are aimed at the utilization of renewable biomass-based precursors and reaction conditions that are neutral to the environment to obtain N-CDs with a lower ecological footprint and enhanced acceptable food-related and bio-applicability.[81] In green synthesis, several biomass sources abundant in carbon and nitrogen (*e.g.*, plant leaves, fruit peels, seeds, food waste (*e.g.*, shrimp shells, eggshell membranes), and animal-based products such as silk, wool, and gelatin) are used as the carbon skeleton, as well as the nitrogen source,[82] as shown in Fig. 7. These precursors do not only remove the necessity of using dangerous chemicals, but they also increase the inherent nitrogen content, which allows simple *in situ* doping in the course of the synthesis.[83] Solvent-free and aqueous-based fabrication processes have received extensive research on environmentally friendly fabrications. Hydrothermal, solvothermal, and microwave-assisted aqueous reactions allow the controlled carbonization and passivation of the precursors under mild and safe conditions to produce N-CDs with consistent particle size, high water solubility, and photoluminescence tuneability. Direct pyrolysis, or solid-state heating of biomass, and solvent-free or dry thermal processes have additional benefits of scalability, energy efficiency, and simplification by removing the necessity of using a solvent as

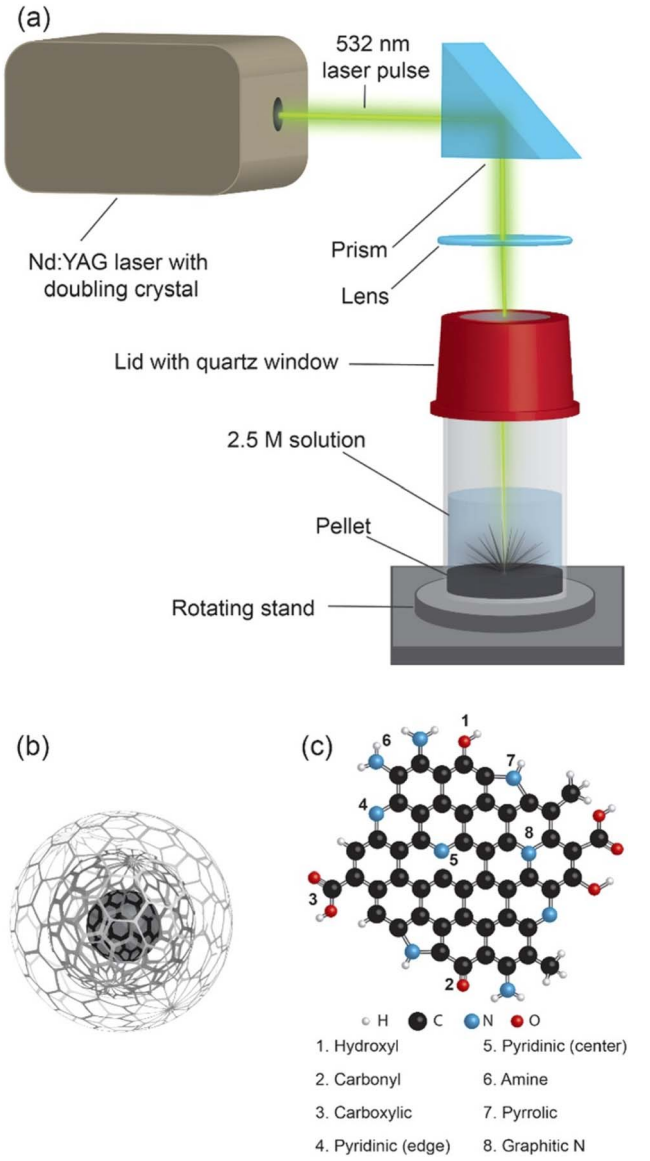


Fig. 6 A typical laser ablation setup (a). When the laser irradiation, the precursor CNOs (b) are transferred to the graphene quantum dots (c), this figure has been reproduced from ref. 62 with permission from the American Chemical Society, copyright 2019.

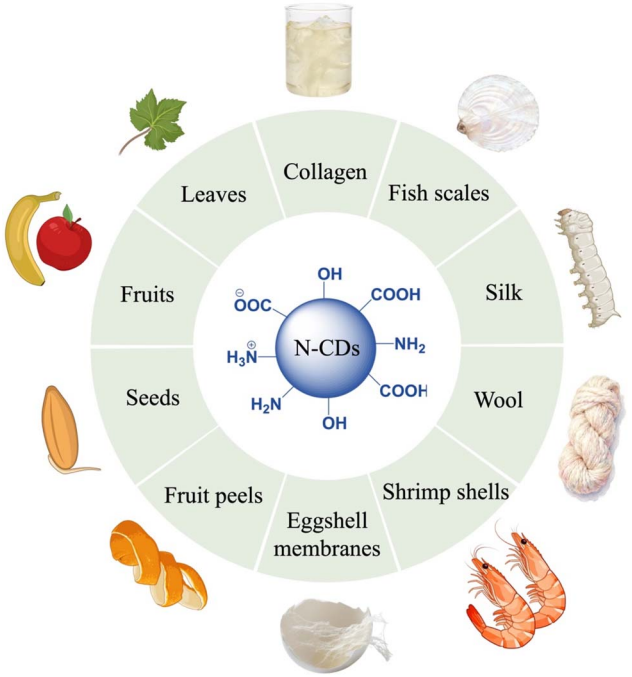


Fig. 7 Illustrative overview of various biomass sources used for the green synthesis of N-CDs.

well as reducing the number of purification steps required after the synthesis process.[84–86] N-CDs synthesized green have tended to be heteroatom co-doped (*e.g.*, with nitrogen, sulfur, or phosphorus) and rich in surface functionalities to improve their optical capabilities and sensing capabilities in complex food systems. In addition, they have low cytotoxicity and are inherently biocompatible, and as such, they are very promising in food safety surveillance and biological imaging. Although these benefits exist, there are still such challenges as batch-to-batch variability caused by the heterogenous structure of biomass precursors. The solution to these drawbacks involves standard precursor pretreatment, optimization of synthesis procedures, and stringent purification to attain repeatability and a uniform quality of materials.[87,88]

Several studies have pointed out the green synthesis of N-CDs through the precursors with biomass sources and eco-friendly techniques. Atchudan *et al.*[89] showed a simple hydrothermal process for making N-CDs using the extract from *Chionanthus retusus* fruit, which have high photoluminescence and biocompatibility, making them suitable for detecting metal ions in the body and in biology. In an analogous strategy, Immanuel Edison *et al.*[90] used a high-speed microwave-assisted method with L-ascorbic acid and 2-alanine as the sources of carbon and nitrogen, respectively, and obtained N-CDs with high blue fluorescence, high quantum yield (approximately 14 percent), and low cytotoxicity, which were effective in bioimaging. The multifunctional capabilities of other N-CDs produced using biomass have been demonstrated.

Rajapandi *et al.*[91] produced N-CDs by the use of *Opuntia ficus-indica* fruits and exhibited good photocatalytic activity in degrading methyl orange and good antibacterial properties against various bacterial strains. Lastly, Raji *et al.*[92] prepared N-CDs with a high fluorescent level using jackfruit seeds through a green method with the help of a microwave that exhibited satisfactory solubility, photostability, and storage stability. These N-CDs allowed sensitive and selective fluorimetric detection of the Au^{3+} ions and were used in *in vitro* multiplex cell imaging, in addition to green synthesis of gold nanoparticles.

Overall, it is shown that N-CDs based on green, biomass-based methods can be readily synthesized by hydrothermal or microwave-assisted, diverse methods and have a range of applications in sensing and bioimaging, photocatalysis, and antibacterial activity. The fact that natural carbon and nitrogen sources have been used and that the mild or solvent-free

conditions have been used highlights how these approaches can be used to facilitate sustainable nanomaterial fabrication and promote better environmental practices by research in the discipline.

3. Physicochemical and optical characterization of nitrogen-doped carbon dots

Effective characterization of N-CDs is crucial in their application in food sensing, as it ensures high sensitivity, selectivity, and stability. The transmission electron microscopy (TEM) and high-resolution TEM (HRTEM) analysis reveal that N-CDs usually exhibit a quasi-spherical morphology with a size range from 2 to 10 nm. Well-defined lattice fringes indicate partial graphitic crystallinity, which supports strong fluorescence in complex food matrices.[93] Similarly, scanning electron microscopy (SEM) characterization enables aperturing profound insights into the structures and morphological features of N-CDs.[94] The X-ray diffraction (XRD) patterns commonly display broad (002) reflections characteristic of amorphous or turbostratic carbon structures. Nitrogen doping modifies the interlayer distance, enhancing the optical properties that may be applied in the identification of the contaminants.[95] The structural order is supported by Raman spectroscopy, which presents typical D and G bands; the I_D/I_G ratio indicates that a significant number of flaws in the structure are introduced by nitrogen to increase reactivity of the surface, thus promoting functionalization with specific recognition elements on food analytes.[96]

FTIR (infrared) analysis indicated that a lot of oxygen- and nitrogen-carrying functional groups (*e.g.*, hydroxyl, carbonyls, and amines) are present, which enhances the dispersibility in water and conjugates them with the biomolecules to target specific foodborne pathogens and adulterants.[97] Photons are utilized through the X-ray photoelectron spectroscopy (XPS), which gave a refined interpretation of the spatial information concerning surface chemical states to encompass pyridinic nitrogen, pyrrolic nitrogen, and graphitic nitrogen, along with other forms of nitrogen, which are pivotal parts of moderating harmonic density and improving sensor sensitivity.[98] UV-vis spectroscopy elucidated electronic transitions, including π–π^* transitions of aromatic C=C bonds and n–π^* transitions of C=O or C–N bonds, with corresponding absorbance spectra serving as potential indicators for food safety testing.[99] Photoluminescence (PL) measurements proved that the fluorescence was excitation dependent, with quantum yields of nitrogen-doped materials being substantially enhanced, and multiplexed fluorescence detection of several analytes was possible on a single food matrix.[100]

In testing, thermogravimetric analysis (TGA) verified considerable thermal stability, a requirement in sensing processing or heating used in food systems, and zeta potential analysis indicated that there was robust colloidal stability, thus reducing aggregation in a food system across the storage period or in complex food suspensions.[101] For example, Hu *et al.*[102] synthesized N-CDs and characterized their structural features, morphology, elemental composition, and surface functionalities with TEM, FTIR, XPS, and optical spectroscopy. The TEM analysis (Fig. 8a) proved the establishment of a homogeneously dispersed, quasi-spherical N-CD whose dimensions were nanoscale. XPS (Fig. 8b) also explained the mechanism of successful nitrogen integration into the structure and described the bonding structure of C, N, and O, which validated the structural source of their fluorescence properties. The FTIR (Fig. 8c) showed a large number of functional groups present on the surface, including hydroxyl, carboxyl, and amine groups, which make the materials dispersible in an aqueous medium and also provide them with sensing capabilities. The UV-vis absorption and fluorescence emission spectra (Fig. 8d) indicated high optical activity with clear absorption peaks and excitation-dependent fluorescence, which indicated that the N-CDs could be utilized as a highly sensitive fluorescent probe targeting pyrophosphate and alkaline phosphatase. These descriptions confirm that the structural and chemical properties of the N-CDs also explain their usage as highly sensitive fluorescent indicators to detect a pyrophosphate and alkaline phosphatase, as illustrated in Fig. 8.

Atchudan *et al.*[103] described the study of X-ray diffraction (XRD) and Raman spectroscopies to characterize natural nitrogen-doped carbon dots (NN-CDs). XRD spectra (Fig. 9a) revealed a wide diffraction pattern in the range of $\theta \approx 22$–$25°$, which reflected the amorphous spreading carbon character of the NN-CDs containing some graphitic regions. The Raman spectroscopy (Fig. 9b) showed definite D and G bands, respectively related to structural collisions and applied graphitic carbon, in accordance with the level of graphitization and the carbonaceous structure of the NN-CDs. The combination of these methods gave complementary results for both the structural and graphitic properties of the synthesized NN-CDs, as shown in Fig. 9.

4. Sensing mechanisms of N-CDs in food applications

N-CDs have emerged as highly effective and have also become effective fluorescent nanomaterials for food sensing due to their photophysical properties, excellent water solubility, chemical stability, low toxicity, and tunable surface functionalities imparted by nitrogen heteroatoms. Their sensing performance in food analysis is mainly attributed to their excitation-dependent and highly sensitive photoluminescence (PL), which is further enhanced by nitrogen-induced defect states, abundant surface functional groups, and high quantum yields. Together, these features provide a versatile platform for interaction with a wide range of analytes, including foodborne toxins, heavy metals, antibiotics, and dyes,[104,105] as illustrated in Fig. 10.

The incorporation of nitrogen dopants modifies the electronic structure of carbon dots by increasing the electron density and introducing mid-gap states, thereby facilitating electron, charge, or energy transfer processes with target molecules. These interactions can modulate the PL intensity or

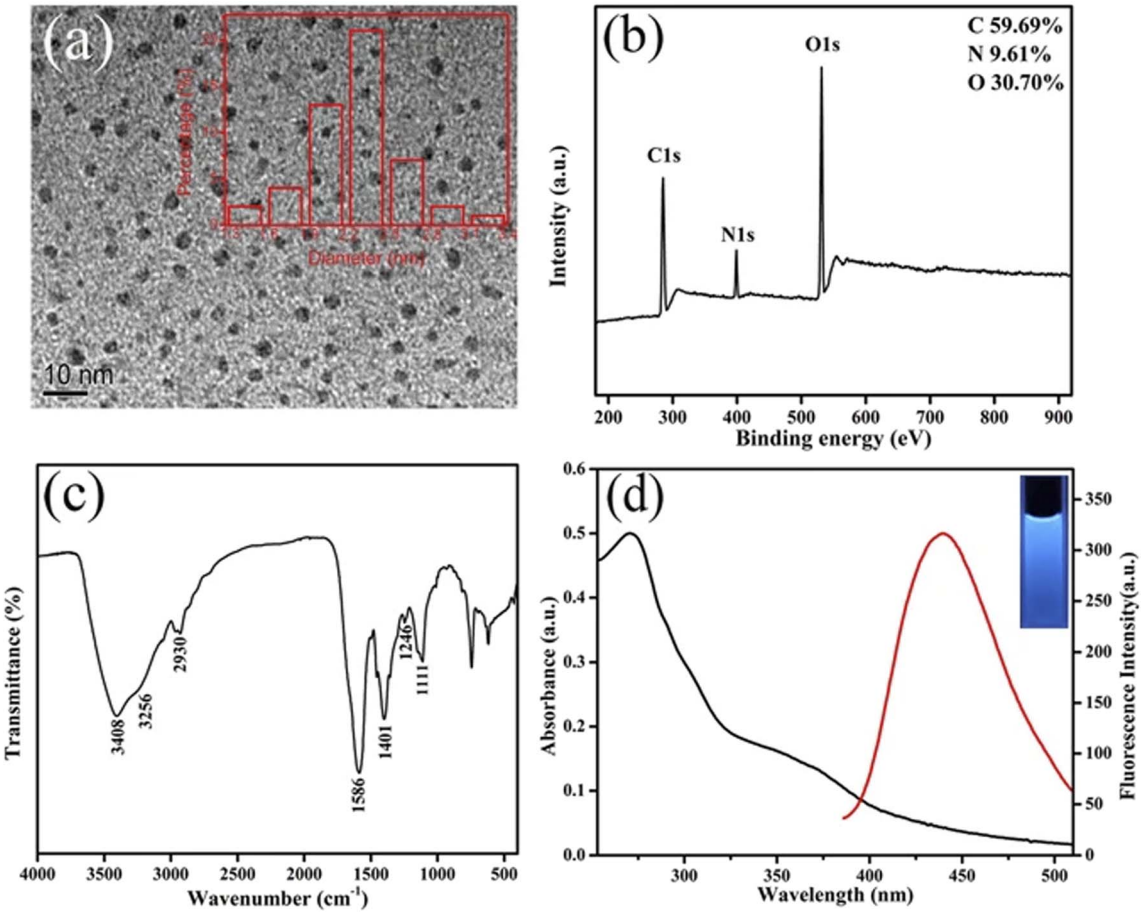


Fig. 8 (a) TEM image of N-CDs. Inset: Corresponding histograms of the N-CDs size distributions. (b) The XPS spectrum of N-CDs. (c) The FTIR spectrum of N-CDs. (d) Absorption and fluorescence emission spectrum of N-CDs. Inset: N-CDs solution fluorescence image under UV irradiation, this figure has been reproduced from ref. 102 with permission from Springer Nature, copyright 2017.

emission wavelength, forming the basis for various sensing modes, such as turn-off, turn-on, and ratiometric detection modes.[106] In food applications, these mechanisms have been exploited to detect harmful contaminants, including amaranth dye in candy,[107] perfluorooctyl sulfonate,[108] aflatoxin B1 in grain,[109] formaldehyde in seafood,[110] and indicators of food freshness, including glutathione[111] or enzymatic activity.[112]

The mechanisms based on the photoluminescence can be divided into the following three groups: fluorescence quenching (turn-on), fluorescence enhancing (turn-off), and ratiometric fluorescence. The most commonly reported is fluorescence quenching, in which the PL of N-CDs is selectively quenched in the presence of the analyte *via* the dynamic quenching mechanism, static quenching, the inner filter effect (IFE),

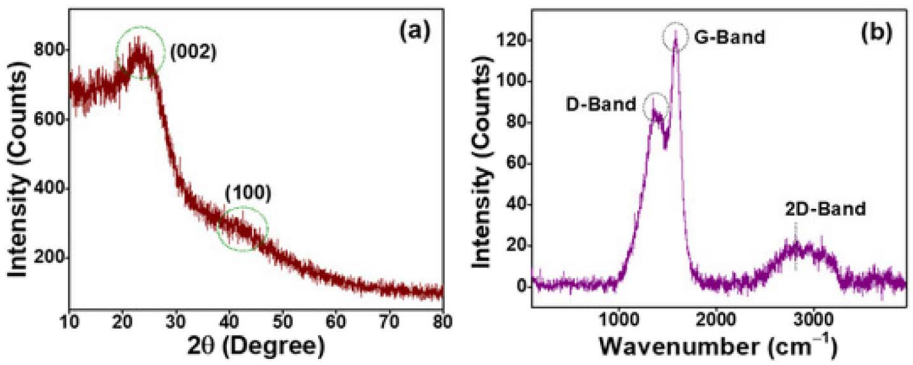


Fig. 9 (a) XRD pattern and (b) Raman spectrum of natural nitrogen-doped carbon dots (NN-CDs), this figure has been reproduced from ref. 103 with permission from MDPI, copyright 2023.

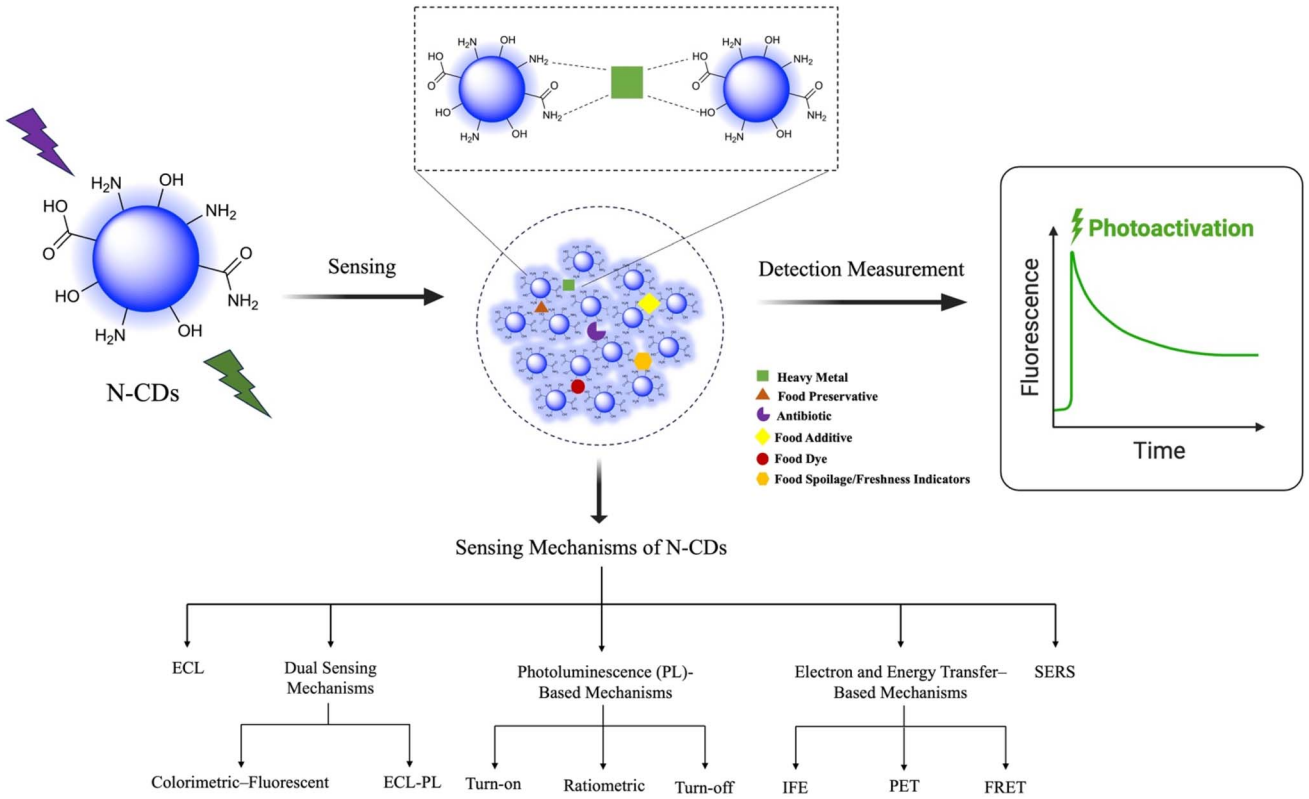


Fig. 10 Schematic diagram of N-CDs for food pollutants detection and their sensing mechanisms.

photoinduced electron transfer (PET) or even Förster resonance energy transfer (FRET). For instance, N-doped graphene quantum dots exhibited strong PL quenching in the presence of amaranth dye, enabling sensitive detection in confectionary products through stacking and electrostatic interactions.[107] Similarly, blue-emissive N-CDs synthesized from citric acid were quenched by picric acid *via* a combination of electron transfer and static quenching mechanism.[113] In food-related biological matrices, it involved the detection of dopamine through a quenching process in the case of N-CD using H-bonding and electron donation and acceptor interactions.[114,115] In contrast, fluorescence enhancement mechanisms involve analyte-induced passivation of surface traps, catalytic reactions, or aggregation-induced emission (AIE) to increase PL intensity. A notable example is the acid-triggered fluorescence enhancement of robust N-CDs for Fe^{3+} detection,[116] where surface protonation improved radiative recombination efficiency, and the Fe3^{+}–GSH "on–off–on" system showed potential for monitoring antioxidant levels related to food spoilage.[111,117] Other pathways for fluorescence enhancement include metal ion-catalyzed changes in nitrogen speciation[118] or the formation of complexes, such as the Fe^{3+}-catalyzed detection of Al^{3+} using N-CDs.[119] Ratiometric fluorescence sensing, on the other hand, relies on simultaneous changes in two distinct emission bands, producing self-calibrated signals that reduce environmental interference and matrix effects in complex food samples. For example, N-CDs have been combined with terbium complexes[120] or metal–organic frameworks[121] to develop dual-emission probes capable of detecting analytes relevant to nutritional supplements, food adulteration, adenosine monophosphate, or metformin. Similarly, two-wavelength ratiometric systems have been successfully applied to detect phosalone pesticide residues[122] and glutathione in food extracts,[123] providing higher specificity compared with single-channel sensors.

Beyond modulation of PL intensity, many N-CD sensors function *via* photoinduced electron or charge transfer processes. An example is the existence of the IFE, in which fluorescence is quenched due to the overlapping absorption of the analyte with the excitation or emission spectrum of N-CDs, respectively, without making any direct contact. Similarly, N-CDs quenched the SERS signal extensively with gold nanoparticles to detect bisphenol A[124] in the context of tracking migration into food quality sensing through N-CDs utilized particular IFE overlap in absorption.[125] The technique to monitor food spoilage was the detection of glutathione on N-CDs–Hg^{2+} complexes applied in the selective quantity of seafood matrices.[117] FRET is a non-radiative process of energy transfer during which energy is non-radiatively transferred from the excited-state N-CDs (donor) to an acceptor chromophore within a distance of ~10 nm and poses a demand on spectral overlap and dipole–dipole coupling. The use of FRET-based N-CD sensors has also been established in a variety of applications, including metal detection,[126] sensing curcumin in food matrices,[127] and sensing creatinine[128] to determine nutritional metabolism markers in dairy and meat products. PET processes occur between an analyte and states that transfer electrons onto

or take electrons off the N-CD excited state and change the rates of recombination. As an example, PET of N-CDs with Hg^{2+} facilitated sensitive readings in water and beverage samples,[117] whereas PET sensing of aspartic acid and H_2O_2 (ref. 129) in foods are indirect pathways to spoilage studies of perishable foods that use enzymes. The reliability is further increased using a dual or multimodal sensing option where the readout alternative to PL is combined with significantly different detection modes.

Dual or multimodal sensing mechanisms further enhance reliability by combining PL readouts with complementary detection modes. Colorimetric–fluorescent dual-mode systems integrate visual color change with fluorescence modulation, offering both naked-eye detection and sensitive quantitative analysis. N- and P-co-doped CDs have been applied for dual-mode detection of formaldehyde,[110] a hazardous additive in fish preservation, and Fe^{3+} detection[130] using peroxidase-like activity in beverage samples. N-CD dual-mode systems have also been used to detect curcumin of relevance in spice authentication[131] and nitrite in processed meats using orange-emitting N-CDs, which made fluorescence colorimetry correlations.[132] Such two-mode schemes are more accurate in complicated food matrices because they reduce false positives. Electrochemiluminescence (ECL)-based PL systems combine the optical signal of N-CDs with ECL sensor platforms to achieve enhanced sensitivity in the detection of traces of analytes. An example is the integration of graphene quantum dots with nitrogen doping to ECL sensors to detect folic acid[133] that are important in food supplements, nutritional sources, and farm-related environmental water sources.

4.1. Mechanistic classification of N-CD-based sensing

Building on the detailed food-sensing examples presented above in Section 4, the photoluminescence (PL)-based mechanisms of N-CDs can be mechanistically classified to rationalize their sensitivity, selectivity, and reliability in complex food matrices. These mechanisms are broadly categorized as fluorescence quenching (turn-off), fluorescence enhancement (turn-on), ratiometric/dual-emission sensing, and energy-transfer-based processes such as FRET or electrochemiluminescence (ECL). Fluorescence quenching is often observed *via* dynamic or static quenching, photoinduced electron transfer (PET), or the inner-filter effect (IFE). IFE is more likely to occur when the analyte exhibits strong spectral overlap with the N-CD excitation or emission but does not form direct interactions with the N-CD surface; it is generally faster to observe and simple to implement but is highly dependent on analyte concentration and spectral overlap, which can reduce selectivity in complex food matrices. PET, in contrast, requires close interaction between the analyte and N-CD surface functional groups, often mediated by pyridinic nitrogen, enabling high sensitivity and selectivity toward metal ions such as Hg^{2+} or Cu^{2+}.[107,113–115] PET is typically more selective than IFE but can be slower if analyte diffusion is limited. Fluorescence enhancement (turn-on) occurs when analytes passivate surface traps, induce aggregation, or catalyze radiative recombination. Pyrrolic nitrogen plays a key role in creating emissive defect states that selectively respond to analytes such as Fe^{3+}, where acid-triggered enhancement improves radiative efficiency.[111,116] Turn-on mechanisms generally offer low background interference, improving sensitivity, but can be affected by competing ions or environmental conditions in complex foods. Ratiometric and dual-emission systems exploit multiple emissive centers generated by heteroatom co-doping or surface functionalization, providing self-calibrated signals that reduce matrix interference and improve specificity for analytes such as aflatoxins or pesticide residues.[120–123] While highly selective, these systems require more complex synthesis and careful optimization of dual emission centers.

Energy-transfer-based mechanisms, including FRET and ECL-coupled PL, allow complementary readouts and trace analyte detection. FRET relies on donor–acceptor spectral overlap within ~10 nm, making it highly sensitive but requiring precise design, whereas ECL combines optical and electrochemical readouts to improve reliability in complex matrices.[124–127]

Mechanistically, the prevailing sensing pathway for a given analyte is dictated by the nitrogen doping type, co-doping strategy, surface functional groups, and analyte properties. Fast response times are usually associated with IFE or surface-mediated PET, high selectivity with PET or turn-on processes, and high sensitivity and reliability with ratiometric or energy-transfer systems. However, limitations exist in complex food matrices: IFE can be confounded by colored matrices, PET may be disrupted by competing electron donors, and turn-on mechanisms may be affected by pH or ionic strength. This critical classification framework not only links the type of nitrogen doping to mechanism and sensing performance but also provides practical guidance for designing N-CDs with tunable speed, selectivity, and sensitivity for real-world food applications. It enables the rational development of multi-functional N-CD probes tailored to diverse analytes and matrix complexities.

5. Performance and comparative analysis of N-CDs

5.1. Nitrogen-doping forms and sensing performance

The nitrogen doping of carbon dots (N-CDs) is a crucial factor when it comes to the electronic structure, surface chemistry, and, finally, the sensing characteristics. Nitrogen may enter the carbon skeleton in various forms, and the most frequent are pyridinic, pyrrolic, and graphitic (quaternary) forms with different electronic and chemical characteristics affecting the recognition and fluorescence behavior of the analytes.[134,135]

The pyridinic nitrogen, which is usually found at the edges of the graphene-like domains, adds one lone pair of electrons to the π-system, increasing electron-donating capacity and surface polarity. This geometry was demonstrated to enhance close interactions with metal ions, promoting fluorescence quenching or fluorescence enhancement *via* coordination or electron-transfer processes. Pyridinic sites can be good binding hot-spots, allowing selective binding of transition metal ions (*e.g.*,

Cu^{2+}, Fe^{3+}, or Hg^{2+}), which can enhance the sensitivity of ratiometric or dual-emission sensors.[113,136]

The pyrrolic nitrogen incorporated in the carbon lattice as a five-membered ring is also a contributor of two electrons to the π-conjugated system, generating localized defect states that act as emissive centers. These centers have the capability of switching the intensity and lifetime of fluorescence and hence affect responses of analytes specific to their signal. Pyrrolic nitrogen has been linked to an increased fluorescence quantum yield as well as the development of excitation-dependent emission, which is especially beneficial in multicolor sensing and multiplex detection of organic molecules and biomolecules.[137,138]

Graphitic (quaternary) nitrogen that replaces carbon atoms on the sp^2-hybridized graphitic planes alters the electronic band structure to allow the introduction of electron-rich centers with preservation of lattice conjugation. This format has been shown to increase the charge carrier mobility and stabilize the carbon dot framework and leads to improved photostability and tunable emission. Photoinduced electron transfer processes are especially sensitive to graphitic nitrogen, which has been found to be useful in modulating them to achieve selective sensing of redox-active analytes and provide strong ratiometric sensing.[100,139] Mechanistically, the interactions of these chemically formed nitrogen dopings determine the distribution of electronic states, surface polarity, and density of defects, which determine the process of analyte binding, energy- or electron-transfer processes, and fluorescence modulation.[140–142] Overlapping of several nitrogen configurations can often lead to synergistic properties, which are high sensitivity (provided by pyridinic sites), tunable emission (provided by pyrrolic sites), and photostability (provided by graphitic sites), enhancing the overall sensing performance of N-CDs with a wide range of different analytes, including metal ions, small molecules, and biomacromolecules. To recap it all, it is important to have insight into and to manage the relative proportion and spatial distribution of pyridinic, pyrrolic, and graphitic nitrogen to rationally design the N-CDs into high selectivity, sensitivity, and multiplexed detection. This mechanistic understanding gives an underlying platform to the customization of N-CDs to particular sensing needs in the environment, food, and biomedical setups.[143,144]

5.2. Comparative assessment of N-CDs and other fluorescent nanomaterials

Fluorescent nanomaterials have become the foundation of optical sensing in the contemporary world, created by the capability of creating highly sensitive, miniaturized and multifunctional detection platforms in environmental, biological, and food analysis. Of them, semiconductor quantum dots (QDs), noble metal nanoclusters (MNCs) and carbon-based materials (especially nitrogen-doped carbon dots) are the three major classes of materials that are defining this area. All of them have their unique benefits that depend on their composition, photophysical process, and synthesis method. QDs are inorganic semiconductor nanoparticles with high quantum yields and limited emission spectra; MNCs are atomically precise (usually Au, Ag or Cu) metallic aggregates with molecule-like electronic transitions; and N-CDs are a new carbon-based substitute with higher quantum yields and better chemical stability. In this range, N-CDs have received particularly thorough attention due to their combination of the attractive optical versatility of QDs and the safety, biocompatibility, and green synthesis pathways of metal-based systems. Their cheap, low-temperature and frequently biomass-based synthesis permits scalable and eco-friendly production of the same, and nitrogen doping optimizes the fluorescence efficiency and affinity to the analyte.[145,146]

Conversely, QDs and MNCs, despite their excellent optical accuracy, tend to require expensive precursors, require high-energy synthesis, and use reagents that are environmentally unsafe, which pose challenges toward sustainable and large-scale sensing studies. These trade-offs are highlighted in a critical comparative analysis that has been supported by the recent literature. Semiconductor QDs, including CdSe and PbS systems, were demonstrated to provide superior quantum yields (>80%) and sharp emission bands, due to which Qureshi *et al.*[147] and Zhao *et al.*[148] demonstrated the capability in multiplexed biosensing and photoelectrochemical devices. Their synthesis is, however, high temperature (at least 250 °C) and uses toxic solvents and heavy-metallic precursors, thus making them costly and hazardous to the environment. Noble metal nanoclusters (MNCs), including those reported by Ou *et al.*[149] and Yuan *et al.*,[150] are, on the other hand, more atomic-scale in control of luminescence and have exclusive catalytic capabilities, but these advantages are confined by the high cost of the material and instability during real-world sensing conditions. Contrarily, Liu *et al.*[151] show that N-CDs can be prepared by simple, low-temperature, and metal-free methods to generate greener and multifunctional nanoprobes, such as in humidity sensing and information encryption. Nonetheless, a thorough critical examination should acknowledge that N-CDs are objectively declining in performance. QDs are still the gold standard in optical precision, with higher quantum yields (QY) and narrow symmetric emission peaks that are essential in applications with the highest spectral resolution, including state-of-the-art multiplexing and display technologies.[152]

N-CDs are also very photostable and tunable, but they usually have broader emissions and lower QYs (10–60%), which in practice can be a constraint on their brightness and color purity. On the whole, the three materials have different niches, which are complementary. QDs are the best in high-precision optical applications with small emission bandwidth and high brightness; MNCs in applications that rely on catalytic or redox activity; and N-CDs in applications based on cost-effectiveness, environmental compatibility, and functionalization simplicity. N-CDs address the significant sustainability and toxicity constraints of their inorganic analogues and retain adequate quantum yields and photostability to be used in food, environmental, and biomedical applications.[153] Conclusively, N-CDs cannot be considered to replace QDs or MNCs, but they are green, scalable, and multi-purpose, and they are relevant to the current analytical considerations that focus on safety and

sustainability. The findings of Qureshi *et al.*,[147] Zhao *et al.*,[148] Ou *et al.*,[149] Yuan *et al.*,[150] and Liu *et al.*[151] indicate that advancements in heteroatom doping and surface passivation are progressively closing the optical performance gap between N-CDs and conventional fluorescent nanomaterials, positioning these light sources as primary candidates for future sensing technologies.

5.3. Comparative evaluation of N-CD-based sensors and conventional methods

N-CD-based sensors have also improved their ability to perform analytically, and, in this context, they are not only substitutes but also complementary to the conventional food safety analysis that has certain gaps. When critically compared to the existing methods such as high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), atomic absorption spectroscopy (AAS), and enzyme-linked immunosorbent assay (ELISA), a unique performance space is identified, comprising trade-offs between detection limits, response time, cost, and scalability,[154,155] as shown in Fig. 11. For many targets, such as metal ions (Hg^{2+}, Cu^{2+}) and mycotoxins (aflatoxin B1), N-CD sensors have limits of detection (LODs) of nanomolar to micrograms-per-litre, which directly compares to the sensitivity of AAS, ICP-MS, or ELISA.[156,157] The response time, however, is the most transformative difference. When N-CD is utilized, the sensing process of the system is based on the immediate interactions with the surface, such as electron transfer or inner-filter effects, which occur over the course of seconds to minutes. This is the opposite of chromatographic or immunoassay methods in which the analysis time can take weeks because of the required derivatization, incubation or physical separation procedure.[158] This difference of performance is based on some basic principles of operation. Traditional techniques frequently assume physical isolation (chromatography) or biochemical identification (ELISA), which need complicated equipment and controlled laboratory conditions. In comparison, the functionality of N-CD sensors is based on their photophysical characteristics at the nanoscale: their large surface-to-volume ratio and the presence of nitrogen-doped functional groups provide numerous and accessible sites of interactions with analytes binding and signal transduction. This essential distinction can be used to create low-cost and convenient platforms, including paper-based stripes and smartphone-based detectors, to perform screening in a decentralized, on-site fashion.[154,159] Regardless of these benefits, critical analysis should not ignore the existing strong points of traditional approaches and the issues that N-CDs have to face. While N-CD sensors excel in high-throughput, qualitative, or semi-quantitative screening, traditional chromatographic methods continue to maintain their undisputed position as a higher-throughput, multi-analyte determinant for verifying a post-factum in complex matrices. Limitations of N-CDs are mainly limited reproducibility between batches, non-standardized validation procedures and susceptibility to matrix-induced fluorescence quenching in unprocessed food samples. To sum up, the analogy is not that of replacement but of strategic usage. N-CD sensors are a radical innovation that can be used in rapid, cheap, and mobile surveillance that is best suited to primary screening where it is needed. In the meantime, traditional techniques are necessary in validation and full quantification. Continued synergies between nanomaterial engineering and analytical science are actively helping to overcome these constraints with N-CDs, bridge the performance gap, and make them usable as part of a larger food safety surveillance framework.[160–162]

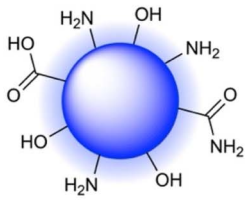
5.4. Mitigation of matrix effects and enhancement of selectivity in complex samples

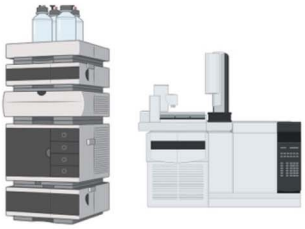
The analytical performance of N-CD-based sensing platforms in real-world applications such as food matrices, biological fluids, and environmental waters is often hindered by matrix effects, including the presence of coexisting ions, organic molecules, and macromolecular interferences. These components can alter fluorescence response through quenching, scattering, or non-specific adsorption, thus affecting both sensitivity and selectivity.[163] To overcome these challenges, various strategies have been developed and optimized in recent literature, combining surface engineering, hybrid material design, and assay calibration approaches.[164] Fig. 12 provides a conceptual overview of how functionalized N-CDs achieve selective detection in complex samples. The schematic highlights the N-CD core, the engineered surface functional groups that act as selective "keys," the target analyte, and the surrounding complex matrix. It visually illustrates how the functionalization promotes selective binding of the analyte while rejecting interferents, thereby mitigating matrix effects and enhancing sensor performance. This framework sets the stage for discussing specific strategies to address these analytical challenges.

One of the most effective approaches involves surface functionalization and passivation of N-CDs to control their surface polarity and reduce nonspecific interactions. For instance, polyethylene glycol (PEG), silica shells, or zwitterionic polymers have been employed to create hydrophilic barriers that minimize protein or lipid adsorption in biological media, leading to improved signal reproducibility.[165] Similarly, introducing functional groups such as –COOH, $–NH_2$, or –OH enhances the specific coordination affinity of N-CDs to target metal ions or molecular analytes, suppressing interference from coexisting species. Surface functionalization with molecular receptors or recognition moieties (*e.g.*, thiols for Hg^{2+}, boronic acids for glucose, and carboxylates for Fe^{3+}) has proven particularly effective in enhancing analyte discrimination.[166]

Another important class of strategies relies on integration with selective recognition materials. The combination of N-CDs with molecularly imprinted polymers (MIPs), aptamers, or nanozyme-based catalysts introduces specific binding sites or catalytic environments that selectively recognize target molecules even in complex matrices. For example, MIP–N-CD composites have demonstrated outstanding selectivity in detecting antibiotics and pesticides in milk or river water samples, effectively eliminating matrix interferences that often hinder classical fluorescence assays. These hybrid systems

Comparison of N-CD-Based Sensors and Conventional Methods





N-CD-Based Sensor	Conventional Methods
Exhibit nanomolar to μg L^{-1} detection limits, comparable to conventional method; enable fluorescence-based real-time detection.	Provide high sensitivity and quantitative accuracy but require calibration and controlled laboratory conditions.
Rapid response within seconds to minutes due to direct surface interactions (electron transfer, IFE, FRET).	Require lengthy sample preparation, separation, or incubation steps (hours to days)
Easily integrated into portable, paper-based, or smartphone-assisted platforms for on-site analysis.	Generally bulky and laboratory-bound (HPLC, GC-MS, AAS) with limited field applicability.
Low-cost synthesis and simple optical readouts; minimal reagent and power requirements.	High instrumentation cost, complex maintenance, and need for trained personnel.
Still face challenges with batch-to-batch variability and lack of standardized validation procedures.	Highly reproducible and standardized with established regulatory protocols.
Maintain fluorescence and selectivity in diverse food, environmental, and biological matrices with appropriate surface modification.	Often require extensive pretreatment and matrix cleanup to prevent interference.

Fig. 11 Performance comparison between N-CD-based sensors and conventional methods, highlighting the trade-offs between detection limits, response time, cost, and scalability in food safety detection.

benefit from the synergistic coupling of N-CD fluorescence responsiveness with the molecular recognition precision of the host matrix.[118,167] Ratiometric and dual-emission sensing approaches represent another advanced method to mitigate matrix-induced artifacts. By employing two emission bands one responsive to the analyte and one as an internal reference ratiometric sensors can self-correct for fluctuations caused by pH, ionic strength, or turbidity. Such dual-channel N-CDs have been used for reliable quantification of Fe^{3+}, dopamine, and nitrite in serum or food samples, where traditional single-emission sensors exhibit signal drift. Similarly, time-resolved and lifetime-based fluorescence techniques further minimize interference by separating true photoluminescence from background autofluorescence.[120–123,168]

Sample pretreatment and microextraction techniques are also key in improving performance under complex conditions. Solid-phase extraction (SPE), dispersive micro-solid phase extraction (d-μSPE), and simple dilution–filtration methods can effectively reduce organic load or metal ion competition before analysis. For example, Sikolenko *et al.*[169] combined matrix purification with portable electrochemical detection to enhance Pb^{2+} analysis in wine, a concept that parallels pretreatment approaches increasingly applied in fluorescence-based N-CD sensing.

Finally, hybrid analytical systems combining N-CDs with microfluidic or optical fiber platforms have demonstrated powerful anti-interference capabilities. The confinement and controlled flow within these systems allow precise sample handling, minimal reagent consumption, and rapid washing

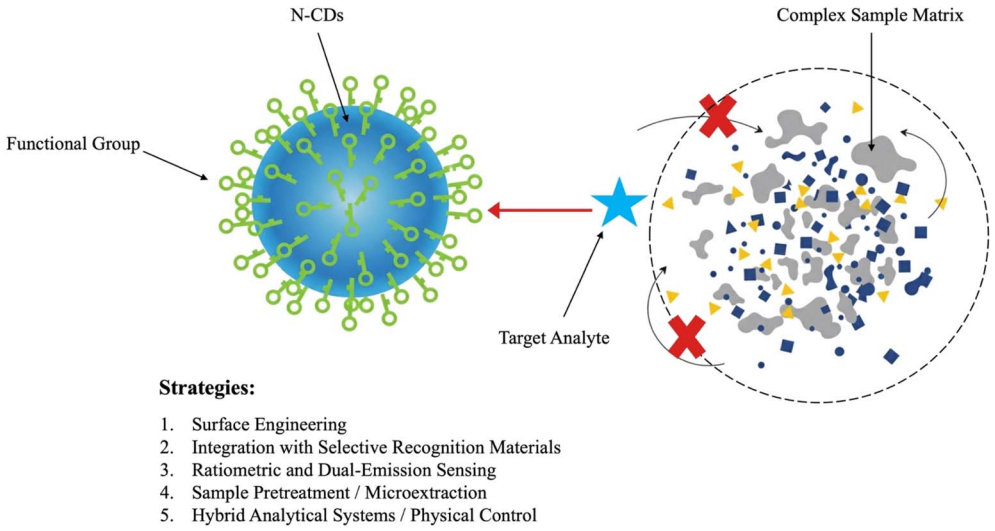


Fig. 12 Conceptual schematic illustrating the mitigation of matrix effects and enhancement of selectivity by functionalized N-CDs in complex samples. The blue sphere represents the N-CD core, which serves as the photoluminescent sensing material. The green keys are the surface functional groups (chemical receptors, ligands, or polymers) that have been designed to recognize the target analyte (red star) and exclude the interferents (the gray, blue, and yellow shapes) of the complex sample matrix. The schematic highlights two critical mechanisms: (1) selective binding: the functional groups are very specific to interact with the target analyte, and an observable fluorescence response occurs; (2) matrix rejection: the other species do not interact on the N-CD surface, and therefore non-specific adsorption, quenching, or scattering effects are minimized. This key-lock format shows that surface engineering N-CDs allows the stable and precise detection of N-CDs in complex matrices like food extracts. This schematic also illustrates the key strategies to address analytical challenges: surface engineering and functionalization, combination with selective recognition materials, ratiometric or dual-emission sensing, sample pretreatment or microextraction, and hybrid analytical systems.

steps, significantly mitigating matrix noise. Coupling with smartphone-based or ratiometric readout systems further increases analytical robustness in field and point-of-care applications.[170,171] In summary, overcoming matrix effects in N-CD-based assays requires an integrated strategy that merges chemical selectivity (*via* surface and molecular design) with physical discrimination (*via* optical or microfluidic control). Continued progress in rational surface modification, hybrid nanocomposite design, and multiplex optical calibration will be key to achieving reliable, interference-free sensing in practical, real-world environments.

6. Applications

N-CDs have demonstrated remarkable potential in sensing applications, particularly for antibiotics, heavy metals, multifunctional additives and preservatives, food dyes, and spoilage indicators. Their nitrogen-enriched surfaces enhance electron transfer and provide abundant binding sites, enabling strong interactions with target analytes, as illustrated in Fig. 13.

6.1. Antibiotic residue detection

Residues of antibiotics in food are a significant concern due to the extensive use of antibiotics in agriculture and livestock practices, which can result in their accumulation in various food products, including meat, milk, and dairy products. Consumption of these residues leads to the emergence of antibiotic-resistant bacteria, a significant risk to the health of human beings.[172,173] Hence, it is necessary that the detection of antibiotics within the food be lightning-fast and sensitive, and biosensors have emerged as promising candidates for this need since they are selective, sensitive, and capable of being monitored in real time.[174] Tetracyclines (TCs) are one of the broad-spectrum classes of common antibiotics and are found to

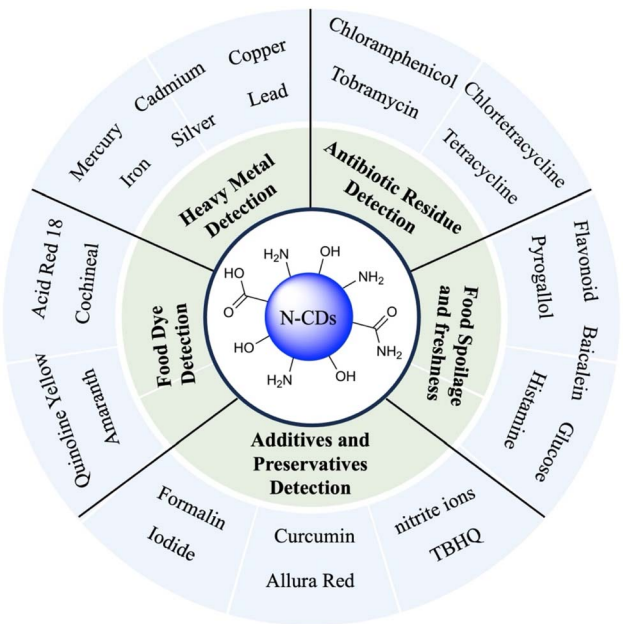


Fig. 13 Schematic representation of the diverse food-sensing applications of N-CDs.

have application in a large scope in the veterinary field, which requires efficient detection systems in their food commodities.[175] N-CDs have proven to have high potentials in antibiotic sensing since their receptive surfaces contain functional groups that are capable of attracting tetracycline molecules strongly, resulting in a significant alteration in fluorescence, which can be measured.[175,176] For example, Xie *et al.*[177] provided a green synthesis of a nitrogen-doped graphene quantum dot (N-GQD) fluorescent probe to detect tetracycline (TC) with high sensitivity and selectivity in food products. The sensor is designed to use the internal filtration effect (IFE) of TC on N-GQDs, thereby providing a straightforward and environmentally benign detection strategy, as shown in Fig. 14.

In another study, Jia *et al.*[178] synthesized N-CDs by the hydrothermal method using pitaya peel and 1,2-ethylenediamine. These N-CDs serve as a dual-mode fluorescence sensor for detecting three tetracycline antibiotics, tetracycline (TC), oxytetracycline (OTC), and chlortetracycline (CTC), in biological and food samples. TC and OTC quench the fluorescence of N-CDs by an absorption induction process including bandgap transition, inner filter effect (IFE), static quenching (SQ), and electrostatic interaction. Conversely, in the presence of CTC, the result is a fluorescence gain owing to aggregation-induced emission (AIE). Moreover, a sensor array of multiple N-CDs has been designed to detect different tetracyclines in real samples. This work highlights the potential of biomass-derived N-CDs as multifunctional sensors for antibiotic detection in food safety applications. Similarly, Zhang *et al.*[179] synthesized a fluorescence sensor based on N-GQDs with a molecularly imprinted polymer (MIP) coating to detect TC in animal products. The MIP layer was prepared through the precipitation polymerization process with TC as a template molecule and designed binding sites on the N-GQDs.

In addition to tetracycline, which is widely reported as an antibiotic contaminant in food, there are several other antibiotics of major concern, including chlortetracycline, tobramycin, chloramphenicol, tinidazole, and other classes of antibiotics, as presented in Table 1. Chlortetracycline is the first-generation tetracycline antibiotic, which has found wide application in veterinary medicine and as a growth promoter in livestock and chlortetracycline residues have been identified in foods of animal origin. Recent developments in the field of nanomaterial-based sensing have shown that N-CDs offer a promising fluorescent basis to identify chlortetracycline in foodstuffs. According to Zhang *et al.*,[180] N-CDs prepared using hawthorn allowed a rapid and highly sensitive and selective detection of chlortetracycline in pork samples, with the detection of the antibiotic being facilitated by a strong interaction between the antibiotic and surface functional groups of N-CDs, resulting in fluorescence quenching. Similarly, Ren *et al.*[181] modified the N-CDs chemically by immobilizing molecularly imprinted polymers (MIPs) on their surface that selectively recognize the target molecule, chlortetracycline. Such a molecular imprinting strategy led not only to increases in selectivity but also to increases in stability due to food matrix interference. Furthermore, Li *et al.*[182] constructed an N-CDs-based fluorescence probe in which chlortetracycline induced a rapid and efficient quenching response, attributed to inner filter effect (IFE) and photoinduced electron transfer (PET) mechanisms. This method finds particular application in food safety, where it can be used to detect residues of the antibiotics in meat

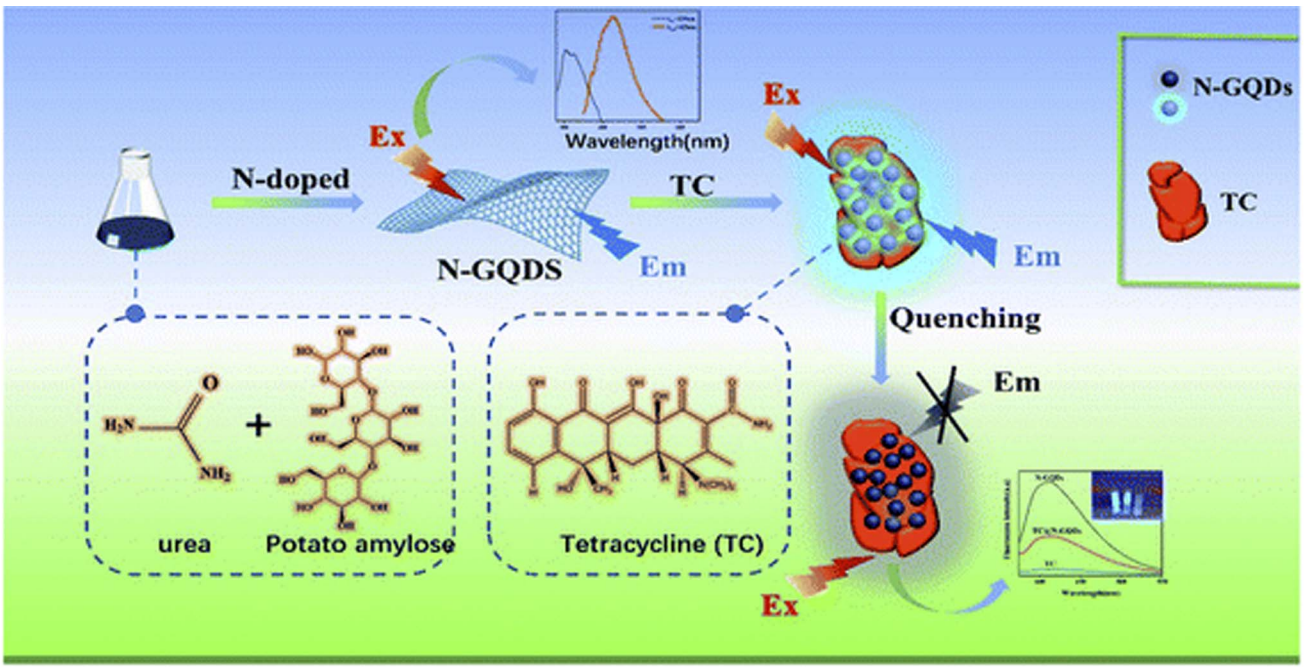


Fig. 14 Schematic diagram of tetracycline detection based on an N-GQDs fluorescent sensor, this figure has been reproduced from ref. 177 with permission from Royal Society of Chemistry, copyright 2022.

Table 1 Overview of N-CD-based fluorescent sensors and their mechanisms for antibiotic detection in food samples

Types of N-CDs/modification	Antibiotics	Sensing mechanism	Sample matrix	Ref.
Self-N doped CDs	Tetracycline	Fluorescence quenching (PET/IFE)	Animal-origin foods	175
In situ synthesized N-CDs	Tetracycline	Turn-off fluorescence (PET)	Food samples	176
Green N-GQDs	Tetracycline	Fluorescence quenching (FRET/IFE)	Food samples	177
Biomass N-CDs	Tetracycline	Dual-mode (fluorescence + colorimetric)	Food samples	178
MIP–N-GQDs	Tetracycline	MIP selectivity + fluorescence quenching	Animal-derived foods	179
Biomass (hawthorn) N-CDs	Chlortetracycline	Fluorescence quenching	Pork samples	180
MIP–N-CDs	Chlortetracycline	Specific binding + fluorescence	Animal-derived foods	181
N-CDs	Chlortetracycline	Fluorescence quenching	Food samples	182
MIP–N-CDs	Tobramycin	Turn-off fluorescence	Milk	183
N-GQDs	Chloramphenicol	Fluorescence interaction/turn-off	Chicken feed	184
N-CDs	Tinidazole	Fluorescence quenching	Milk	185
Cu-functionalized N-CDs	Ciprofloxacin	Turn-off–on fluorescence (PET)	Food samples	186
S,N-doped CDs	Tetracycline	Turn-off fluorescence	Animal-derived foods	187
P,N-C nanosheets	Nitrofuran antibiotics	Fluorescence	Fish	188
Biomass N-GQDs	Nitrofurans	Dynamic quenching (PET)	Food samples	189
F,N-CDs	Tigecycline	Fluorescence quenching	Food samples	190
B,N-GQDs	Tetracycline	Turn-off fluorescence	Food samples	191
Fe/N-porous carbon	Chloramphenicol	Electrochemical detection	Animal-derived foods	192
N-CQDs	Oxytetracycline	Fluorescence	Food samples	193
N self-doped porous	Furazolidone	Electrochemical detection	Animal-derived foods	194

products in low concentrations, enabling responsiveness to food safety guidelines.

The antibiotic tobramycin, which is also an aminoglycoside, is applied both in human and veterinary practice, and this may also contaminate the food running into the food chain, like milk. It is nephro- and ototoxic and so should be monitored due to the presence of residues. Ren *et al.*[183] synthesized a fluorescent probe by loading MIPs on N-CDs; the cavities of imprinted structures selectively recognized tobramycin. Tobramycin binding to these openings changed the local electronic conditions of N-CDs, and this caused a measurable quenching of fluorescence. This process enabled selective and sensitive determination of tobramycin in milk, having minimal levels of matrix interferences. Chloramphenicol is a broad-spectrum antibiotic that has been prohibited in food-producing animals in a large segment of the countries due to its presence in direct relation to severe side effects like aplastic anemia. However, traces of residues have even been seen in foodstuffs, such as animal feed. Tsai *et al.*[184] demonstrated that N-GQDs interact strongly with chloramphenicol through hydrogen bonding and π–π stacking interactions. This interaction allows the transfer of non-radiative energy of the excited N-GQDs to chloramphenicol and leads to the quenching of fluorescence that is proportional to the concentration of antibiotics. The procedure was usefully employed in the sensitive determination of chloramphenicol in chicken feed. Finally, tinidazole is a nitroimidazole-based antibiotic. Qian *et al.*[185] synthesized nitrogen-doped carbon nanodots (N-CNDs) as a sensitive fluorescent probe to detect tinidazole in milk. N-CNDs exhibited a powerful and steady fluorescence with a quantum yield of 5.11 and an averaged fluorescence lifetime of 5.79 ns. When N-CNDs interact with tinidazole, the fluorescence intensity of N-CNDs is quenched with concentration dependences, and tinidazole in milk can be quantitatively determined selectively and quickly. This study indicated that N-CNDs could be used as high-fidelity, cost-efficient sensors to track the presence of antibiotic residuals in foodstuffs and thus as an efficient way of managing food safety and quality control.

6.2. Heavy metal detection

Heavy metals are among the most hazardous contaminants in food systems, primarily because of their non-biodegradability, high toxicity, and strong bioaccumulative properties. Being exposed to metals like lead (Pb), cadmium (Cd), mercury (Hg), silver (Ag), iron (Fe), and copper (Cu) is linked to having severe health effects, including carcinogenicity, neurotoxicity, nephrotoxicity, and birth defects.[195,196] Such pollutants enter the food chain along a variety of routes: environmental pollution of agroecosystems by industrial effluents, mining, wastewater irrigation, and road transport, which increases soil and crop metal burdens considerably,[197] and after-harvest contamination during processing, packaging, and storage, with extra dangers introduced by leaching in equipment or additives.[198] This widespread contamination reiterates the necessity of the very sensitive, selective, and accurate detection platform. N-CDs are a potential solution in this regard because they are highly water-soluble, their photoluminescence can be tuned by adjusting the surface functional groups, and they can exhibit exceptional sensitivity to heavy metals *via* electron transfer processes, static/dynamic quenching, and coordination interactions,[199] as shown in Table 2. For instance, Wongsing *et al.* developed a portable fluorescence-based device utilizing N-CDs for the simultaneous determination of lead (Pb^{2+}) and formalin (FA) in food samples. The sensors were based on photo-induced electron transfer (PET) of Pb^{2+} (which caused fluorescence quenching) and the silver mirror reaction on FA (fluorescence enhancement). Experimental validation demonstrated linear detection ranges of 0.01–10 mg L^{-1} for Pb^{2+} and 25–150 mg L^{-1} for FA, with

Table 2 Summary of the precursor materials, synthesis routes, and sensing characteristics of N-doped carbon nanomaterials for heavy metal detection

Target ion	Precursor(s)	Synthesis method	Detection mechanism	Limit of detection (LOD)	Ref.
Hg^{2+}	Citric acid, urea	Solvothermal	Fluorescence "Turn-off"	2.3 nM	199
Ag^{+}	Citric acid, urea	Solvothermal	Fluorescence quenching	0.28 μM	200
Hg^{2+}	*p*-Phenylenediamine	Solvothermal	Fluorescence quenching	14.7 nM	201
Hg^{2+}	Citric acid, urea	Microwave	"On–off–on" (for Hg^{2+} & thiamine)	33 nM	202
Fe^{3+}	Citric acid, urea	Hydrothermal	Multi-probe quenching	0.15 μM (Fe^{3+})	203
Cu^{2+}, Cd^{2+}	Graphene oxide, glutathione	Hydrothermal	Ratiometric fluorescence	0.28 μM (Cu^{2+}), 0.26 μM (Cd^{2+})	204
Ag^{+}	*Clerodendrum wallichii* petals	Hydrothermal	Fluorescence quenching	17.5 nM	22
Hg^{2+}	Jengkol peels	Solvothermal	Fluorescence quenching	5.2 nM	21
Hg^{2+}, Pb^{2+}, Cd^{2+}	Citric acid, diethylenetriamine	Hydrothermal	Fluorescence quenching	—	205
Hg^{2+}, S^{2-}	Lentils, urea	Hydrothermal	Sequential "off–on" sensing	2.7 nM (Hg^{2+})	206
Multiple ions	Ethanolamine	Plasma-in-liquid	Fluorescence quenching	—	207
Hg^{2+}	Citric acid, urea	Pyrolysis	Fluorescence quenching	0.47 nM	208
Hg^{2+}	Citric acid, thiourea	Hydrothermal	Fluorescence quenching (S,N co-doping)	0.12 nM	209
Fe^{3+}	Chitosan	Hydrothermal	Selective fluorescence quenching	90 nM	210
Hg^{2+}	Sago waste biomass	Hydrothermal	Adsorption & fluorescence quenching	0.36 μg L^{-1}	211
Cr(VI)	Citric acid, cysteamine	Thermal decomposition	FL enhancement (inner filter effect)	40 nM	212
Fe^{3+}, Hg^{2+}	Citric acid, EDTA	Hydrothermal	Dual-ion detection (quenching)	0.22 μM (Fe^{3+}), 0.41 μM (Hg^{2+})	213
Cd^{2+}, Pb^{2+}, Hg^{2+}	Graphene oxide, NH_3	Thermal	Electrochemical (DPASV)	ppb level	214
Fe^{3+}	Citric acid, urea	Hydrothermal	Fluorescence quenching & anti-counterfeiting	0.95 μM	215
Fe^{3+}	Palm bunches	Pyrolysis	Fluorescence quenching	0.43 μM	216
Pb^{2+}	Citric acid, cysteamine	Microwave	Fluorescence quenching	3.2 nM	217
Fe^{3+}, Cu^{2+}	Aspartic acid	Hydrothermal	Selective fluorescence quenching	0.12 μM (Fe^{3+}), 0.14 μM (Cu^{2+})	218
Hg^{2+}	Citric acid, ethylenediamine	Hydrothermal	Selective fluorescence quenching	5.6 nM	219

satisfactory accuracy and precision. Furthermore, the N-CQDs synthesized by Lu *et al.*[200] were prepared through a solvothermal process of 1,2,4-triaminobenzene as a carbon source. The N-CQDs had a quantum yield of 5.11 and an average fluorescence lifetime of 5.79 ns. Their sensitivity and selectivity increased with surface modification by amino groups toward silver ions (Ag^{+}). There was fluorescence quenching when it interacted with Ag^{+}, with linear detection ranges of 0–10 μM and 10–30 μM. The N-CQDs showed satisfactory reproducibility in trace Ag^{+} detection in food packaging materials with a relative deviation of 6.24% against flame atomic absorption spectrometry. The results indicate that N-CQDs hold potential as a fast, easy, and sensitive Ag^{+} detector in food packaging systems.

Fu *et al.*[201] described highly fluorescent N-CDs possessing the ability to selectively detect Hg^{2+} in beverages, showing that the robust fluorescence quenching by Hg^{2+} ions enables quick and sensitive monitoring in complex liquid food systems (Fig. 15). Thanomsak *et al.*[202] further advanced this concept by designing a fluorescent nanosensor with three states (on–off–on) based on N-CDs to simultaneously detect Hg^{2+} in food samples, where Hg^{2+} quenches the signal (off-state), demonstrating the bidirectional sensing ability of N-CDs in the detection of both toxic metals and vital nutrients. Karali *et al.*[203] further utilized N-doped carbon nanodots in multi-analyte detection utilizing highly fluorescent N-CDs as a multi-probe quenching system to quantify ferric ions in different food matrices, including processed meats and beverages, focusing the flexibility of N-doped carbon nanodots in more food systems that might have multiple food contaminants present. In a complementary study, Gao *et al.*[204] developed an N-GQDs-based ratiometric fluorescent sensor in combination with gold nanoparticles to achieve a sensitive response toward copper and cadmium ions in scallops, which, based on the ratiometric response, could reduce the matrix interference of seafood and increase the analytical reliability.

6.3. Multi-functional additives and preservatives detection

Multi-functional additives and preservatives have a large part in food quality, shelf life prolongation, and chemical or microbial spoilage prevention. Precise detection of these compounds must be done to ensure consumer safety and regulatory compliance. As a result of exceptional photoluminescence, biocompatibility, and fantastic surface functionalization capacity, N-CDs have become very versatile fluorescent probes, enabling them to be sensitive and selective when it comes to the detection of various food additives. Nitrogen-doped fluorescence carbon dots were used to detect iodide and curcumin in biological and food samples, showing satisfactory performance in complex food matrices,[220] as summarized in Table 3. Highly fluorescent nitrogen-doped carbon dots incorporated into a 3D-printed smartphone platform have facilitated fast and sensitive detection of curcumin, demonstrating the potential of portable

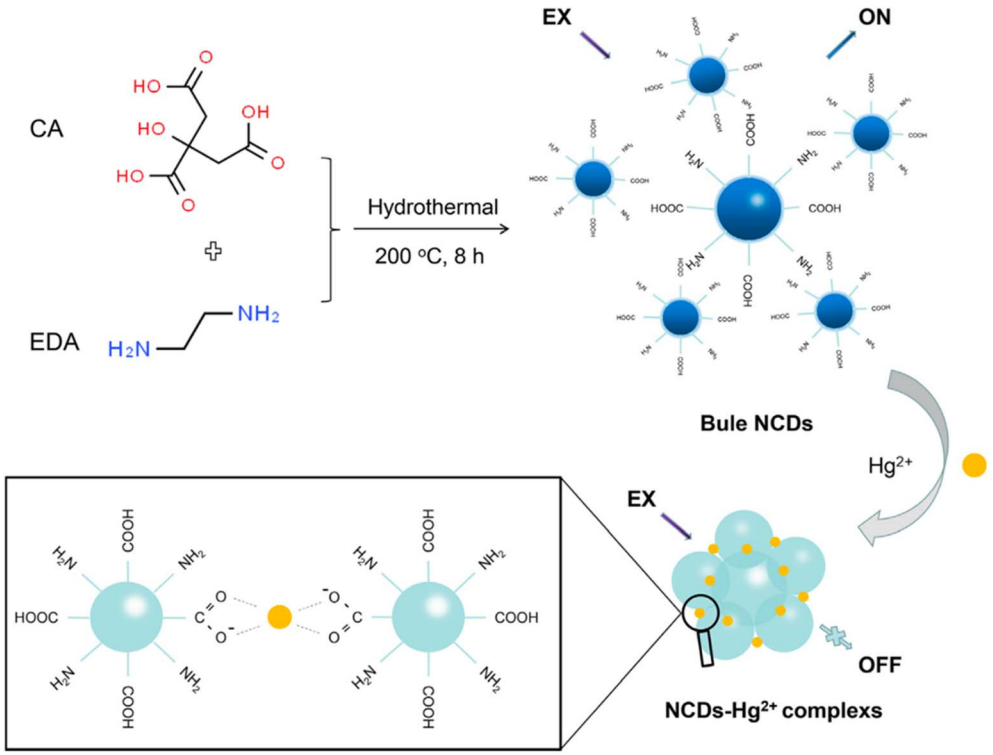


Fig. 15 Schematic illustration of the one step hydrothermal synthesis of NCDs and detection of Hg^{2+}, this figure has been reproduced from ref. 201 with permission from Elsevier, copyright 2022.

food safety monitoring.[221] Moreover, N-CDs have been utilized as off–on fluorescent probes to screen formalin in food matrices, implying their high selectivity in detecting the hazardous preservatives.[222]

In addition to these uses, N-CQDs have been applied to the detection of dangerous food dyes like Allura Red in beverages, which exhibit strong reactions, high sensitivity, and reproducibility according to Salman *et al.*[223] In another study, Li *et al.*[224] developed a nitrogen-doped carbon dot-based cyan-blue fluorescent probe capable of sensing nitrite ions, which are also a common food preservative in ham sausage. The N-CDs had excellent stability and fluorescence, but their fluorescence was quenched by nitrite in a concentration-dependent manner. The probe was very sensitive, with low detection limits and high reproducibility parameters, rendering it very useful in the monitoring of nitrite levels in processed meats. The paper proves the use of N-CND-based detectors to detect food additives; the results can be helpful in the maintenance of food safety and quality. In addition, Wang *et al.*[225] prepared Na/N-doped carbon dot (Na/N-CD) nanozymes with a more efficient peroxidase-like behaviour. These N-CDs could catalyze the decomposition of hydrogen peroxide, which generated reactive oxygen species which prevent microbial growth, indicating the possibility of antimicrobial food preservation.

With the ability to tune photoluminescence and imitate enzyme-linked xenobiotics, Mn-doped N-rich carbon dots can be used to detect nitrite in a sensitive and bimodal colorimetric and fluorometric fashion and thus provide rapid and dependable monitoring of a widely used preservative (Wang *et al.*[226]). In the same way, the conjugation effects of N-CDs and a copper-cerium oxide nanozyme allow ratiometric dual-mode detection of tertiary butylhydroquinone in edible oils, thereby improving selectivity and detection limits of antioxidants (Zhang *et al.*[227]). Collectively, the studies indicate that doped N-CDs can be used as highly versatile systems to concurrently and precisely detect multiple food additives, which is critical to guaranteeing food safety and quality control.

6.4. Food dye detection

The potential of N-CDs in food dye detection constitutes one of the most significant areas of application of the nanomaterial, with N-CDs showing superior analytical capabilities towards the detection of synthetic food colorants in food matrices. The use of N-CDs to act as fluorescent sensors has transformed food safety analysis by offering fast, easy, and inexpensive detection of several artificial dyes commonly applied in food processing. Scaled-up methods used in gram-scale synthesis have allowed the development of a highly efficient N-CD on the basis of a sustainable source, such as locusts, that can achieve part-per-billion levels of detection and with outstanding specificity when testing food samples that are complex in nature.[228] N-CDs are not only applicable as a single-mode detector; recent applications have also realized dual-mode sensing platforms integrating fluorometric and colorimetric responses, which increase the analytical confidence level by manyfold and provide visual readouts that do not require complicated

Table 3 Summary of N-doped carbon dot (N-CD) based sensors for the detection of food additives, dyes, freshness and food safety, and spoilage indicators, organized by application category

Study	Analyte	Sensing mechanism	Application category
Tang *et al.*[220]	Iodide, curcumin	Fluorescence quenching, inner filter effect (IFE)	Food additive detection
Wang *et al.*[228]	Sunset yellow	Fluorescence "turn-off" *via* PET	Food dye detection
Wang *et al.*[235]	Resveratrol	PET-based fluorescence enhancement	Food quality monitoring
Wongsing *et al.*[244]	Formalin	Fluorescence quenching	Food preservative detection
Zhang *et al.*[234]	Amaranth	Fluorescence quenching (IFE)	Food dye detection
Wang *et al.*[236]	Ascorbic acid	Sequential fluorescence modulation	Food spoilage monitoring
Chen *et al.*[237]	Nitrite	Ratiometric fluorescence	Food spoilage monitoring
Nath *et al.*[221]	Curcumin	Fluorescence enhancement	Food additive detection
Malahom *et al.*[238]	Cyanide	Off–on fluorescence	Toxic compound/food quality monitoring
Zhou *et al.*[229]	Nitrite	Fluorescence quenching + colorimetric response	Food additive detection
Huang *et al.*[239]	Rutin	Fluorescence enhancement	Food spoilage monitoring
Sun *et al.*[241]	Glucose	Colorimetric reaction *via* enzyme mimic	Food freshness monitoring
Zhang *et al.*[230]	Acid red 18	Fluorescence quenching + chromogenic response	Food dye detection
Wang *et al.*[231]	Quinoline yellow	Fluorescence quenching	Food dye detection
Salman *et al.*[223]	Allura red	Fluorescence quenching	Food dye detection
Liu *et al.*[232]	New coccine	Fluorescence enhancement	Food dye detection
Tohamy *et al.*[245]	Tomato spoilage	pH-sensitive fluorescence	Food spoilage monitoring
Deng *et al.*[240]	Baicalein	Fluorescence quenching	Food bioactive compound monitoring
Wang *et al.*[233]	Nitrite	Fluorescence + colorimetric response	Food additive monitoring
Sun *et al.*[242]	pH, histamine	Fluorescence + colorimetric response	Food quality monitoring
Ali *et al.*[243]	Pyrogallol	Fluorescence + colorimetric response	Food additive monitoring
Thanomsak *et al.*[202]	Thiamine	On–off–on fluorescence	Food contaminant detection
Wang *et al.*[203]	Nitrite, nitrate	Multi-probe fluorescence	Food additive & metal monitoring
Liu *et al.*[224]	Nitrite	Cyan blue fluorescence	Food additive detection

instruments.[229] Such double recognition systems have been particularly efficient when applied towards the monitoring of acid red 18 in food products through mobile phone-based support facilities that offer convenient field-testing and are used in such food quality controlling applications.[230]

The structural characteristics of N-CDs, especially their variable photoluminescence and surface modification, render them good candidates in identifying different quinoline-based food colors, with the nitrogen dopants acting as not only the electron supplier but also the binding sites of particular dye molecules.[231] Novel N-CD formulations with phosphorus co-doping have been shown to exhibit ultra-sensitive detection to new cochineal, with detection limits below regulatory levels, whilst retaining label-free operation and high selectivity to interfering compounds prevalent in food matrices.[232] Advances in the design of ratiometric sensing platforms utilizing N-CDs and complementary reagents such as *o*-phenylenediamine have also broadened the analytical applicability, realizing simultaneous sensing of various analytes such as nitrites in the context of food colorants; therefore, thorough food safety tracking through a single type of assay.[233]

Beyond these applications, red-emissive N-CDs have also been designed specifically to detect amaranth by demonstrating high selectivity and sensitivity *via* the fluorescence quenching principle by accurately quantifying it in complex food matrices (Fig. 16), as reported by Zhang *et al.*[234] Similarly, a simple, fast, green, and straightforward fluorescence method to detect amaranth gastronomic samples using nitrogen-doped graphene quantum dots has also been implemented, indicating the feasibility of N-CDs in on-site and real-time food analysis according to Li *et al.*[107] These works demonstrate the usefulness of N-CDs as adaptive sensors, able to measure food dyes at low concentrations with high accuracy. In addition, their integration with dual-mode or wearable platforms helps increase their usefulness in regulatory compliance and consumer protection, as summarized in Table 3.

6.5. Food spoilage, freshness, and safety monitoring

The monitoring of food spoilage, freshness, and safety is a critical issue for food security, nutritional quality, and consumer protection. N-CDs are an engaging nanomaterial that is considered a prospective product to create sensitive and affordable platforms that could be utilized to identify essential spoilage biomarkers and chemical hazards in food systems,[235] as summarized in Table 3. Due to their tunable photoluminescence, excellent biocompatibility, and diverse surface functionalities, N-CDs have the potential to serve as sensitive fluorescent probes to detect chemical signatures that indicate quality loss during storage and processing. N-CDs have been used to detect biogenic amines and ascorbic acid, which are closely associated with microbial spoilage and oxidative deterioration and nutrient loss in food matrices, respectively, serving as key indicators of food spoilage.[236] In addition, waste biomass N-CDs have already been used as fluorescent sensors to detect resveratrol in food products, providing rapid, sensitive, and eco-friendly monitoring of antioxidant content and overall food quality.[235] Beyond single-analyte detection, N-CDs have also been employed in lateral flow assays to develop ratiometric fluorescent sensors to detect nitrite, permitting portable and on-site assessment of processed food spoilage or quality.[237]

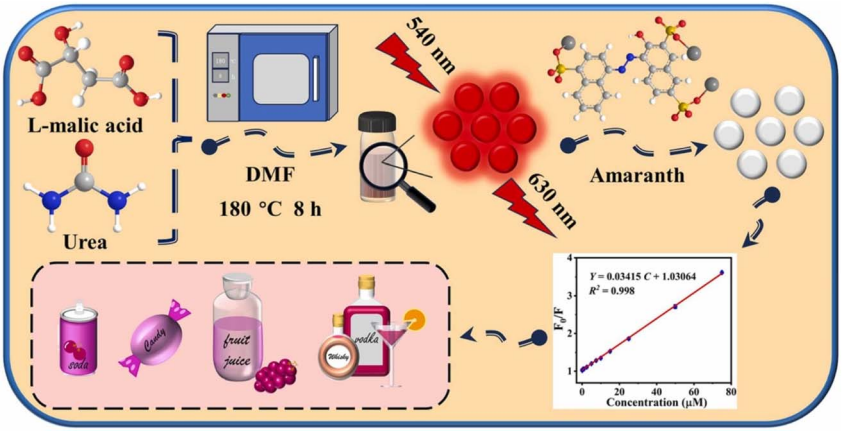


Fig. 16 The preparation of R-NCDs for amaranth detection, this figure has been reproduced from ref. 234 with permission from Elsevier, copyright 2024.

Another study provides have been reported as nitrogen-doped graphene quantum dot-embedded paper-based kits as fluorescent probes and demonstrated the use of their fluorescence in response to being inserted into cyanide, a toxicant that may be agglomerated in processed foods that are not treated properly, thus expanding the scope of food-safety screening.[238] Similarly, the nitrogen-doped carbon quantum dots have been claimed to take to task in a short time and are sensitive to rutin, a commonly used flavonoid as an indicator of freshness and quality of food products.[239] Further, N-CDs prepared using rapeseed meal have exhibited the high sensitivity of fluorescent sensing for baicalein, highlighting the multifunctional applications of N-CDs as both analyte probes and food supplements, as reported by Zhang *et al.*[240]

Beyond the use of fluorescence solely, N-CDs derived from locust biomass have shown intrinsic peroxidase-like catalytic activity, providing a smartphone-based colorimetric method to measure glucose in food samples, which is highly pertinent to perishable foods,[241] as shown in Fig. 17. These results demonstrate that N-CDs can respond as optical probes and catalytic mimics, providing their multi-functional applications in food quality monitoring.

In addition to these methods, dual-mode sensing platforms have been developed that have increased the number of monitoring indicators for spoilage. An example is colorimetric plus fluorescent, dual-mode, N-CD sensors by Zhang *et al.*[242] targeting the pH and histamine, a biogenic amine considered a vital spoilage marker in fish and meat products. In another example, Ali *et al.*[243] introduced a dual-mode nanoprobe based on the complexation of copper(II) with N-CDs to achieve a sensitive detection of the oxidation-related pyrogallol, a food degradation-linked compound. The ratiometric and dual-mode approaches address the sensitivities of one-signal sensing and enhance the accuracy and stability of freshness detection. Collectively, these studies confirm that N-CDs offer a powerful, green, and cost-effective platform for food spoilage and freshness detection, with applications ranging from antioxidants and nutrients to toxic contaminants and spoilage amines. The integration of N-CDs into portable, smartphone-assisted, and paper-based devices further supports their translation toward real-time, consumer-level monitoring systems, ultimately contributing to improved food safety and quality assurance.

6.6. Multiplex detection

The recent research has therefore indicated the possibility of using nitrogen-doped carbon dots (N-CDs) as multifunctional fluorescent probes to meet the multidimensional detection in multiplexes due to their tunable emission, superior photostability, and multifaceted surface properties. Nitrogen doping causes the appearance of defect-related emissive centers and the changes in the electronic band structure, which provide several fluorescence channels, which may react differently to other analytes. Such spectral characteristics can be further tuned by co-doping with other heteroatoms and by customizing surface functionalization (*e.g.*, attaching ligands covalently or DNA or nanoparticle decoration) so that ratiometric or dual-emission and multicolor sensing of multiple targets simultaneously is possible.[246]

Meng *et al.* have created multifunctional N-CDs that incorporate multisensing and imaging properties, where both intrinsic surface groups and the following post-synthetic functionalization acquired different fluorescence reactions to various analytes, and the identical probe could be utilized in various detecting modes.[247] Du *et al.* observed two emission bands at 490 and 590 nm of bismuth and nitrogen co-doped CDs (Bi,N-CDs); the system used determined interactions between surface sites and doxorubicin to produce a consistent ratiometric signal (F_{590}/F_{490}) and a corresponding colorimetric signal, a result of the combination of co-doping and surface chemistry.[248] Zhang *et al.* demonstrated that Fe,N-co-doped CDs can be used as a universal ratiometric surface to detect hydrogen peroxide and other relevant metabolites in which surface coordination sites and doping-generated emissive centers both contributed to producing analyte-specific spectral shifts.[249] Explicit functionalization N-CDs with fluorophore-labeled single-stranded DNA (ssDNA) have been surface

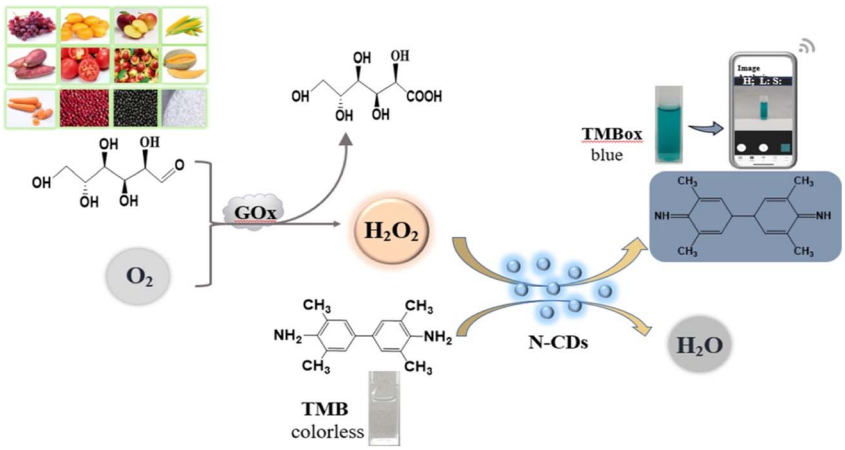


Fig. 17 A schematic of the smartphone-based colorimetric assay of glucose with N-CDs as the peroxidase mimic, this figure has been reproduced from ref. 241 with permission from Elsevier, copyright 2023.

functionalized to selectively change fluorescence in response to 6-mercaptopurine *versus* Hg(II) due to sequence-specific binding and differing fluorescence quenching at the surface.[250] Patir and Gogoi have used surface-available binding sites and a simple immobilization to develop an on–off–on N-CD sensor to concurrently detect Cu^{2+} and Hg^{2+} in both solution- and paper-based microfluidic sensors to demonstrate that surface contacts and device-format functionalization facilitate multiplex readout.[251] Wang *et al.* used N-CDs along with silver nanoparticles (a surface-modification/hybridization strategy) to acquire a rapid fluorescence–colorimetric decision on ochratoxin A in complex food samples, showing how nanoparticle decoration can offer orthogonal signals to multiplex-capable sensing.[252]

Heteroatom co-doping together with targeted surface engineering has further expanded multiplex capability. Tummala *et al.* synthesized boron-and-nitrogen co-doped CDs (B,N-CDs) that combined co-doping-induced energy-level tuning with surface-responsive sites to simultaneously sense *p*-nitrophenol, Fe^{3+}, and temperature *via* multi-signal outputs.[253]

Expanding the multiplex capability of N-CD-based sensors beyond small-molecule and metal-ion detection, Xu *et al.*[254] developed a rapid, label-free fluorescence sensor array using nitrogen-doped carbon dots synthesized within one minute through a facile one-step process. The system comprised four types of N-CDs with distinct surface states, whose differential fluorescence responses formed unique optical fingerprints for various proteins. By applying linear discriminant analysis (LDA) to these fluorescence patterns, the array could simultaneously discriminate eight proteins with different isoelectric points and molecular weights at nanomolar concentrations. Remarkably, accurate identification was maintained for protein mixtures and in complex biological matrices such as human urine and serum, allowing effective distinction among samples from rectal cancer patients, Alzheimer's disease patients, and healthy individuals. This work highlights the potential of nitrogen doping and surface-state diversity to generate spectrally distinct fluorescence signatures, establishing N-CD arrays as promising tools for multiplex biosensing and clinical diagnostics. Cross-disciplinary innovations offer key design principles for N-CD multiplexed sensing. The one-pot isothermal assay using fluorogenic Mango II aptamer[255] provides a model for simple nucleic acid detection adaptable to N-CD pathogen sensors. Similarly, molecular probes yielding distinct multi-analyte signals, like the dual-response sensor for viscosity and peroxynitrite by Li *et al.*[256] demonstrate a general design principle that can inspire future work on N-CDs: the creation of multiple, independent recognition pathways to achieve simultaneous detection of contaminant combinations like pesticides and heavy metals.

Overall, these reports depict the fact that nitrogen (co-) doping, with surface functionalization by covalent ligands, biomolecular probes (*e.g.*, ssDNA), nanoparticle decoration, or device immobilization, is in the center of multiplex detection with N-CDs. Surface chemistry controls selective binding of analytes, energy- or electron-transfer reactions, and the local microenvironment in the emissive sites and is therefore a significant design handle to generate different spectral channels, ratiometric, or multi-mode optical measurements of multiple analytes in food, environmental, and biomedical samples.

7. Biocompatibility, stability, and toxicity considerations for food-safe N-CD sensors

The successful conversion of N-CD-based sensors out of laboratory work and into practical food analysis is critically reliant upon the three basic issues being addressed: their natural biocompatibility, their stability under food-processing conditions, and where they would fit in the food chain. There is now a strong body of evidence that is based upon both materials science and toxicology literature that demonstrates that well-designed N-CDs can be used in food-contact applications to meet the stringent specifications.[257,258] Reduced cytotoxicity and

desirable biocompatibility. The safety of N-CD is based on the argument of their composition and synthesis. The N-CDs produced using precursors of foodstuffs (*e.g.*, citric acid, urea, chitosan, and fruit juices) have a proven high biocompatibility, unlike heavy-metal-based quantum dots. For example, non-doped carbon dots introduced into zebrafish models did not interfere with embryonic development and showed high biocompatibility.[259,260] This innate safety profile plays an essential role in avoiding contamination in the event of any sensor material accidentally leaking out onto the food. Strong stability of multifaceted food matrices. There is no meaning in the analysis performance of a sensor, which would be lost in the food environment. Compared to organic dyes, N-CDs exhibit greater photostability, as they can resist photobleaching for a significantly longer duration under prolonged excitation. Moreover, the carbonaceous core gives them resistance to various pH levels (usually 4 to 10) as well as high ionic strength, necessary to analyze different products from acidic beverages to saline sauces.[261,262] Research has demonstrated that the N-CDs functionalized with polyethyleneimine (PEI) retained more than 90 percent of their original fluorescence intensity to the 30th day in buffer storage and as a spike into milk samples, demonstrating their stability of operations in a complex food environment.[263] The focus is on avoiding toxicity while maintaining trust in environmental sciences. The danger of potential toxicity risk is related, first of all, to synthetic by-products, rather than to the carbon core itself. These dangers are successfully addressed by means of stringent post-synthesis purification (*e.g.*, dialysis, chromatography). Simulation studies of digestion perhaps provide the greatest evidence of safety. The study of chitosan-derived N-CDs revealed that they degrade into small non-toxic carbon particles under simulated gastrointestinal conditions, implying that they are unlikely to bioaccumulate.[264] This ability to degrade oneself is one of the main benefits, which will guarantee that N-CDs do not remain as environmental pollutants and will not become a significant threat to toxicity in the long run.[260]

8. Practical challenges in commercialization and device integration of N-CDs sensors

Despite the promising analytical performance, biocompatibility, and stability of nitrogen-doped carbon dots (N-CDs), several practical challenges remain that hinder their large-scale commercialization and integration into real-world sensing devices. One major limitation is the reproducibility of N-CD synthesis. Factors such as precursor type, temperature, reaction time, and pH can significantly influence particle size, surface functional groups, and quantum yield. Consequently, batch-to-batch variations may lead to inconsistent fluorescence intensity, sensitivity, and selectivity, limiting the reliability of N-CD-based sensors in routine applications. Standardized protocols, rigorous quality control, and post-synthetic purification (*e.g.*, dialysis, chromatography) are essential to minimize these variations. Computational and data-driven approaches, similar to those applied for predicting complex biological associations,[265] may provide valuable insights for optimizing synthesis parameters and improving reproducibility.

Many N-CD synthesis routes, including hydrothermal, microwave-assisted, or biomass-derived methods, are optimized at laboratory scale. Scaling up these methods for industrial production can introduce challenges such as uneven heating, uncontrolled nucleation, or aggregation, which affect particle uniformity and optical performance. Continuous-flow reactors and scalable green synthesis approaches are being explored to overcome these limitations, but large-scale production with consistent quality remains a bottleneck.[192]

Incorporating N-CDs into commercial sensing platforms requires stable immobilization on substrates (*e.g.*, paper, hydrogels, microfluidic chips) without losing fluorescence performance. Challenges include maintaining strong adhesion, preventing photobleaching or quenching, and ensuring compatibility with electronic or optical readout systems. Additionally, complex food matrices may introduce fouling or matrix effects, further complicating device reliability. Lessons from nucleic acid aptamer-based biosensors demonstrate that biorecognition interface design and surface immobilization strategies can substantially improve signal stability and device integration, offering guidance for N-CD-based sensor development.[266]

While N-CDs are inherently less toxic and more sustainable than heavy-metal-based quantum dots, the cost of high-purity precursors, post-synthetic purification, and device fabrication can still be significant for commercial deployment. Regulatory approval for food-contact or clinical devices requires standardized safety and migration testing, which adds additional hurdles. In summary, while N-CDs offer compelling advantages in sensitivity, tunability, and environmental compatibility, addressing reproducibility, scalable production, device integration, and regulatory compliance is critical for their transition from laboratory research to commercially viable food sensing technologies.

9. Future perspectives

Although significant advances have been made in the use of nitrogen-doped carbon dots applications in food sensing, some obstacles are left that still need to be neglected to facilitate its implementation on a larger scale. A major drawback stems in the lack of complete insight on underlying processes which dominate their light production modulation with an analyte interaction. Sensing responses have been ascribed to fluorescence quenching or enhancement in many studies, but the individual contributions of electron transfer, energy transfer or inner filter effects are inadequately explained. More highly resolved spectroscopic and computational experiments are thus necessary to disentangle the photophysical mechanisms occurring at work, and hence the optimal design of N-CD probes that are selective and efficient at baseline. Moreover, the synthetic strategies are heterogeneous and there are no standardized protocols, which makes synthesis reproducibility and cross-comparisons beyond laboratories difficult. Future

directions must focus on the development of controllable, green, scalable synthesis procedures, and real-time food sensing that produce structurally well-defined N-CDs with tunable emission and surface.

Another urgent angle entails scaling up laboratory-scale examples to real-world applications of food monitoring systems. Existing N-CD-based sensors show decent sensitivity and selectivity toward targeted analytes in clean conditions, although sensitivity and selectivity are weakened with complex food compounds, fats, and proteins interfering with measurements. To address it, in the future, more emphasis must be placed on incorporating N-CDs into state-of-the-art platforms, including microfluidic systems, handheld sensing kits, and smartphone-based detection, enabling quick, on-site analytical procedures using minimal sample preparation.

A promising future direction in food-safety monitoring is the development of multiplexed "barcode" sensing using N-doped carbon dots (N-CDs). Individual N-CDs are designed to have different fluorescence emission profiles in this technique and, therefore, multiple analytes can be detected in one assay. Such a feature would be able to boost analytical throughput significantly, and would be able to give more detailed information to complex food matrices, where various contaminants or quality indicators have to be observed at the same time. N-CDs are often functionalized with other functional materials to enhance their performance with respect to selectivity, sensitivity, and stability. Metal–organic frameworks (MOFs) offer a porous structure that is able to pre-concentrate desired molecules as well as inhibit aggregation of N-CDs without interference with their optical characteristics. Tunable surface chemistry, biocompatibility, and resistance to fluorescence quenching can be offered with polymers, whereas plasmonic interactions can be used to amplify fluorescence signals with the use of metallic nanoparticles (ex: gold or silver). Other nanocomposites possess all those benefits, forming multifunctional platforms, which consolidate recognition, signal amplification, and stability. Multiplexed N-CDs systems can be incorporated into microfluidic devices, handheld kits, or smartphone-based platforms to detect samples rapidly on-site with little sample preparation. Moreover, N-CDs can also be used with molecularly imprinted polymers (MIPs), enzymes, or any other biorecognition functionalities to increase specificity and strength in real food environments. Overall, multiplexed barcode sensing is a promising and new concept in the next generation of food-safety sensors, utilizing the tunability of the optical properties of N-CDs and the capability of state-of-the-art material in the capability of simultaneous multi-analyte sensing.

10. Conclusion

Nitrogen-doped carbon dots have become a rather universal category of nanomaterials with considerable potential in the area of food safety monitoring primarily due to their selective photophysical features, synthetically adjustable surface chemistry, and easy production using a wide range of precursors. Within the last ten years, considerable success has been realized in utilizing and profiling their photoluminescence-based approaches in the detection of numerous food contaminants, such as antibiotics, dyes, and heavy metals. These accomplishments reflect the potential of N-CDs to solve nagging issues with existing analytical methods with potentially rapid, sensitive, and inexpensive on-site analytes that can overcome potential performance limitations of traditional methods. Furthermore, their inherent biocompatibility and environmental friendliness have a unique competitive edge over conventional sensing materials, with such a trend expected due to the increasing demand in the world of safe, environmentally accepted and efficient monitoring solutions. However, its existing body of work is still in an exploratory phase, and most studies are demonstrated at a proof-of-concept level in laboratory conditions only. Significant concerns like reproducibility of synthesis, signal stability in complex food matrixes and standardization of analytical procedures still limit their large-scale applicability. Future efforts should seek broader and global context rather than case studies because they have the potential to transform the potential of N-CDs through consolidating nanomaterials science, food chemistry and device engineering as the three interdisciplinary approaches. N-CDs in this respect is not only a new set of instruments to support food quality assurance, but is also a note on a broader movement of nanotechnology in transforming contemporary analytical sciences. Overcoming existing constraints and moving toward scalable, real-life applications, N-CDs may become a decisive step towards implementing next-generation food-sensing infrastructures and, eventually, to the promotion of better public health and food security across the globe.

Ethical statement

This article does not include any research involving human or animal subjects.

Consent to participate

The author grants permission for their work to be included in the manuscript.

Author contributions

A. S. M.: conceptualization, writing – original draft, writing – review & editing, visualization.

Conflicts of interest

The author declares no competing interests.

Data availability

No datasets were generated or analysed during the current study.

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