Environmental Chemistry Letters
https://doi.org/10.1007/s10311-024-01779-3

REVIEW ARTICLE

Food safety aspects of carbon dots: a review

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Received: 19 November 2023 / Accepted: 10 September 2024

Abstract
Discovered in 2004, carbon dots have garnered a major attention due to their unique optical properties, nanoscale size, and cost-effectiveness. Their potential uses are applicable for bioimaging, electronics, and the food industry. Carbon dots are promising tools for detecting contaminants, identifying harmful bacteria, and monitoring essential nutrients. Here, we review the safety risks associated with applying carbon dots in the food industry, focusing on their integration into global food safety frameworks. We highlight recent advancements in the detection capabilities of carbon dots, showcasing their sensitivity and specificity in identifying foodborne pathogens and contaminants. We discuss strategies to mitigate potential health risks, such as optimizing carbon dot synthesis to minimize their toxicity and ensuring thorough regulatory assessments. Current research shows that carbon dots improve food safety, but research is needed to address safety concerns and ensure consumer confidence.

Keywords Carbon quantum dot · Cytotoxicity · Human health · Food industry · Nanosensor · Safety risk · Bioaccumulation · Carbon nanodot

Introduction

Carbon dots, also known as carbon nanodots, are minuscule luminescent particles with diverse potential applications in the food industry (Shi et al. 2019). These particles consist of carbon atoms organized in a nanoscale arrangement, typically measuring less than 10 nm in diameter, smaller than most viruses and bacteria (Xu et al. 2004). Their unique characteristics include intensive fluorescence, large surface area, biocompatibility, low cost, one-step production, and stability (Kang et al. 2020). In recognition of their groundbreaking research on carbon dots, the 2023 Nobel Prize in Chemistry was awarded to three scientists (NobelPrize 2023). Because of these exceptional attributes, carbon dots have the potential to revolutionize the food industry, especially in the context of ensuring food safety by providing new and effective ways to detect contaminants, foodborne pathogens, measure nutrients, and extend the shelf life of food products (Ezati et al. 2022; Gao et al. 2024; Rossini et al. 2019; Zhang et al. 2022; Zhao et al. 2021a). For example, carbon dots-based sensors are being developed to detect foodborne pathogens such as *Staphylococcus aureus* or *Escherichia coli* (Gao et al. 2024; Zhao et al. 2021a), and carbon dots-coated packaging materials are being used to extend the shelf life of avocados until 14 days (Ezati et al. 2022). Carbon dots also can form inclusion complexes with a wide range of molecules. This property has been exploited to develop probes and sensors for detecting contaminants in food samples, such as pesticides, herbicides, or heavy metals (Bera and Mohapatra 2020; Chen et al. 2020; Hoang et al. 2023; Pajewska-Szmyt et al. 2020). However, integrating carbon dots into food products necessitates a comprehensive understanding of its safety aspects.

Food safety is a major global concern, with approximately 600 million people falling ill each year due to contaminated food (WHO 2022). To address this, key interventions

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Published online: 30 September 2024

include selecting appropriate foods, following good hygiene practices, ensuring food ingredient safety, and preventing cross-contamination during food processing (Njoagwuani et al. 2023). In the case of carbon dots, research on their toxicity is still in its early stages, and findings are often conflicting. While some studies have suggested that carbon dots are biocompatible and non-toxic (Emam et al. 2017; Yang et al. 2009b), others have found that their cytotoxicity can be influenced by factors such as size, dosage, and exposure to light (Liu et al. 2021; Wang et al. 2011). Research on the cytotoxicity of carbon dots has revealed that their photodegradation under light exposure can lead to the production of toxic molecules, posing a potential risk to human cells (Liu et al. 2021). The surface functionalization of carbon dots also plays a crucial role in their cytotoxicity, with carboxylic groups and polyethylene glycol-modified carbon dots with neutral charge showing the most promise for biological applications (Havrdova et al. 2016). Regarding biodistribution and clearance, carbon dots are efficiently excreted from the body, with different injection routes resulting in varying blood clearance patterns and tumor uptakes (Huang et al. 2013). These findings highlight the need for further research to fully understand the potential risks and benefits of using carbon dots in food applications.

While previous review articles have highlighted the potential of carbon dots in various food applications (Li et al. 2021; Sharma et al. 2021; Shi et al. 2019; Zhang et al. 2022), an essential consideration often overlooked is the safety risks associated with their usage. Several strategies were proposed to mitigate the risks associated with the use of carbon dots in prior review articles. For instance, one approach involves synthesizing carbon dots from biomaterials (Wu et al. 2023). This review article aims to provide a comprehensive understanding of the food safety aspect of carbon dots, including their potential applications in the food industry, along with addressing the associated safety risks and proposing mitigating strategies, illustrated in Fig. 1.

Carbon dots

Carbon dots and properties

Carbon dots are a new class of nanomaterials with unique properties, including tunable fluorescence, biocompatibility, and surface state energy-gap tuning, making them promising candidates for various applications. These nanomaterials exhibit bright photoluminescence, resembling the properties commonly found in semiconductor quantum dots (Cao et al. 2013). The unique fluorescence characteristics of carbon dots can be tailored for applications in bioimaging, intracellular imaging, and optical sensing, with the ability to create "artificial" tunable carbon dots through composition and surface state modifications (Bao et al. 2015; Fu et al. 2015). Furthermore, carbon dots have been found to possess physicochemical and photochemical stability, making them suitable for applications in bioimaging and fluorescence imaging in vivo (Yang et al. 2009a). The potential use of carbon dots for in vitro and in vivo applications has been discussed, highlighting their non-toxic and high-performance fluorescence imaging capabilities (Yang et al.

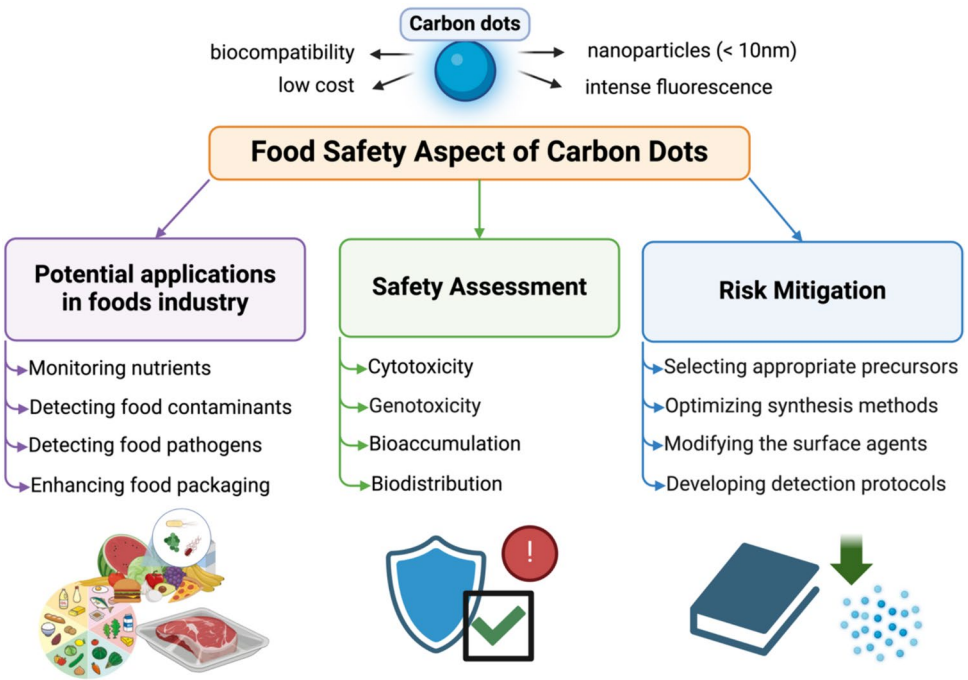

Fig. 1 Potential applications of carbon dots in the food industry include monitoring nutrients, detecting food contaminants, detecting food pathogens, and enhancing food packaging. The safety of carbon dots is assessed in terms of cytotoxicity, genotoxicity, bioaccumulation, and biodistribution. Strategies to mitigate these risks include selecting appropriate precursors, optimizing synthesis methods, modifying surface agents, and developing specific protocols to detect carbon dots in foods

2009a). Additionally, the biocompatibility and antioxidant capabilities of carbon dots have been investigated, further emphasizing their characteristic properties, including luminescence and ease of synthesis (Rodríguez-Varillas et al. 2022). Overall, the multifaceted properties of carbon dots, encompassing fluorescence, luminescence, biocompatibility, and tunability, render them versatile nanomaterials applicable in bioimaging, sensing, drug delivery, pharmacetical analysis and optical devices (Ali et al. 2020; Fu et al. 2015; Hoan et al. 2018; Omer et al. 2022). Figure 2 illustrates the procedure for synthesizing carbon dots, listing the most commonly applied method in recent studies.

Synthesis of carbon dots

Carbon dots can be synthesized through two primary approaches: top-down and bottom-up. The top-down approach involves breaking down larger carbon materials into smaller carbon dots, aiming for a narrow size distribution and controlled optical properties (Wang et al. 2023). However, achieving precise control over size and structure can be challenging with this method. In contrast, the bottom-up approach assembles carbon dots from smaller molecular precursors, offering greater versatility and control over size, structure, and optical properties, making it more suitable for specific applications (Shin et al. 2015; Wang et al. 2019, 2015). Top-down approaches transform macroscopic carbon structures into carbon dots using methods such as arc

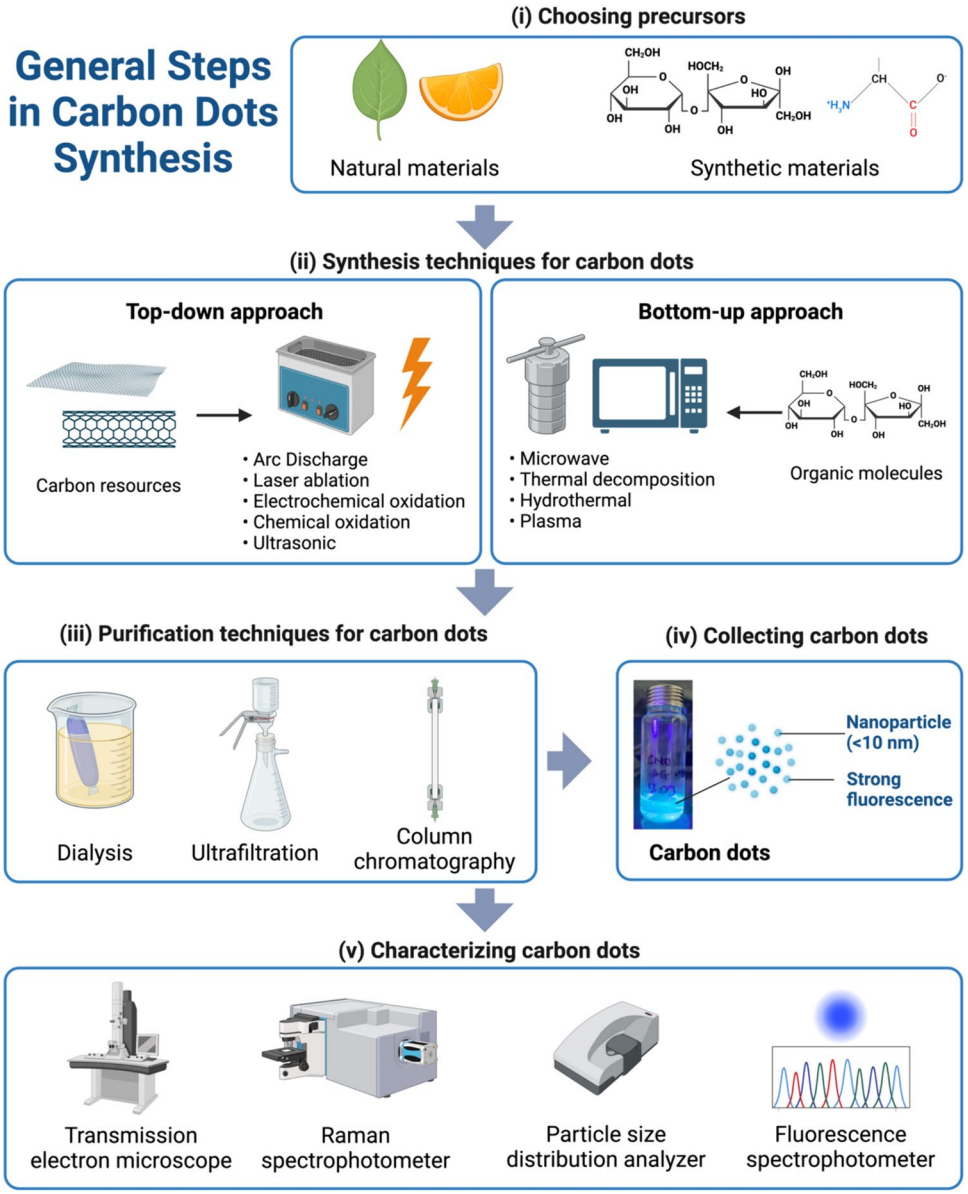

Fig. 2 Common procedures for carbon dot synthesis. Precursors can be chosen from natural or synthetic materials (**i**). Various techniques are employed to synthesize carbon dots based on two primary approaches: top-down and bottom-up (**ii**). The synthesized carbon dots are purified using techniques such as, dialysis, ultrafiltration, and column chromatography (**iii**). The purified carbon dots exhibit intense fluorescence and nanoscale size (**iv**). Carbon dots are characterized using methods, including transmission electron microscope (TEM), Raman spectrophotometer, particle size distribution analyzer, and fluorescence spectrophotometer (**v**)

discharge, laser ablation, electrochemical oxidation, chemical oxidation, and ultrasonic synthesis (Wang et al. 2017). On the other hand, bottom-up approaches create carbon dots from molecular precursors like citric acid, sucrose, and glucose through methods such as microwave synthesis, thermal decomposition, hydrothermal treatment, template-based routes, and plasma treatment (Wang et al. 2017).

While various methods have been employed for carbon dots synthesis, recent studies have emphasized distinctive properties, with hydrothermal and microwave methods standing out in top-down approaches, and chemical oxidation and electrochemical oxidation in bottom-up methods (Fig. 2). Each method presents a unique set of benefits and challenges (Wang et al. 2017). For instance, chemical oxidation offers ease of operation and suitability for large-scale production but is associated with nonuniform size distribution. Microwave synthesis provides a short reaction time and easy size control, yet it incurs a high energy cost. Hydrothermal treatment is known for high quantum efficiency and cost-effectiveness but yields lower quantities of carbon dots (Wu et al. 2021). Electrochemical oxidation, while offering high-purity carbon dots with controllable size and good reproducibility, requires careful optimization for high yields. Selecting the most appropriate synthesis approach depends on specific requirements and considerations in the production of carbon dots.

Purification of carbon dots

The purification of carbon dots is a pivotal step to ensure their quality and suitability for diverse applications. Various purification methods have been proposed in the literature, each offering unique advantages to address specific challenges related to impurities and by-products, including dialysis, ultrafiltration, and column chromatography. González-González et al. (2022) proposed a dialysis methodology to purify carbon dots synthesized by a chemical oxidation method for 360 h. This approach underscores the importance of overcoming purification challenges to obtain high-quality carbon dots. Similarly, Essner et al. (2018) conducted carbon dot syntheses using hydrothermal and microwave routes, employing citric acid paired with urea or ethylenediamine as a nitrogen source. They followed this with purification steps involving dialysis or ultrafiltration, highlighting the significance of purification in ensuring the quality of the resulting carbon dots. Furthermore, Sato et al. (2022) demonstrated the purification of surface-modified carbon dots using silica gel column chromatography, resulting in an increased photoluminescence quantum yield. This purification method illustrates the impact of purification on enhancing the optical properties of carbon dots. Additionally, Otten et al. (2022) emphasized the role of purification in removing impurities and enhancing the optoelectronic properties of carbon dots, underscoring the importance of consistent characterization during the purification process.

Application of carbon dots in the food industry

Carbon dots are a class of nanomaterials with unique properties, such as fluorescence, biocompatibility, and antimicrobial activity (Zhang et al. 2022). These properties make carbon dots promising candidates for a variety of applications in the food industry, including (1) developing probes and sensors for detecting contaminated toxins and other hazardous substances, (2) developing antimicrobial and antifungal food packaging materials, (3) detecting foodborne pathogens and (4) measuring the essential nutrients in food, which were visualized in Fig. 3. Residuals of these toxic elements can be found in any steps of food production, such as cultivation, production, storage, transportation, and consumption (Hoehl et al. 2012). Several harmful contaminated substances in food products were listed by the European Commission such as metal ions, mycotoxins, plant toxins, processing contaminants, banned additives, organic pollutants, and pesticides (EU-Commission 2023), which need to be detected and controlled within certain limits.

Probes and sensors

Detection of metal ions

The most concerning metal ions include chromium, lead, mercury, arsenic, and cadmium (EFSA 2023). Mercury (II) ion is one of the contaminants in milk that causes irreversible damage to neurological and renal systems. It is known as a neurotoxicant and a poison for the liver and kidneys (Wise et al. 2022). The presence of lead (II) ions in drinking water can cause neurodevelopmental effects on children (Levallois et al. 2018), whereas cadmium (II) ions present in rice can also pose a health risk like "itai-itai disease," a bone disease (Yu et al. 2017). These metal ions can be contaminated in foods and accumulated over time, causing actual disease.

The development of carbon dots-based sensors to detect metal ions has several advantages over traditional methods, which reported higher sensitivity and their ability to be used to detect metal ions in real time (Shi et al. 2019). Carbon dots are fluorescent nanomaterials that can be functionalized to bind to specific metal ions. When carbon dots bind to a metal ion, its fluorescence is quenched. This change in fluorescence can be used to detect the presence of metal ions in food samples, which was reported in various studies (Table 1). Carbon dots-based probes and sensors have shown a significant effect on detecting these commonly contaminated metal ions in water with a low

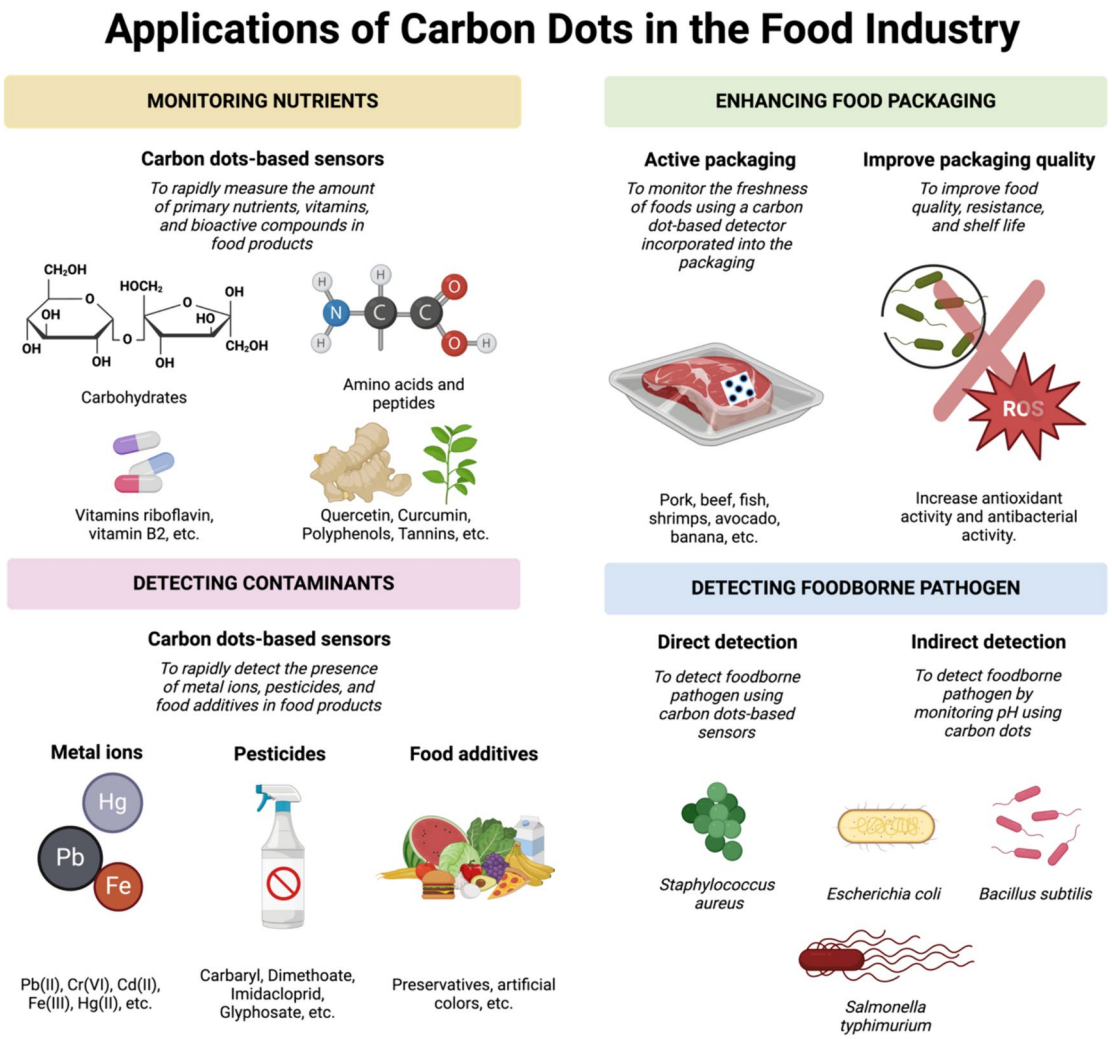

Fig. 3 Applications of carbon dots in the food industry. Carbon dots-based sensors monitor primary nutrients such as carbohydrates, amino acids, peptides, vitamins, and bioactive compounds. Carbon dots are incorporated into food packaging to enhance quality or monitor the freshness of foods. Carbon dots sensors detect food contaminants such as metal ions, residual pesticides, or food additives. Carbon dots are used to detect foodborne pathogens indirectly and directly, including *Staphylococcus aureus*, *Escherichia coli*, *Bacillus subtillis*, or *Salmonella typhimurium*

limit of detection, including chromium (VI) with 2.3 nM, lead (II) with 0.08 ppb, cadmium (II) with 0.29 nM, iron (III) with 0.07 µM and 63 nM (Du et al. 2023; Pandey et al. 2020; Sahu and Khan 2020; Zhang et al. 2020; Zhao et al. 2021b). Lately, multifunctional fluorescent probes have been developed to detect metal ions simultaneously to reduce time with low detection limits. For example, lead (II) and iron (III) could be detected in water simultaneously by dual emission carbon dots based on the different fluorescent intensity changes with a detection limit of 0.80 ppm and 4.74 ppm, respectively (Hoang et al. 2023). Furthermore, modifying the surface of nitrogen-carbon dots can lower the detection limit of the sensor to detect mercury (II) to 10 nM (Aziz et al. 2019).

Carbon dots-based sensors to detect metal ions have been developed using two main quenching mechanisms, illustrated Fig. 4 based on the detailed explanation (Albrecht 2008). Most of these sensors were developed based on fluorescent quenching, where metal ions combine with carbon dots, reducing fluorescence (Zhang et al. 2022). Briefly, one common mechanism is static quenching (Fig. 4a). Initially, the fluorophore and metal ions (the quenchers) form a non-fluorescent complex (Fig. 4b), which results from the diffusion of both molecules, which is a time-dependent reaction. When this complex is excited with energy, it reaches the excited state. It comes back immediately to the ground state without the emission of photos but in the form of fluorescence (Fig. 4c). This difference between the non-fluorescent

Table 1 Recent studies on carbon dots sensors for detecting metal ions

Type of analyte	Analyte	Probes	Linear range	Limit of detection	Measured sample	References
Metal Ions	Zinc (II)	Chelation-enhanced carbon dots	0.02–5 µM	5 nM	Fetal bovine serum, milk powder	Lu et al. 2023
	Mercury (II)	Nitrogen–Carbon dots	2–14 µM	0.44 µM	Breast milk	Pajewska-Szmyt et al. 2020
	Chromium (VI)	Nitrogen–Carbon dots	0.01–4.5 µM	2.3 nM	Tap water	Zhang et al. 2020
	Iron (III)	Nitrogen–Carbon dots	0.8–27 µM	0.07 µM	Environmental water	Zhao et al. 2021b
	Iron (III), lead (II)	Carbon dots	0–128 µM	63 nM	Tap water	Du et al. 2023
	Lead (II), cadmium (II)	Carbon dots	10–200 µM	59 µM	–	Boobalan et al. 2020
		Carbon dots	1–8 nM	0.29 nM	Tap water, pond water	Pandey et al. 2020
	Cobalt (II)	Nitrogen and Sulfur co-doped carbon dots	1–50 µM	26 nM	–	Sun et al. 2021
	Cobalt (II), Copper (II)	Nitrogen and Sulfur co-doped carbon dots	1–100 µM	200 nM	Water	Bisauriya et al. 2022
	Copper (II), iron (II)	Nitrogen-Doped Carbon Dots	0–40 µM	Copper (II): 0.5 µM Iron (II): 0.31 µM	Animal feed, tablets	Guo et al. 2023
	Lead (II), iron (III)	Dual emission carbon dots	0–100 ppm	Lead (II): 0.80 ppm Iron (III): 4.74 ppm	Water	Hoang et al. 2023
	Manganese (II)	Carbon dots	0–500 µM	0.58 µM	Tap water	Kumar et al. 2023

Carbon dots are used to develop sensors that detect numerous metal ions in foods and waters with high sensitivity. Doping carbon dots-based sensors is a common technique to enhance their sensitivity. The growing interest in the simultaneous detection of multiple metal ions is highlighted

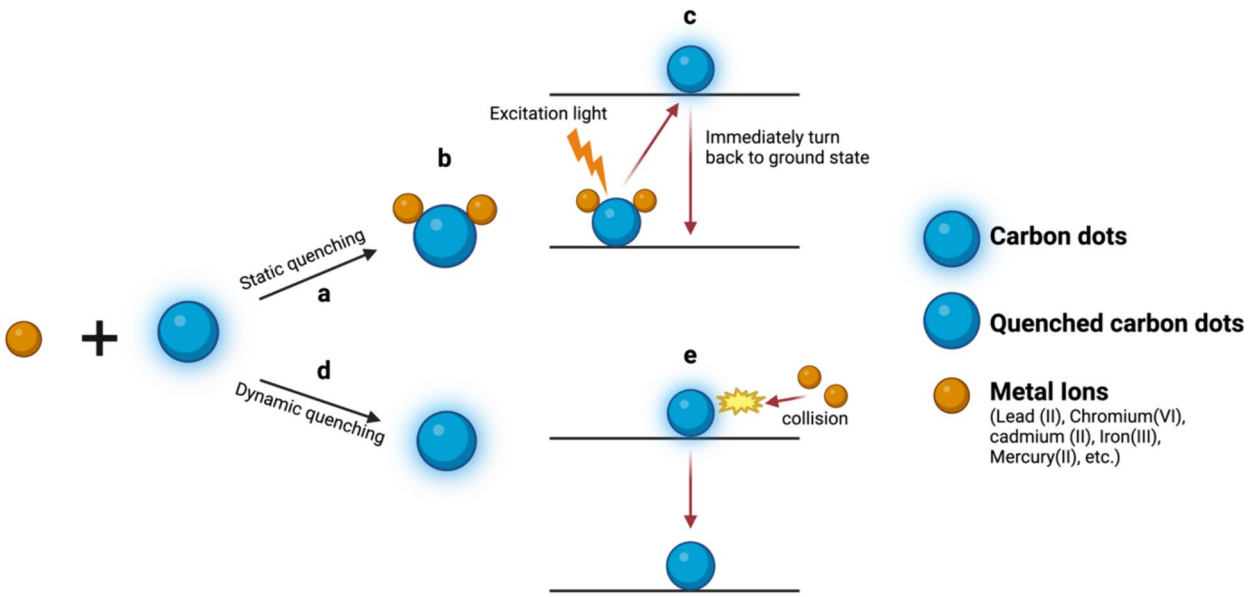

Fig. 4 Mechanisms of carbon dots sensors for detecting metal ions in foods. (**a**) Static Quenching: The fluorescence of carbon dots is quenched by metal ions forming a non-fluorescent complex (**b**). This non-fluorescent complex becomes fluorescent under excitation light (**c**). (**d**) Dynamic Quenching: The fluorescence of carbon dots changes due to collisions with metal ions (**e**)

metal ion complex state and the fluorescent metal ion complex state gives the concentration of the unknown metal ion in the food samples (Albrecht 2008). Another common mechanism is dynamic quenching (Fig. 4d), in which metal ions (quencher) are added to the fluorophore. The non-fluorescent complex is formed due to the collision between the quencher and the fluorophore (Fig. 4e). The unknown metal ion (quencher) concentration can be determined by measuring the difference between the fluorescence (Galletto and Bujalowski 2002).

Detection of pesticide residues

Pesticides can be categorized into four main classes, including herbicides, fungicides, insecticides, and acaricides (Fernandes et al. 2023). Pesticide residues can not only cause disease but also lead to death beyond a specific limit. This information was well-summarized by El-Nahhal and El-Nahhal (2021), who stated that exposure to pesticides can cause reproductive toxicity, cardiotoxicity, an increased risk of various types of cancers, and Parkinson's disease. Pesticide residues in tea have become a threat to human health; therefore, they are strictly controlled with specific maximum limits detailed in the legislation of the European Union, USA, and Japan (Fernandes et al. 2023).

Unlike the mechanism of carbon dots-based sensors to detect metal ions, these sensors detect pesticides based on an "off–on-off" quenching mechanism, which is illustrated in detail in Fig. 5 (Shi et al. 2019). There are two main pathways to explain the mechanism of this sensor, where both start from forming the non-fluorescent complex between carbon dots with metal ions or nanoparticles (Fig. 5a). For the first pathway, carbon dots were fluorescent again when pesticides were combined with metal ions or nanoparticles bound with carbon dots (Fig. 5b). The change in fluorescent intensity was converted to the residual pesticide concentration in food samples. Enzymes play a central role in the second pathway (Fig. 5c). Enzymes react with substrates, forming the products of enzyme reaction, and then they will bind with metal ions or nanoparticles bound with carbon dots, making carbon dots fluorescent again (Fig. 5d). When the sensors interact with pesticides, pesticides will inactivate the enzyme reaction so that the metal ions and nanoparticles are combined again with carbon dots, forming a non-fluorescent complex (Fig. 5e).

The design of carbon dots-based sensors to detect pesticides was modified depending on the specific case; however, all cases were based on the "on–off" principles of carbon dots, as illustrated in Fig. 5. The fluorescence of carbon dots could be turned on or turned off by different compounds like metal ions, nanoparticles, or products of enzyme reactions, described in detail by Shi et al. (2019). While Chen et al. (2020) developing a carbon dots sensor with gold nanoparticles, enzymes can be used to develop these sensors to detect pesticides, which could act as fluorescent probes or quenchers in enzyme-based reactions (Huang et al. 2019). These sensors detect changes in the fluorescence of carbon dots caused by the presence of pesticides in a sample, enabling the determination of the pesticide concentration (Zhang et al. 2022). Cao and Guo (2024) developed carbon dots sensors to detect imidacloprid based on Förster Resonance Energy Transfer (FRET) methods, where the emission

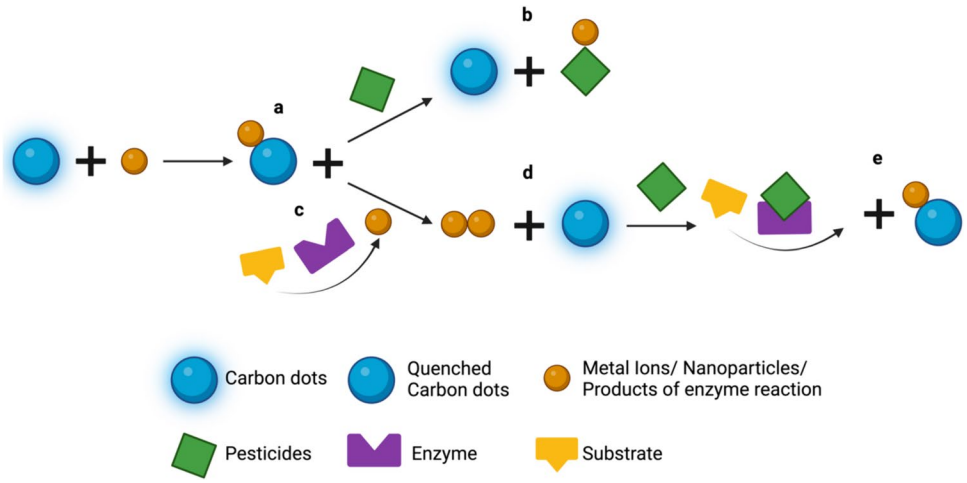

Fig. 5 Mechanisms of carbon dots sensors based on "off–on-off" quenching for detecting pesticides, modified from Shi et al. (2019) with two proposed mechanisms. In the first mechanism, fluorescent carbon dots react with metal ions to form a non-fluorescent complex (**a**). The fluorescent turns again in the presence of pesticides as the metal ions preferentially react with the pesticides (**b**). In the second mechanism, metal ions react with the enzymatic product instead of carbon dots, turning on the fluorescence (**c**). When pesticides are present, they inhibit the enzyme–substrate reaction, preventing the formation of the fluorescent product and causing the fluorescence of the carbon dots to turn off again by forming a non-fluorescent complex (**d** and **e**)

spectra of carbon dots overlap with the absorption spectrum of Imidacloprid, resulting in fluorescent quenching of carbon dots. Table 2 lists the recently published studies about carbon dots-sensors for detecting pesticides.

Carbon dots-based sensors have shown potential in rapidly detecting pesticides with broad linear correlations and reasonable detection limits. Carbon dots were applied to detect several pesticides in water, including carbaryl (Chen et al. 2020) and dimethoate (Liu et al. 2020). Furthermore, imidacloprid, a pesticide contaminant in vegetables, was detected with a carbon dots-based sensor with a detection limit of 1.87 ng/kg (Cao and Guo 2024). In terms of herbicides, glyphosate, one of the most common herbicides worldwide, was detected in cucumber, pepper, and ginger with carbon dots- cadmium telluride probes with excellent linear correlations ranging from 10 to 1000 nM and a detection limit of 2 pM (Bera and Mohapatra 2020). Yang et al. (2023) synthesized carbon dots from mulberry leaves and sodium hydroxide, subsequently, a carbon dots-sensor was developed to simultaneously detect glyphosate and parathion-methyl in herbal samples with the detection limit of 0.60 µM and 0.14 µM, respectively. Recently, Vadia et al. (2023) studied a multipurpose sensor to detect iron (III) ion and propiconazole in pharmaceutical and vegetable samples with a linear correlation range from 0.5 to 180 µM for iron (III) and 0.1–40 µM for propiconazole with the detection limit of 0.18 µM and 0.054 µM, respectively.

Table 2 Recent studies on carbon dots sensors for pesticide detection

Type of analyte	Analyte	Probes	Linear range	Low of detection	Measured sample	References
Pesticides	Carbaryl	Red emissive carbon dots	0–20 µg/mL	0.52 ng/mL	Tap water, lake water	Xu et al. 2024
	Dimethoate	Carbon dots / Dithizone	0.15–5 µM	0.064 µM	River water, farm water	Liu et al. 2020
	Imidacloprid	Carbon dots	0.037–0.2 mg/L	0.00187 mg/kg	Lettuce, cole, spinach, and pakchoi with spiked	Cao and Guo 2024
	Organochlorine pesticides: Heptachlor, Endosulfan, Chlordimeform and 2,4-dichlorophenoxyacetic acid	The surface-engineered fluorescent blue emissive-carbon dot	1–19 µM	Heptachlor: 0.002 µM Endosulfan: 0.099 µM Chlordimeform: 0.16 µM 2,4-dichlorophenoxyacetic acid: 0.082 µM	Water, soybean sprout, mung bean sprout	Nethaji et al. 2024
Herbicide	Glyphosate	Carbon dots / Cadmium telluride	10–1000 nM	2 pM	Cucumber, pepper, ginger	Bera and Mohapatra 2020
	Glyphosate	A dual emissive carbon dot	0–10 ppm	0.03 ppm	Water	Clermont-Paquette et al. 2023
Herbicide,Pesticide	Glyphosate, Parathion-methyl	Carbon dots	Glyphosate: 1.0–110.0 µM Parathion-methyl: 0.3–65.0 µM	Glyphosate: 0.60 µM Parathion-methyl: 0.14 µM	Food/herbal samples	Yang et al. 2023
Metal Ions, Pesticide	Iron (III) ion, Propiconazole	Carbon dots	Iron (III) ion: 0.5–180 µM Propiconazole: 0.1–40 µM	Iron (III) ion: 0.18 µM Propiconazole: 0.054 µM	Pharmaceutical, and vegetable samples	Vadia et al. 2023
Fungicide	Dodine	Bamboo stem biomass carbon dots	0.1–10.0 nM	4.3 nM	Peach, plum, apple, onion leaf, kidney beans	Adaikalapandi et al. 2024
	Thiophanate-methyl	Yellow-green fluorescent carbon dots	0–10 µM	50.7 nM	Pear, orange tomato	Wang et al. 2024

Various studies focus on developing carbon dots-based sensors to detect pesticides, herbicides, and fungicide residues in food samples. The primary objectives in this field include increasing sensor sensitivity, lowering detection limits, and developing sensors capable of detecting multiple pesticides simultaneously

Detection of food additives

Food additives have been used in many processed foods for several years to maintain their structure, enhance their appearance, and improve their flavor. While food additives can have remarkable benefits for the food industry, consuming large amounts of these compounds can have adverse effects on food quality and even consumer health. Additionally, several food additives have been banned in some countries due to health concerns. There are varied ways to produce carbon dots sensors to detect food preservatives, however, static quenching (Fig. 4) and "off–on-off" quenching (Fig. 5) are the two most common methods, which were described in subSects. "Detection of metal ions" and "Detection of pesticide residues". Sensors made from carbon dots can be used to detect a variety of food preservatives, including nitrile, formaldehyde, borax, and sulfite, listed in Table 3. Nitrile, a common preservative used to extend the shelf life of meat products, can be rapidly detected with carbon dots sensors with a linear range of 0–4.3 µM and a limit of detection of 0.5 nM (Hu et al. 2019). Formaldehyde, a banned preservative in several countries, is still used in some food products, such as noodles, fish, and meat, to increase elasticity and shelf life. Nitrogen, phosphorous-carbon dots can detect formaldehyde in sprouted beans with a detection limit of 0.47 µM (Qu et al. 2020). Borax, which has been

Table 3 Recent studies on carbon dots sensors for detecting food additives

Type of analyte	Analyte	Probes	Linear Range	Low of detection	Measured sample	References
Preservatives	Nitrite	Crystal violet carbon dots	0–20 mg/L	0.6 mg/L	Mustard, sausage, water	Liu et al. 2024
		Carbon dots	0–4.3 µM	0.5 nM	Ham	Hu et al. 2019
		Carbon dots	0.1–100 µM	31.6 nM	Bacon, sausage, pickle, milk samples	Liu et al. 2019
	Potassium sorbate, vitamin B12	Boron–carbon dots	0.2–24 µM	6.1 nM	Vinegar and bread	Jia et al. 2019
	Formaldehyde	Nitrogen, phosphorous-carbon dots	0–40 µM	0.5 µM	Sprouted beans	Qu et al. 2020
	Borax	Carbon dots	100–500 µM	1.5 µM	Fishball	Prathumsuwan et al. 2019
	Bisulfite, sulfite	Carbon dots / zeolitic imidazolate framework	10 µM–8.5 mM	2.7 µM	Sugar	Wang et al. 2023
		Carbon dots / silver nanoparticles / hydrogen peroxide	20–200 µM	3 µM	Food samples and herbs	He et al. 2023
Artificial colors	Tartrazine (Yellow #5)	Nitrogen-carbon dots / Iron (III) ion	0.10–30.00 µM	48 nM	Orange juice	Yang et al. 2020
	Sunset yellow (Yellow #6)	Nitrogen-carbon dots	0.5–40 µM	28 nM	Soft drinks, wine, sugar rolls, dried plum, swiss roll	Su et al. 2022
	Sudan Red II	Nitrogen, oxygen-carbon dots	0–8 mg/L	0.6 mg/L	Spiked spice samples	Ramoğlu et al. 2021
	Sudan Red I	Nitrogen, phosphorous-carbon dots	43 nM–52 µM	43 nM	Paprika	Zhao et al. 2021b
	Indigo Carmine	Nitrogen-carbon dots	0.73–10 µM	0.24 µM	Fruit juice and soft drink	Ali et al. 2021
		Europium-carbon dots	1.5–10 µg/ml	0.4 µg/ml	Juice samples	Albalawi et al. 2023
	Sunset Yellow	Carbon dots	0–60 µM	0.4 µM	-	Huang et al. 2017
Artificial colors and Metal Ion	Allura red (Red #40), Iron (III)	Carbon dots	0–30 µM	Red #40: 0.61 µM; Iron (III): 0.26 µM	Juice, syrups, tap water, wastewater, distilled water	Vijeata et al. 2022

Carbon-dot-based sensors detect various food additives, including preservatives and artificial colors. This is essential for maintaining food safety and mitigating consumer risks. Doping carbon dots in these sensors increases their sensitivity. A wider range of carbon dots has been studied and measured for this purpose

used as a food preservative in some countries to prevent the growth of bacteria and molds, is now illegal for use in foods in the USA following regulations from the Food and Drug Administration (FDA 2023). The combination of carbon dots and silver nanoparticles for biosensors can detect both sulfite and bisulfite in several food and herb samples with a detection limit of 3.02 µM (He et al. 2023). Although carbon dots-based sensors can find the presence of several food preservatives, there is still early research about this, there are hundreds of preservatives that need to be studied.

Not like preservatives, carbon dots can detect almost primary artificial colors in food including tartrazine and sunset yellow for yellow color; sundan red I and sundan red II for red color; Indigo carmine for blue color (Albalawi et al. 2023; Ali et al. 2021; Ramoğlu et al. 2021; Su et al. 2022; Yang et al. 2020; Zhao et al. 2021a). For example, in India, sudan red I and sudan red IV are permitted for use in certain food products, such as chili powder and turmeric powder, which can be measured using carbon dots-based sensors with low detection on 43 nM for sudan red I (Zhao et al. 2021a) and 0.6 mg/L for sudan red II (Ramoğlu et al. 2021). Tartrazine was detected in orange juice by nitrogen-carbon dots / iron (III) ion sensor with a linear range from 0.1 to 30 µM with a detection limit of 48 nM (Yang et al. 2020).

Active packaging

The mechanism of carbon dots-based packaging is based on two main properties of carbon dots: their sensitivity to different pH and their antimicrobial and antioxidant activity. The development of active packaging with carbon dots is still in the early stages, but the reported results are remarkable, which are listed in Table 4. Due to their sensitivity to pH, the fluorescence of carbon dots could

Table 4 Recent studies on carbon dots sensors for active packaging

Packaging materials	Research Objects	Results	References
Carbon dots / chitosan / gelatin-based composite films	Avocado	Extended shelf life of more than 14 days; Antimicrobial activity on *Listeria mon ytogenes* and *Escherichia coli;* Antifungal activity on mold (*Aspergillus flavus* and *Colletotrichum orbiculare*); negligible cytotoxicity to L929 cells (after 72 h)	(Ezati et al. 2022)
Carbon dots / cellulose nanofiber / essential oil nanoemulsion / gelatin films	Tomato	Extended shelf life up to 6 days; Antimicrobial effects against *Escherichia coli*	(Bao et al. 2023)
Nitrogen-carbon dots / chitosan	Pork	Maintained pork freshness; Antioxidant activity; Antibacterial activity of *Staphylococcus aureus* and *Escherichia coli*	(Lin et al. 2022)
Carbon dots / carboxymethyl cellulose / agar-based film	Not available	The addition of carbon dots reduced the mechanical strength and surface hydrophobicity, maintained the water vapor barrier and improved UV blocking, antioxidant, and antibacterial activities	(Tammina and Rhim 2023)
Carbon dots / chitosan	Blueberries	Extended shelf life until 15 days; Stabilized the anthocyanin content (chitosan / 3% nitrogen-carbon dots); Delayed the spoilage	(Chen et al. 2023)
Zinc-carbon dots / carrageenan films	Shrimps	UV-blocking; Antimicrobial activity; Antioxidant activity; Extended shelf life	(Khan et al. 2024)
Carbon dots / alginate	fiordilatte cheese	Against *Escherichia coli*; Extended the shelf life until 10 days	(Lacivita et al. 2023)
Carbon dots / antimicrobial bacterial cellulose membranes	Ground beef	Significantly reduced the growth of *Escherichia coli*	(Ghorbani et al. 2024)
Carbon dots / gelatin / poly(vinyl alcohol)-based functional films	Ground pork	Improved shelf life during the 48 h storage period at 20 °C; Prevented bacteria growth	(Min et al. 2023)
Carbon dots / anthocyanin / cellulose nanofiber	Pork, fish, shrimp	Improved UV barrier; Maintained antioxidant properties	(Wagh et al. 2023)
Carbon dots / alginate	Banana	Enhanced surface hydrophobicity of films; Damaged slightly gas barrier properties; Increased the anti-browning ability; Extended the shelf life	(Mao et al. 2023)

Incorporating carbon dots with other packaging materials enhances packaging quality by increasing UV-blocking capabilities. Additionally, carbon dots improve the antimicrobial activity of packaging, thereby extending the shelf life of various food types, including meat products, seafood, and fruits

be changed depending on different pHs. Carbon dots have been combined with several packaging materials, such as chitosan, gelatin, and alginate to create active packaging that can be controlled by changes in fluorescence (Bao et al. 2023; Chen et al. 2023; Lacivita et al. 2023). Combining carbon dots and chitosan as modified active packaging for fresh-cut cucumber has been shown to significantly prolong the overall appearance and inhibit the growth of *Staphylococcus aureus* and *Escherichia coli* with increasing carbon dots concentration (Fan et al. 2019). Carbon dots have also been used as an edible coating in combination with alginate, which doubled the shelf life of fiordilatte cheese to 10 days (Lacivita et al. 2023). Moreover, carbon dots-based packaging has been shown to positively extend the shelf life of fruits, including avocados up to 14 days (Ezati et al. 2022), tomatoes up to 6 days (Bao et al. 2023), and blueberries up to 15 days at 25 °C (Chen et al. 2023). Adding carbon dots in the packaging even prevented the browning reaction of banana peel during ripening (Mao et al. 2023).

The incorporation of carbon dots in active packaging created a positive effect for not only fruit products but also meat products. The freshness of pork can also be monitored by the increase in fluorescent intensity of packaging made from carbon dots and chitosan (Lin et al. 2022). Carbon dots added into antimicrobial bacterial cellulose membranes significantly reduced the growth of *Escherichia coli* and extended the shelf life of ground beef up to 9 days at 4 °C (Ghorbani et al. 2024). In addition to its antioxidant and antimicrobial activity, carbon dots-based packaging can also maintain UV-blocking properties (Khan et al. 2024; Tammina and Rhim 2023). Tammina and Rhim (2023) concluded that incorporating carbon dots into an agar-based film can reduce the film's mechanical strength and surface hydrophobicity, but the effects on the mechanical strength of films may depend on the type of film. For example, in Khan et al. (2024) it was reported that zinc-carbon dots did not affect the strength of the carrageenan-zinc-carbon dots film.

Foodborne pathogen detection

Foodborne pathogens are a crucial problem that needs to be controlled in food safety. In recent years, researchers have made significant advancements in the development of detection methods for foodborne pathogens using carbon dots. Carbon dots were reported to detect several major foodborne pathogens including *Staphylococcus aureus* (Gao et al. 2024; John et al. 2020; Zhao et al. 2021a), *Escherichia coli* (John et al. 2020; Zhao et al. 2021a). The representative studies focusing on foodborne pathogen detection of carbon dots are shown in Table 5. Aflatoxin B, a main toxic produced by certain molds, particularly *Aspergillus flavus* and *Aspergillus parasiticus*, also can be detected with carbon dots probes (Li et al. 2024). The antimicrobial properties of carbon dots, combined with their nanoscale size, make them an ideal candidate for pathogen detection. Carbon dots have a core of carbon nanoparticles and a thin surface passivation layer, allowing them to interact with bacteria and toxins effectively (Abu et al. 2020). Research has shown that carbon dots can be used in conjunction with other nanomaterials, such as dye-filled nanoparticles, magnetic nanomaterials, and silver nanoshells, to enhance detection sensitivity and reduce detection time (Gao et al. 2024; John et al. 2020).

The integration of nanosensors into food packaging has emerged as a key application in the detection of pathogens and toxins in food products. Fluorescent nanoparticles, such as carbon dots, have shown great potential in this field. For example, studies have demonstrated that carbon dots coupled with immunomagnetic separation can effectively detect foodborne pathogenic bacterial species like *Salmonella typhimurium* and *Escherichia coli* in milk and apple juice (Zhao et al. 2009). Another approach to detecting the presence of *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis,* and *Proteus vulgaris* in food products is through pH-sensitive detection (Pathak et al. 2020). This change can be easily detected and quantified, providing a rapid and sensitive method for pathogen detection.

Table 5 Recent studies on carbon dots sensors for detection of foodborne pathogens

Foodborne pathogen	Probes	Minimum Inhibitory Concentration/ Low of detection	Measured sample	References
Aflatoxin B	Nitrogen-doped carbon dots	77 pg/mL	Coix seed	Li et al. 2024
Escherichia coli	Nitrogen, phosphorous-carbon dots	0.5 mg/mL	paprika	Zhao et al. 2021a
	Carbon dots / amoxicillin	1.5×10^{-8} CFU/ml	–	John et al. 2020
Staphylococcus aureus	Carbon dots / amoxicilin	1.5×10^{-8} CFU/ml	–	John et al. 2020
	Carbon dots / manganese dioxide	9 CFU/mL	–	Gao et al. 2024
	Nitrogen, phosphorous-carbon dots	7.5 µg/mL	paprika	Zhao et al. 2021a

Carbon dots sensors can detect foodborne pathogens, including aflatoxin B, *Escherichia coli*, and *Staphylococcus aureus*. In addition to detecting pathogens, staining bacteria with carbon dots solutions can differentiate between bacterial types

Monitoring of food nutrients

Food nutrient monitoring is essential for ensuring the quality and safety of food products. Additionally, it plays a crucial role in assessing the nutritional content of food and enabling individuals to make informed dietary choices. Traditional methods for food nutrient monitoring, such as ion exchange chromatography and mass spectrometry, often require complex procedures, expensive equipment, and lengthy analysis times. Therefore, the development of rapid measurement for control of the nutrient content in foods is necessary. One promising food nutrient monitoring approach is carbon dots (Table 6). Carbon dots have been used to develop novel nanosensors and nano biosensors for food quality control including glucose, amino acids, and vitamins B_2 (Lin et al. 2019; Rossini et al. 2019; Tabaraki and Abdi 2019; Yuxin et al. 2022). These carbon-based nanomaterials have shown great potential in enhancing the sensing signals and improving the accuracy of food nutrient monitoring devices (De Paula et al. 2019). Besides the essential nutrients, the combination of carbon dots detects other nutrients like quercetin, curcumin, and tea polyphenol (De Paula et al. 2019; Han et al. 2019; Wei et al. 2020).

Food safety assessments of carbon dots

Besides the remarkable application of carbon dots in the food industry, the food safety of carbon dots needs to be fully understood. One risk is their potential cytotoxicity, which refers to the ability of carbon dots to cause harm or damage to living cells at a certain dose. Furthermore, the genotoxicity of carbon dots is also an important aspect to be aware of, as it refers to their potential to damage genetic material and cause mutations. The accumulation and distribution of carbon dots in biological systems also need to be discussed. The overall food safety assessment of carbon dots is illustrated in Fig. 6.

Table 6 Recent studies on carbon dots sensors for monitoring food nutrients

Type of nutrients	Nutrients	Monitoring methods	Linear range	Low of detection	Samples	References
Carbohydrates	Glucose	Carbon dots / glucose oxidase / horseradish peroxidase	10^{-6}–10^{-5} M	–	Biofluids	Rossini et al. 2019
	Gluocose, glutathione	Silver-Carbon dots / peroxidase	Gluocose: 50–800 µM Glutathione: 1–60 µM	Gluocose: 11.30 µM Glutathione: 3.54 µM	Saliva, urine	Haiyang et al. 2024
	Glucose, lactase	Carbon dots / oxidase	Gluocose: $21–38\times10^{-6}$ M Lactate: 1.0–7.5×10^{-4} M	Gluocose: 2.60×10^{-6} M Lactate: 8.14×10^{-7} M	Saliva	Rossini et al. 2021
	Glucose	Iron-Carbon dots / tetramethylbenzidin / hydrogen Peroxide	0.08–10.00 mM	0.029 mM	Urine	Yuxin et al. 2022
Amino acids, Peptides	Aspartic acid	Nitrogen-Carbon dots	0.5–50 µM	90 nM	Sport supplements	Tabaraki and Abdi 2019
Vitamins	Riboflavin	Zinc and Chlorine Co-doped carbon dots	0–10 µg/mL	12.5 ng/mL	Apple juice	Meng and Wu 2024
Others	Quercetin	Nitrogen- and Sulfur-codoped carbon dots	0–29.7 µM	17.3 nM	Red wine, onion	Sasikumar et al. 2023
	Curcumin	Nitrogen- and Sulfur-codoped carbon dots	2.0–18.0 µM	0.04 µM	Urine	Han et al. 2019
	Polyphenol	Carbon dots / copper(II) ion	1–30 µM	0.31 µM	Green tea	Wei et al. 2020

Carbon dots-based sensors can quantify the nutrient content in foods, such as carbohydrates, amino acids, vitamins, and other bioactive compounds. Doping carbon dots with nitrogen, sulfur, silver, or copper enhances sensor sensitivity. Sensors are designed to optimize performance depending on the specific nutrient being detected

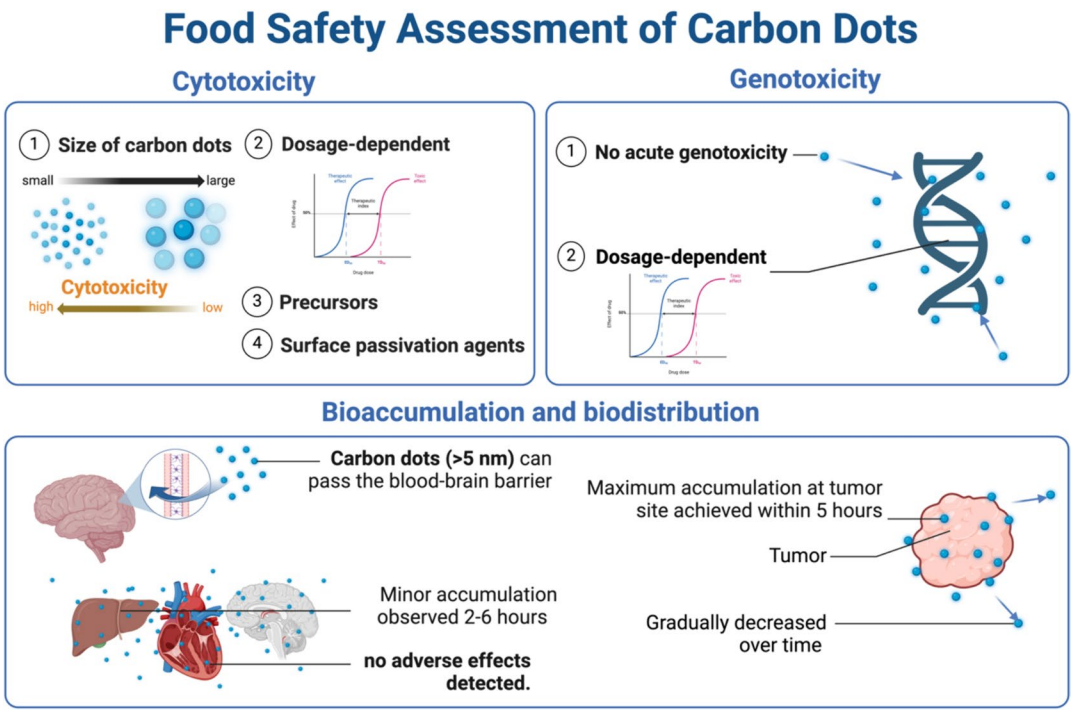

Fig. 6 Food safety assessment of carbon dots. The cytotoxicity of carbon dots is influenced by various factors such as size, dosage, precursors, and surface passivation agents. The genotoxicity of carbon dots is primarily associated with dosage and does not cause acute effects on genetic materials. Bioaccumulation and biodistribution studies indicate that small-sized carbon dots can cross the blood–brain barrier and accumulate in the heart, brain, liver, and tumors; however, no adverse effects have been detected

Cytotoxicity

Carbon dots, while generally considered to have lower cytotoxicity than semiconductor quantum dots, can still exhibit cytotoxic effects depending on various factors involved in their synthesis and design (Hola et al. 2014; Sahu et al. 2012). Wang et al. (2011) emphasized in a systematic review of the cytotoxicity of carbon dots that while carbon dots have shown great potential for imaging applications, their cytotoxicity needs to be carefully evaluated to ensure their safe use. The cytotoxicity of carbon dots was affected by several factors, including dose, precursor materials, surface passivation agents, and size of carbon dots. First, the cytotoxicity of carbon dots was affected by the precursor materials. For instance, different organic precursors like glucose, sucrose, glycol, glycerol, and citric acid can introduce impurities or toxic components during the carbonization process, thereby affecting the cytotoxicity of the resulting carbon dots (Sahu et al. 2012). Additionally, the composition of carbon dots has been identified as a key determinant of their cytotoxic behavior. Studies have shown that carbon dots synthesized from natural precursors, such as orange juice, demonstrated excellent biocompatibility and low cytotoxicity (Sahu et al. 2012). The cytotoxicity of carbon dots was also dose-dependent (Li et al. 2018a). The results of this study indicated that 80% of cells survived at 1 mg/mL, whereas 90% of cells experienced death at 10 mg/mL. However, carbon dots obtained from Kvass, a type of beverage, showed no cytotoxicity below 20 mg/mL (Liao et al. 2015). Different precursor materials with different doses can affect the cytotoxicity of carbon dots.

The cytotoxicity of carbon dots is also dependent on the selection of the surface passivation agent and the size. Surface modifications with biocompatible molecules can enhance the biocompatibility of carbon dots and reduce their cytotoxic effects (Nygård et al. 2000). Mukherjee et al. (2022) mentioned that the presence of heteroatoms on the surface of carbon dots, such as amine, hydroxyl, carboxyl, or thiol functional groups, can improve their physicochemical qualities, quantum yield, and likelihood of visible light absorption, eliminating the need for additional surface passivation (Mukherjee et al. 2022). Similarly, the size of carbon dots plays a crucial role, with smaller dots exhibiting higher cellular uptake and potentially inducing cytotoxic effects (Nygård et al. 2000). The significance of size-dependent cytotoxicity has been observed in studies on carbon dot quantum dots, where smaller quantum dots displayed higher toxicity than larger ones (Derfus et al. 2004). While it is essential to acknowledge that carbon dots generally exhibit low cytotoxicity (Du et al. 2023), it's important to note that the specific cytotoxic effects can vary depending on experimental conditions and cell types (Hola et al. 2014). Some

studies have indicated that high concentrations or prolonged exposure to carbon dots can lead to cell death or affect cellular functions (Hola et al. 2014; Li et al. 2018a; Liao et al. 2015). Nonetheless, such effects are typically observed at concentrations significantly higher than those typically used for imaging or therapeutic applications.

Genotoxicity

Genotoxicity refers to the ability of a substance to cause damage to genetic material, such as DNA, leading to mutations or other genetic alterations. In the case of carbon dots, several studies have investigated their genotoxicity. Carbon dots do seem not to cause any acute damage to the genetic materials, according to the results of published articles about the genotoxicity of carbon dots. One study by Pelaz et al. (2017) evaluated the genotoxicity of carbon dots in animals. The study found that carbon dots dosages of 51 mg/kg body weight did not cause any genotoxic effects or abnormalities in the organs of the animals. Another study by Zaidi et al. (2022) conducted a biosafety evaluation of photoluminescent carbon dots produced by nitric acid oxidation. This study found no acute toxicity, genotoxicity, or abnormalities in the organs of mice. The genotoxicity depends on the dose of carbon dots. For example, Havrdová et al. (2021) investigated the genotoxic effects of carbon dots on cells. The study found that quantum carbon dots up to 400 µg/mL concentration did not significantly affect cell viability or DNA content. However, at higher concentrations, carbon dots could lead to changes in the morphology of cells, causing cell death.

Bioaccumulation and biodistribution

In terms of the accumulation and distribution of carbon dots in biological systems, Yang et al. (2009a) a study was conducted on the biodistribution of carbon dots in vivo. The study results indicated minor accumulations of carbon dots in the organs, suggesting low bioaccumulation. This finding is consistent with the absence of any significant damage to the organs. However, the study also emphasized the need for further systematic investigations on the in vivo biodistributions of different types of carbon dots (Yang et al. 2009a). Carbon dots were reported to cause neurodegenerative effects by Song et al. (2018). The study found that carbon dots were distributed in the cytoplasm but not the nucleus after 24 h of incubation. In mice experiments, carbon dots were orally administered, reaching the brain within 2 h, as observed by the increased fluorescent intensity in the mouse brain, indicating passage through the blood–brain barrier. A recent study reported that carbon dots can accumulate in both the nucleus and cytoplasm causing death for L929 cells (Shabbir et al. 2022). Li et al. (2018a) demonstrated that carbon dots derived from Maillard reaction products can readily penetrate both plant and animal cells, distributing themselves either within the cell wall or the cytoplasm.

Additionally, significant accumulation was found in the liver, brain, and heart 2–6 h after administration, indicating potential blood–brain barrier crossing for ultra-small nanoparticles smaller than 5 nm (Li et al. 2018b). Although Li et al. (2018b) proved that carbon dots can be quenched by saliva, gastric juice, and duodenal-bile juice in *vitro* digestion experiments, the accumulation and distribution of carbon dots need to be studied deeply to understand their fate and effects on biological systems (Li et al. 2018b). Due to this potential health risk, further investigation is necessary into the association between carbon dots and bioactive molecules. Moreover, Liao et al. (2021) focused on the in vivo biodistribution, clearance, and biocompatibility of multiple carbon dots containing nanoparticles for biomedical applications. The study investigates the accumulation and fluorescence intensity of carbon dots over time, which found that single carbon dots took 5 h to reach maximum accumulation at the tumor site, and the fluorescence intensity of carbon dots gradually decreased over time. Although the accumulation and distribution of carbon dots have been studied, the conversion and excretion of carbon dots have not been thoroughly researched to obtain a comprehensive database on how carbon dots affect our health.

Strategies for mitigating the risk

To ensure the safe use of carbon dots in various applications, researchers have developed or proposed various mitigating strategies, including surface modification and functionalization (Yao et al. 2019), using natural precursors (Sahu et al. 2012), and controlling the size of carbon dots via different synthesis and purification methods (Derfus et al. 2004). After studying the toxicity and the possibility of accumulating carbon dots in organs, developing standardized carbon dots with a reliable analytical method must be a concern. Figure 7 illustrates the overall diagram of the four main mitigating strategies.

Selecting the appropriate precursors

Selecting the appropriate precursors is an effective strategy for mitigating the risks associated with carbon dots. The selection of precursors can strongly influence the properties and performance of carbon dots, including their optical properties, surface chemistry, and biocompatibility (Hola et al. 2014; Peng et al. 2016; Yao et al. 2019; Zeng et al. 2021). Several carbon dots were synthesized from various precursors listed in Table 7 and divided into two main groups, including natural materials and synthetic

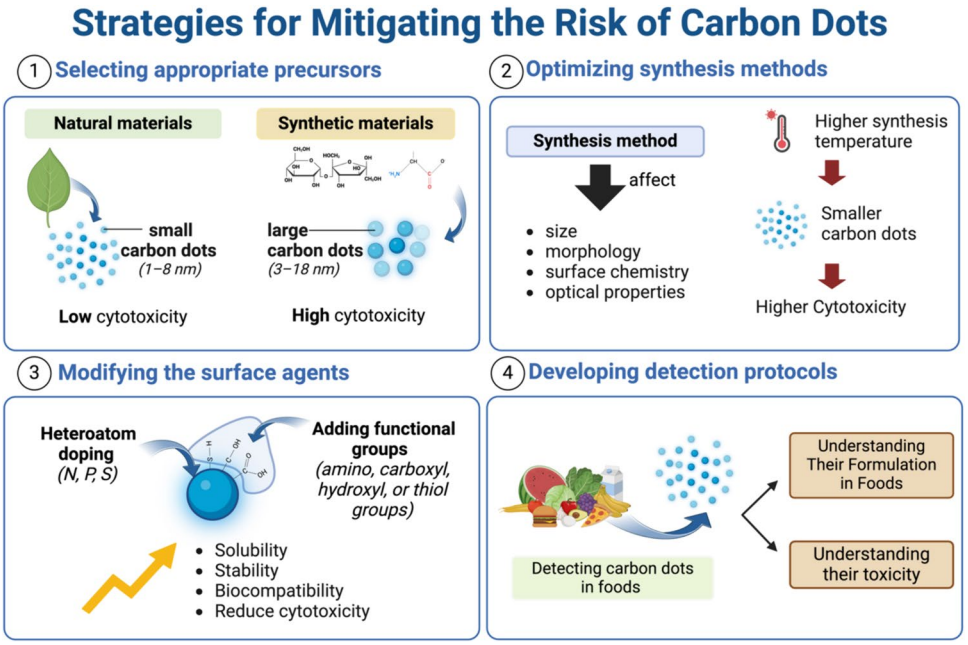

Fig. 7 Strategies for mitigating the risk of carbon dots. **1** Selecting appropriate precursors, such as natural materials, can produce smaller carbon dots with lower cytotoxicity, thereby reducing potential toxicity. **2** Optimizing synthesis methods can significantly impact the size, morphology, surface chemistry, and optical properties of carbon dots, directly influencing their potential toxicity. **3** Surface modification by adding functional groups or incorporating heteroatom doping can enhance solubility, stability, and biocompatibility while reducing cytotoxicity. **4** Developing protocols for detecting carbon dots in foods is crucial for comprehensively understanding their formulation and assessing their toxicity

compounds. The choice of precursors can influence the structural diversity, properties, and cytotoxicity of carbon dots. Different precursors, such as small organic molecules, polymers, or biomass-derived materials can lead to the formation of carbon dots with different structures and functionalities (Zeng et al. 2021). For example, the use of different carbon sources and surface passivation agents can result in carbon dots with varied optical properties (Yao et al. 2019). Sahu et al. (2012) mentioned that using synthetic precursors can produce carbon dots with higher cytotoxicity compared with natural precursors. However, carbon dots synthesized from natural sources obtain a smaller size (1.5–8 nm) than synthetic ones (2.5–17.5 nm) (Table 7).

Furthermore, the appropriate choice of precursors can also allow for controlling other physicochemical properties of carbon dots. For instance, the use of specific synthesis precursors can influence the size, surface charge, and stability of carbon dots (Peng et al. 2016). This allows for the customization of carbon dots for different applications, such as biomedical or optoelectronic applications. Moreover, the selection of precursors can also impact the biocompatibility and toxicity of carbon dots. By choosing safe and non-toxic precursors, the resulting carbon dots can be safer for use in biological applications (Hola et al. 2014). By carefully selecting the precursors, it is possible to tailor the properties of carbon dots to meet specific application requirements and reduce the risk of carbon dots, especially in the food industry.

Optimizing synthesis methods

The synthesis method can significantly impact the properties and performance of carbon dots, including their size, morphology, surface chemistry, and optical properties (Atabaev 2018; De and Karak 2013; Wang et al. 2014). As discussed in Sect. "Synthesis of carbon dots", various methods have been utilized to produce carbon dots, each with its own set of advantages and disadvantages. Hydrothermal and microwave methods are two common techniques for producing carbon dots, involving high temperatures and energy to carbonize the precursors, resulting in carbon dots with high yield and smaller in size (Table 7). Different synthesis methods, such as hydrothermal, solvothermal, microwave-assisted, or pyrolysis methods, can result in carbon dots with varying sizes and shapes (Wang et al. 2014). Our previous study reported that lowering the synthesis temperature and using assist solvents like ethanol can obtain stronger fluorescent carbon dots, smaller size without increasing toxicity (Nguyen et al. 2024). Derfus et al. (2004) reported that the smaller carbon dots displayed higher cytotoxicity, similar to the conclusion of Nygård et al. (2000) higher cellular uptake and cytotoxicity. Furthermore, carbon dots smaller than 5 nm were recorded, passing the blood–brain barriers and accumulating in the brain, heart, and liver after 2–6 h (Li et al. 2018b). By carefully selecting the synthesis method, uniform and well-defined carbon dots can be achieved, enhancing their performance and reducing the potential variability in their properties (De and Karak 2013).

Table 7 Synthesized carbon dots in recent publications

Precursors	Type of precursors	Synthetic method	Size (nm)	Quantumn yield (%)	Excitation/ Emission wavelength (nm)	References
Aloe, Urea	Naturals	Hydrothermal	5.0	60.8	323/441	Yang et al. 2020
Bael Patra fruit	Naturals	Hydrothermal	6.0	57.1	321/350	Vijeata et al. 2022
Citric acid, Urea	Synthetics	Microwave	10.0	–	360/450	Tabaraki and Abdi 2019
Citric acid, tyramine	Synthetics	Microwave	17.5	11.0	355/440	Rossini et al. 2019
Citric acid, Urea, boric acid	Synthetics	Microwave	5.0	–	–	Sahu and Khan 2020
Citric acid, ethylenediamine;	Synthetics	Microwave	5.0	73.7	350/445	Wei et al. 2020
Citric acid, melamine	Synthetics	Hydrothermal	4.9	44.0	352/427	Pajewska-Szmyt et al. 2020
Citric acid, phenylenediamine	Synthetics	Hydrothermal	3.2	30.0	385/489	Chen et al. 2020
Citrate, Urea	Synthetics	Hydrothermal	4.1–6.3	40.0	–	Zhao et al. 2021b
Citric acid, acetoguanamine, trimethylene glycol	Synthetics	–	–	5.3	350/470	Ramoğlu et al. 2021
Citric acid, glycine	Synthetics	Hydrothermal	0.5–4.0	–	340/430	Yuxin et al. 2022
Citric acid, glucose, ethylenediaminetetraacetic acid	Synthetics	Hydrothermal	4.08	–	440/513	Hoang et al. 2023
Coconut husk	Naturals	Hydrothermal	3.3	–	350/440	Chunduri et al. 2016
Corn stalk powder	Naturals	Microwave	1.5–6.0	2.1	326/445	Du et al. 2023
2,3-Diaminobenzoic acid hydrochloride, sulfuric acid	Synthetics	Hydrothermal	7.6	18.0	595/644	Liu et al. 2019
Europium chloride, tannic acid	Synthetics	Hydrothermal	7.0	–	307/340	Albalawi et al. 2023
Glucose, polyethyleneimine, phosphoric acid	Synthetics	Low Temperature	12.0	14.0	430/530	Zhao et al. 2021a
Glucose	Synthetics	Hydrothermal	5.9–11.0	–	350/450	Ezati et al. 2022
Glycine, ethylenediaminetetraacetic acid, sodium salt	Synthetics	Hydrothermal	7.2	28.3	360/428	Ali et al. 2021
Glycine	Synthetics	Hydrothermal	3.3	–	390/470	He et al. 2023
Glycine, sugars	Synthetics	Low temperature, long time	2.5	–	360/438	Nguyen et al. 2024
Lemon peel	Naturals	Hydrothermal	2.0	32.0	378/468	Vadia et al. 2023
Locust powder, nitric acid, diethylenetriamine	Naturals	Chemical Oxidation	2.3	3.1	390/470	Su et al. 2022
Litchi chinensis	Naturals	Hydrothermal	4.1	12.0	–	Tang et al. 2018
Murraya koenigii	Naturals	Hydrothermal	2.0–8.0	5.4	390/450	Pandey et al. 2020
Mushroom	Naturals	Hydrothermal	8.0	–	–	Boobalan et al. 2020
Mulberry leaves	Naturals	Hydrothermal	7.0	–	320/440	Yang et al. 2023
Phenylenediamine	Synthetics	Solvothermal	–	26.7	–	Zhang et al. 2020
	Synthetics	Hydrothermal	10.0	–	365/470	Cao and Guo 2024
Polyethyleneimine iminodiacetic acid,	Synthetics	Hydrothermal	6.7	15.9	360/458	Qu et al. 2020
Phenylboronic acid	Synthetics	Hydrothermal	3.3	12.0	247/323	Jia et al. 2019
Pork rib bones	Naturals	Hydrothermal, Chemical Oxidation	4.2	–	315/453	Liu et al. 2020

Table 7 (continued)

Precursors	Type of precursors	Synthetic method	Size (nm)	Quantum yield (%)	Excitation/ Emission wavelength (nm)	References
Saccharomycetes, ethylenediamine;	Synthetics	Hydrothermal, Microwave	–	16.0	380/460	Yu et al. 2019
Sodium citrate	Synthetics	Hydrothermal	–	9.3	380/450	De Paula et al. 2019
Sodium citrate, thioure	Synthetics	Hydrothermal	2.5	26.9	350/440	Han et al. 2019
Sugarcane molasses	Naturals	Heat treatment	1.9	5.8	305/390	Huang et al. 2017
Sucrose	Synthetics	Microwave	5.3	-	365/520	Hu et al. 2019
Tryptophan, ethylenediamine	Synthetics	Chemical Oxidation	6.2	48.0	350/400	Mintz et al. 2019
Tryptophan, glucose	Synthetics	Hydrothermal	4.0–5.0	18.0	300/450	Ma et al. 2020
Unripe peach	Naturals	Hydrothermal	8.0	15.0	325/404	Atchudan et al. 2016
Water hyacinth leaves	Naturals	Chemical Oxidation	3.7	27.0	400/420–700	Prathumsuwan et al. 2019
Wheat brain	Naturals	Hydrothermal	–	33.2	400/500	John et al. 2020

Numerous precursors are used to synthesize carbon dots, categorized into two main groups: natural and synthetic materials. The size, quantum yield, and fluorescent properties of the synthesized carbon dots vary depending on the synthesis method employed, such as hydrothermal, microwave, chemical oxidation, or heat treatment

Furthermore, the choice of synthesis method can also influence the surface chemistry and functionalization of carbon dots. For example, using surface passivation agents or functionalization during the synthesis process can modify the surface properties of carbon dots, such as their stability, dispersibility, and biocompatibility (Atabaev 2018). This can be particularly important for applications in bioimaging or sensing, where the interaction of carbon dots with biological systems is crucial. Moreover, the synthesis method can also impact the optical properties of carbon dots. Different synthesis methods can lead to carbon dots with distinct photoluminescence properties, such as emission wavelength, quantum yield, and stability (Wang et al. 2014). By selecting the appropriate synthesis method, it is possible to tailor the optical properties of carbon dots for specific applications, such as fluorescence imaging or optoelectronics. Additionally, the choice of synthesis method can also affect the scalability and reproducibility of carbon dot production. Some synthesis methods may be more suitable for large-scale production, while others may be more suitable for small-scale or laboratory-scale synthesis (De and Karak 2013). Considering the scalability and reproducibility of the synthesis method is essential to ensure the consistent and reliable production of carbon dots.

Surface modification and functionalization

Surface modification and functionalization of carbon dots are important strategies to enhance their properties and reduce risks in various applications (Anilkumar et al. 2011; Ding et al. 2014; Park et al. 2016). By introducing functional groups to the surface carbon dots, their stability, biocompatibility, dispersibility, and functionality can be enhanced (Anilkumar et al. 2011; Ding et al. 2014). Functional groups such as amino, carboxyl, hydroxyl, or thiol groups can be added to enhance the solubility, stability, and reactivity of carbon dots (Park et al. 2016). These functional groups can also serve as anchor points for further functionalization or conjugation to biomolecules, dyes, or targeting ligands (Liu et al. 2015). In addition, these surface modification can even lower the detection limit of mercury (II) using nitrogen-carbon dots-based sensors (Aziz et al. 2019). Another approach to surface modification is doping carbon dots with heteroatoms like nitrogen, sulfur, or phosphorus. Doping can alter the electronic structure and surface chemistry of carbon dots, leading to improved photoluminescence, charge transfer, and catalytic activity (Dong et al. 2013; Hu et al. 2016). Nitrogen-doped carbon dots, for example, have shown enhanced fluorescence and improved biocompatibility, making them suitable for bioimaging and sensing applications (Wang et al. 2014). Furthermore, surface modification of carbon dots using appropriate precursors can improve their biocompatibility and reduce cytotoxicity (Yao et al. 2019). For example, Min et al. (2023) synthesized carbon dots from coffee grounds and seed extracts can be used to make active packaging to increase the shelf life of ground pork and prevent the growth of microorganisms.

In addition to functional groups and heteroatom doping, surface modification can involve the encapsulation or coating of carbon dots with polymers, silica, or other materials. This provides additional protection, stability, and functionality to carbon dots (Sawant et al. 2016). For instance, encapsulating carbon dots with polymers can enhance their biocompatibility and enable the controlled

release of encapsulated drugs or biomolecule carbon dots (Sawant et al. 2016). Surface modification and functionalization of carbon dots can be tailored to specific applications. In bioimaging, surface modification by targeting ligands or biomolecules enables specific cellular or tissue targeting (Liu et al. 2015). In sensing applications, surface modification enhances the selectivity and sensitivity of carbon dots toward specific analytes (Shen and Xia 2014). Furthermore, surface modification can improve the performance of carbon dots in energy storage, catalysis, and optoelectronic devices (Balogun et al. 2016).

Development of specific protocols to quantify carbon dots

Developing a quantitative method for measuring the amount of carbon dots is an important strategy for mitigating risks and ensuring accurate dosing in various applications. Several studies have focused on developing such methods to provide reliable and precise quantification of carbon dots. One approach to quantifying carbon dots involves spectroscopic techniques. Fluorescence spectroscopy is commonly used to measure the emission intensity of carbon dots, which can be correlated with their concentration (Li et al. 2012; Nguyen et al. 2024; Pan et al. 2020). By establishing a calibration curve using known concentrations of carbon dots, the emission intensity can be used to determine the amount of carbon dots in a sample. This method allows for rapid and non-destructive quantification of carbon dots. Another method for quantifying carbon dots is based on their absorbance properties. UV–Vis spectroscopy can be used to measure the absorbance of carbon dots at specific wavelengths, which can be correlated with their concentration (Nie et al. 2014). The amount of carbon dots can be determined by comparing the absorbance of a sample to a calibration curve (Churchill et al. 2009). This method is relatively simple and widely applicable.

In addition to spectroscopic techniques, other methods have been explored for quantifying carbon dots. For example, electrochemical methods have been developed, where the current or potential response of carbon dots is measured and correlated with their concentration (Zhao et al. 2022). This approach offers the advantage of high sensitivity and selectivity. Furthermore, advanced techniques such as atomic force microscopy (AFM), scanning electron microscopy (SEM), transmittance electron microscopy (TEM), and Raman microscope can be used to visualize and quantify carbon dots based on their morphology and size (Saraswat and Yadav 2020). These imaging techniques provide valuable information about the size distribution and density of carbon dots in a sample.

Perspective

Moving forward, a concerted effort is needed to establish comprehensive safety guidelines and regulatory frameworks for incorporating carbon dots in food applications. Furthermore, research is needed to elucidate the biodistribution, degradation pathways, and long-term health impacts of carbon dots. By pursuing these endeavors, we can ensure the responsible and beneficial integration of carbon dots in various food technologies while safeguarding consumer health and environmental sustainability. Exciting applications lie ahead, including intelligent food packaging with quality monitoring, enhanced food preservation by precisely targeting and eliminating foodborne pathogens, and delivery systems for essential nutrients. Carbon dots could be the key to creating intelligent food colorants and pathogen sensors. By pursuing these research directions and exploring these applications, we can unlock the full potential of carbon dots for a safer, healthier, and more sustainable food future.

Conclusion

Carbon dots have emerged as a noteworthy nanomaterial with various applications in various industries, including electronics, bioimaging, and pharmaceutical analysis. Recently, significant attention has been directed toward exploring their potential in the food technology sector. However, the absence of specific guidelines for determining toxicity thresholds and permissible levels of carbon dots in food remains a challenge. In this review, we have evaluated the potential risks associated with carbon dots and proposed mitigation strategies to address these concerns. These strategies encompass (1) selecting safe precursor materials, (2) adopting appropriate synthesis methods, and (3) modifying the surface agents to regulate surface properties, size, and characteristics of carbon dots. (4) Furthermore, it is imperative to develop standardized procedures for quantifying carbon dot levels in food products and to establish guidelines for research on the decomposition and potential contaminants introduced by carbon dots in food matrices.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Duyen H.H. Nguyen, Hassan El-Ramady and József Prokisch. The first draft of the manuscript was written by Duyen H.H. Nguyen, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by University of Debrecen. The authors are thankful for the support of the Stipendium Hungaricum Scholarship Program.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose. The authors have no other competing interests to declare.

References

Abu RDI, Mohammed OO, Dong X, Patel AK, Overton CM, Tang Y, Kathariou S, Sun Y-P, Yang L (2020) Carbon dots for highly effective photodynamic inactivation of multidrug-resistant bacteria. Mater Adv 1(3):321–325. https://doi.org/10.1039/D0MA00078G

Adaikalapandi S, Thangadurai TD, Manjubaashini N, Nataraj D, Babu TS, Kumar SM (2024) Bamboo stem biomass waste-derived excitation-dependent carbon dots for nanomolar detection of fungicide dodine in real samples and their ph-sensitive bacterial interaction studies. Diam Relat Mater 141:110692. https://doi.org/10.1016/j.diamond.2023.110692

Albalawi MA, Gomaa H, El Hamd MA, Abourehab MAS, Abdel-Lateef MA (2023) Detection of indigo carmine dye in juices via application of photoluminescent europium-doped carbon dots from tannic acid. Luminescence 38(2):92–98. https://doi.org/10.1002/bio.4417

Albrecht C (2008) Joseph R. Lakowicz: principles of fluorescence spectroscopy. Anal Bioanal Chem 390:1223–1224

Ali H, Ghosh S, Jana NR (2020) Fluorescent carbon dots as intracellular imaging probes. Wires Nanomed Nanobiotechnol 12(4):e1617. https://doi.org/10.1002/wnan.1617

Ali HRH, Hassan AI, Hassan YF, El-Wekil MM (2021) Colorimetric and fluorometric nanoprobe for selective and sensitive recognition of hazardous colorant indigo carmine in beverages based on ion pairing with nitrogen doped carbon dots. Food Chem 349:129160. https://doi.org/10.1016/j.foodchem.2021.129160

Anilkumar P, Wang X, Cao L, Sahu S, Liu J-H, Wang P, Korch K, Tackett Ii KN, Parenzan A, Sun Y-P (2011) Toward quantitatively fluorescent carbon-based "quantum" dots. Nanoscale 3(5):2023. https://doi.org/10.1039/c0nr00962h

Atabaev T (2018) Doped carbon dots for sensing and bioimaging applications: a minireview. Nanomaterials 8(5):342. https://doi.org/10.3390/nano8050342

Atchudan R, Edison TNJI, Lee YR (2016) Nitrogen-doped carbon dots originating from unripe peach for fluorescent bioimaging and electrocatalytic oxygen reduction reaction. J Colloid Interface Sci 482:8–18. https://doi.org/10.1016/j.jcis.2016.07.058

Aziz KHH, Omer KM, Hamarawf RF (2019) Lowering the detection limit towards nanomolar mercury ion detection via surface modification of n-doped carbon quantum dots. New J Chem 43(22):8677–8683. https://doi.org/10.1039/C9NJ01333D

Balogun M-S, Luo Y, Lyu F, Wang F, Yang H, Li H, Liang C, Huang M, Huang Y, Tong Y (2016) Carbon quantum dot surface-engineered vo_2 interwoven nanowires: A flexible cathode material for lithium and sodium ion batteries. ACS Appl Mater Interfaces 8(15):9733–9744. https://doi.org/10.1021/acsami.6b01305

Bao L, Liu C, Zhang ZL, Pang DW (2015) Photoluminescence-tunable carbon nanodots: Surface-state energy-gap tuning. Adv Mater 27(10):1663–1667. https://doi.org/10.1002/adma.201405070

Bao J, Hu Y, Farag MA, Huan W, Wu J, Yang D, Song L (2023) Carbon dots, cellulose nanofiber, and essential oil nanoemulsion from torreya grandis aril added to fish scale gelatin film for tomato preservation. Int J Biol Macromol 245:125482. https://doi.org/10.1016/j.ijbiomac.2023.125482

Bera MK, Mohapatra S (2020) Ultrasensitive detection of glyphosate through effective photoelectron transfer between cdte and chitosan derived carbon dot. Colloids Surf A 596:124710. https://doi.org/10.1016/j.colsurfa.2020.124710

Bisauriya R, Antonaroli S, Ardini M, Angelucci F, Ricci A, Pizzoferrato R (2022) Tuning the sensing properties of N and S co-doped carbon dots for colorimetric detection of copper and cobalt in water. Sensors 22(7):2487. https://doi.org/10.3390/s22072487

Boobalan T, Sethupathi M, Sengottuvelan N, Kumar P, Balaji P, Gulyás B, Padmanabhan P, Selvan ST, Arun A (2020) Mushroom-derived carbon dots for toxic metal ion detection and as antibacterial and anticancer agents. ACS Appl Nano Mater 3(6):5910–5919. https://doi.org/10.1021/acsanm.0c01058

Cao C, Guo W (2024) Carbon dots-based fluorescent probe for the detection of imidacloprid residue in leafy vegetables. Food Chem 435:137578. https://doi.org/10.1016/j.foodchem.2023.137578

Cao L, Meziani MJ, Sahu S, Sun Y-P (2013) Photoluminescence properties of graphene versus other carbon nanomaterials. Acc Chem Res 46(1):171–180. https://doi.org/10.1021/ar300128j

Chen Y, Qin X, Yuan C, Shi R, Wang Y (2020) Double responsive analysis of carbaryl pesticide based on carbon quantum dots and au nanoparticles. Dyes Pigm 181:108529. https://doi.org/10.1016/j.dyepig.2020.108529

Chen S, Zeng Q, Tan X, Ye M, Zhang Y, Zou L, Liu S, Yang Y, Liu A, He L, Hu K (2023) Photodynamic antibacterial chitosan/nitrogen-doped carbon dots composite packaging film for food preservation applications. Carbohydr Polym 314:120938. https://doi.org/10.1016/j.carbpol.2023.120938

Chunduri LAA, Kurdekar A, Patnaik S, Dev BV, Rattan TM, Kamisetti V (2016) Carbon quantum dots from coconut husk: evaluation for antioxidant and cytotoxic activity. Mater Focus 5(1):55–61. https://doi.org/10.1166/mat.2016.1289

Churchill HOH, Kuemmeth F, Harlow JW, Bestwick AJ, Rashba EI, Flensberg K, Stwertka CH, Taychatanapat T, Watson SK, Marcus CM (2009) Relaxation and dephasing in a two-electron ^{13}C nanotube double quantum dot. Phys Rev Lett 102(16):166802. https://doi.org/10.1103/PhysRevLett.102.166802

Clermont-Paquette A, Mendoza D-A, Sadeghi A, Piekny A, Naccache R (2023) Ratiometric sensing of glyphosate in water using dual fluorescent carbon dots. Sensors 23(11):5200. https://doi.org/10.3390/s23115200

De Paula N, Milani R, Lavorante A, Paim AP (2019) Use of carbon dots synthesized from citrate as a fluorescent probe for quercetin determination in tea and beer samples. J Braz Chem Soc. https://doi.org/10.21577/0103-5053.20190145

De B, Karak N (2013) A green and facile approach for the synthesis of water soluble fluorescent carbon dots from banana juice. RSC Adv 3(22):8286. https://doi.org/10.1039/c3ra00088e

Derfus AM, Chan WCW, Bhatia SN (2004) Probing the cytotoxicity of semiconductor quantum dots. Nano Lett 4(1):11–18. https://doi.org/10.1021/nl0347334

Ding C, Zhu A, Tian Y (2014) Functional surface engineering of c-dots for fluorescent biosensing and in vivo bioimaging. Acc Chem Res 47(1):20–30. https://doi.org/10.1021/ar400023s

Dong Y, Pang H, Yang HB, Guo C, Shao J, Chi Y, Li CM, Yu T (2013) Carbon-based dots co-doped with nitrogen and sulfur for high quantum yield and excitation-independent emission. Angew Chem 125(30):7954–7958. https://doi.org/10.1002/ange.201301114

Du Y, Li Y, Liu Y, Liu N, Cheng Y, Shi Q, Liu X, Tao Z, Guo Y, Zhang J, Askaria N, Li H (2023) Stalk-derived carbon dots as nanosensors for Fe^{3+} ions detection and biological cell imaging. Front Bioeng Biotechnol 11:1187632. https://doi.org/10.3389/fbioe.2023.1187632

EFSA (2023, 2023/07/23/) Metals as contaminants in food. European Food Safety Authority. Retrieved November 01 from https://www.efsa.europa.eu/en/topics/topic/metals-contaminants-food

El-Nahhal I, El-Nahhal Y (2021) Pesticide residues in drinking water, their potential risk to human health and removal options. J Environ Manage 299:113611. https://doi.org/10.1016/j.jenvman.2021.113611

Emam A, Loutfy SA, Mostafa AA, Awad H, Mohamed MB (2017) Cyto-toxicity, biocompatibility and cellular response of carbon dots–plasmonic based nano-hybrids for bioimaging. RSC Adv 7(38):23502–23514. https://doi.org/10.1039/C7RA01423F

Essner JB, Kist JA, Polo-Parada L, Baker GA (2018) Artifacts and errors associated with the ubiquitous presence of fluorescent impurities in carbon nanodots. Chem Mater 30(6):1878–1887. https://doi.org/10.1021/acs.chemmater.7b04446

EU-Commission (2023, 2023/04/25) Commission regulation 2023/915 on maximum levels for certain contaminants in food and repealing regulation no 1881/2006. https://food.ec.europa.eu/safety/chemical-safety/contaminants/legislation_en

Ezati P, Rhim J-W, Molaei R, Rezaei Z (2022) Carbon quantum dots-based antifungal coating film for active packaging application of avocado. Food Packag Shelf Life 33:100878. https://doi.org/10.1016/j.fpsl.2022.100878

Fan K, Zhang M, Fan D, Jiang F (2019) Effect of carbon dots with chitosan coating on microorganisms and storage quality of modified-atmosphere-packaged fresh-cut cucumber. J Sci Food Agric 99(13):6032–6041. https://doi.org/10.1002/jsfa.9879

FDA (2023, 2023) *Food additive status list*. U.S. Food and Drug Administration. Retrieved November 01 from https://www.fda.gov/food/food-additives-petitions/food-additive-status-list

Fernandes IDAA, Maciel GM, Bortolini DG, Pedro AC, Rubio FTV, De Carvalho KQ, Haminiuk CWI (2023) The bitter side of teas: pesticide residues and their impact on human health. Food Chem Toxicol 179:113955. https://doi.org/10.1016/j.fct.2023.113955

Fu M, Ehrat F, Wang Y, Milowska KZ, Reckmeier C, Rogach AL, Stolarczyk JK, Urban AS, Feldmann J (2015) Carbon dots: a unique fluorescent cocktail of polycyclic aromatic hydrocarbons. Nano Lett 15(9):6030–6035. https://doi.org/10.1021/acs.nanolett.5b02215

Galletto R, Bujalowski W (2002) Kinetics of the e. Coli replication factor dnac protein− nucleotide interactions. II. Fluorescence anisotropy and transient, dynamic quenching stopped-flow studies of the reaction intermediates. Biochemistry 41(28):8921–8934. https://doi.org/10.1021/bi020127w

Gao X, Zhang H, Liu L, Jia M, Li X, Li J (2024) Nano-biosensor based on manganese dioxide nanosheets and carbon dots for dual-mode determination of *staphylococcus aureus*. Food Chem 432:137144. https://doi.org/10.1016/j.foodchem.2023.137144

Ghorbani M, Moradi M, Tajik H, Molaei R, Alizadeh A (2024) Carbon dots embedded bacterial cellulose membrane as active packaging: toxicity, in vitro release and application in minced beef packaging. Food Chem 433:137311. https://doi.org/10.1016/j.foodchem.2023.137311

González-González RB, González LT, Madou M, Leyva-Porras C, Martinez-Chapa SO, Mendoza A (2022) Synthesis, purification, and characterization of carbon dots from non-activated and activated pyrolytic carbon black. Nanomaterials 12(3):298. https://doi.org/10.3390/nano12030298

Guo L, Li L, Wang X, Zhang Y, Cui F (2023) Synthesis of ph-sensitive nitrogen-doped carbon dots with biological imaging function and their application in Cu^{2+} and Fe^{2+} determination by ratiometric fluorescent probes. ACS Omega 8(40):37098–37107. https://doi.org/10.1021/acsomega.3c04596

Haiyang L, Guantong L, Nan Z, Zhanye Y, Xinge J, Bing Z, Tian Y (2024) Ag-carbon dots with peroxidase-like activity for colorimetric and sers dual mode detection of glucose and glutathione. Talanta 273:125898. https://doi.org/10.1016/j.talanta.2024.125898

Han Z, Zhang H, He L, Pan S, Liu H, Hu X (2019) One-pot hydrothermal synthesis of nitrogen and sulfur co-doped carbon dots and their application for sensitive detection of curcumin and temperature. Microchem J 146:300–308. https://doi.org/10.1016/j.microc.2019.01.024

Havrdova M, Hola K, Skopalik J, Tomankova K, Petr M, Cepe K, Polakova K, Tucek J, Bourlinos AB, Zboril R (2016) Toxicity of carbon dots–effect of surface functionalization on the cell viability, reactive oxygen species generation and cell cycle. Carbon 99:238–248

Havrdová M, Urbančič I, Bartoň Tománková K, Malina L, Štrancar J, Bourlinos AB (2021) Self-targeting of carbon dots into the cell nucleus: Diverse mechanisms of toxicity in nih/3t3 and l929 cells. Int J Mol Sci 22(11):5608

He Y, Wang Y, Wang S (2023) Carbon dot and silver nanoparticle–based fluorescent probe for the determination of sulfite and bisulfite via inner-filter effect and competitive redox reactions. Microchim Acta 190(5):190. https://doi.org/10.1007/s00604-023-05782-3

Hoan BT, Van Huan P, Van HN, Nguyen DH, Tam PD, Nguyen KT, Pham VH (2018) Luminescence of lemon-derived carbon quantum dot and its potential application in luminescent probe for detection of Mo^{6+} ions. Luminescence 33(3):545–551. https://doi.org/10.1002/bio.3444

Hoang NM, Ngoc NTB, Huong PTL, Huyen PTT, Duy DQ, Dao V-D, Tu LT (2023) Dual emission carbon dots for simultaneous detections of Pb^{2+} and Fe^{3+} ions in water via distinct sensing mechanisms. J Fluoresc 33(4):1359–1366. https://doi.org/10.1007/s10895-022-03139-2

Hoehl MM, Lu PJ, Sims PA, Slocum AH (2012) Rapid and robust detection methods for poison and microbial contamination. J Agric Food Chem 60(25):6349–6358. https://doi.org/10.1021/jf300817h

Hola K, Zhang Y, Wang Y, Giannelis EP, Zboril R, Rogach AL (2014) Carbon dots—emerging light emitters for bioimaging, cancer therapy and optoelectronics. Nano Today 9(5):590–603. https://doi.org/10.1016/j.nantod.2014.09.004

Hu Y, Al Awak MM, Yang F, Yan S, Xiong Q, Wang P, Tang Y, Yang L, LeCroy GE, Hou X, Bunker CE, Xu L, Tomlinson N, Sun Y-P (2016) Photoexcited state properties of carbon dots from thermally induced functionalization of carbon nanoparticles. J Mater Chem C 4(44):10554–10561. https://doi.org/10.1039/C6TC03666J

Hu X, Shi J, Shi Y, Zou X, Tahir HE, Holmes M, Zhang W, Huang X, Li Z, Xu Y (2019) A dual-mode sensor for colorimetric and fluorescent detection of nitrite in hams based on carbon dots-neutral red system. Meat Sci 147:127–134. https://doi.org/10.1016/j.meatsci.2018.09.006

Huang X, Zhang F, Zhu L, Choi KY, Guo N, Guo J, Tackett K, Anilkumar P, Liu G, Quan Q (2013) Effect of injection routes on the biodistribution, clearance, and tumor uptake of carbon dots. ACS Nano 7(7):5684–5693. https://doi.org/10.1021/nn401911k

Huang G, Chen X, Wang C, Zheng H, Huang Z, Chen D, Xie H (2017) Photoluminescent carbon dots derived from sugarcane molasses: synthesis, properties, and applications. RSC Adv 7(75):47840–47847. https://doi.org/10.1039/C7RA09002A

Huang S, Yao J, Chu X, Liu Y, Xiao Q, Zhang Y (2019) One-step facile synthesis of nitrogen-doped carbon dots: a ratiometric fluorescent probe for evaluation of acetylcholinesterase activity and detection of organophosphorus pesticides in tap water and food. J Agric Food Chem 67(40):11244–11255. https://doi.org/10.1021/acs.jafc.9b03624

Jia Y, Hu Y, Li Y, Zeng Q, Jiang X, Cheng Z (2019) Boron doped carbon dots as a multifunctional fluorescent probe for sorbate and vitamin b12. Microchim Acta 186(2):84. https://doi.org/10.1007/s00604-018-3196-5

John TS, Yadav PK, Kumar D, Singh SK, Hasan SH (2020) Highly fluorescent carbon dots from wheat bran as a novel drug delivery system for bacterial inhibition. Luminescence 35(6):913–923. https://doi.org/10.1002/bio.3801

Kang C, Huang Y, Yang H, Yan XF, Chen ZP (2020) A review of carbon dots produced from biomass wastes. Nanomaterials 10(11):2316. https://doi.org/10.3390/nano10112316

Khan A, Riahi Z, Tae Kim J, Rhim J-W (2024) Carrageenan-based multifunctional packaging films containing Zn-carbon dots/anthocyanin derived from kohlrabi peel for monitoring quality and extending the shelf life of shrimps. Food Chem 432:137215. https://doi.org/10.1016/j.foodchem.2023.137215

Kumar R, Vincy A, Rani K, Jain N, Singh S, Agarwal A, Vankayala R (2023) Facile synthesis of multifunctional carbon dots derived from camel milk for Mn^{7+} sensing and antiamyloid and anticancer activities. ACS Omega 8(39):36521–36533. https://doi.org/10.1021/acsomega.3c05485

Lacivita V, Tarantino F, Molaei R, Moradi M, Conte A, Alessandro Del Nobile M (2023) Carbon dots from sour whey to develop a novel antimicrobial packaging for fiordilatte cheese. Food Res Int 172:113159. https://doi.org/10.1016/j.foodres.2023.113159

Levallois P, Barn P, Valcke M, Gauvin D, Kosatsky T (2018) Public health consequences of lead in drinking water. Curr Environ Health Rep 5(2):255–262. https://doi.org/10.1007/s40572-018-0193-0

Li H, Kang Z, Liu Y, Lee S-T (2012) Carbon nanodots: synthesis, properties and applications. J Mater Chem 22(46):24230. https://doi.org/10.1039/c2jm34690g

Li D, Na X, Wang H, Xie Y, Cong S, Song Y, Xu X, Zhu B-W, Tan M (2018a) Fluorescent carbon dots derived from maillard reaction products: Their properties, biodistribution, cytotoxicity, and antioxidant activity. J Agric Food Chem 66(6):1569–1575. https://doi.org/10.1021/acs.jafc.7b05643

Li S, Jiang C, Wang H, Cong S, Tan M (2018b) Fluorescent nanoparticles present in coca-cola and pepsi-cola: physiochemical properties, cytotoxicity, biodistribution and digestion studies. Nanotoxicology 12(1):49–62. https://doi.org/10.1080/17435390.2017.1418443

Li T, Li Z, Huang T, Tian L (2021) Carbon quantum dot-based sensors for food safety. Sens Actuators A 331:113003. https://doi.org/10.1016/j.sna.2021.113003

Li Y, Song P, Xu Q, Wu W, Long N, Wang J, Zhou L, Pan R, Kong W (2024) Nitrogen-doped carbon dot and DNA tetrahedron nanostructure based electrochemiluminescence aptasensor for afb1 detection. Sens Actuators B 401:135024. https://doi.org/10.1016/j.snb.2023.135024

Liao H, Jiang C, Liu W, Vera JM, Seni OD, Demera K, Yu C, Tan M (2015) Fluorescent nanoparticles from several commercial beverages: Their properties and potential application for bioimaging. J Agric Food Chem 63(38):8527–8533. https://doi.org/10.1021/acs.jafc.5b04216

Liao J, Yao Y, Lee C-H, Wu Y, Li P (2021) In vivo biodistribution, clearance, and biocompatibility of multiple carbon dots containing nanoparticles for biomedical application. Pharmaceutics 13(11):1872. https://doi.org/10.3390/pharmaceutics13111872

Lin L, Wang Y, Xiao Y, Chen X (2019) Ratiometric fluorescence detection of riboflavin based on fluorescence resonance energy transfer from nitrogen and phosphorus co-doped carbon dots to riboflavin. Anal Bioanal Chem 411(13):2803–2808. https://doi.org/10.1007/s00216-019-01725-1

Lin W, Huang G, Yang W, Zeng S, Luo X, Huang J, Li Z (2022) A dual-function chitosan packaging film for simultaneously monitoring and maintaining pork freshness. Food Chem 392:133242. https://doi.org/10.1016/j.foodchem.2022.133242

Liu J, Liu M, He C, Song H, Chen F (2015) Effect of thermal treatment on the flavor generation from maillard reaction of xylose and chicken peptide. LWT Food Sci Technol 64(1):316–325. https://doi.org/10.1016/j.lwt.2015.05.061

Liu J, Chen Y, Wang L, Na M, Chen H, Chen X (2019) Modification-free fabricating ratiometric nanoprobe based on dual-emissive carbon dots for nitrite determination in food samples. J Agric Food Chem 67(13):3826–3836. https://doi.org/10.1021/acs.jafc.9b00024

Liu H, Ding J, Chen L, Ding L (2020) A novel fluorescence assay based on self-doping biomass carbon dots for rapid detection of dimethoate. J Photochem Photobiol A 400:112724. https://doi.org/10.1016/j.jphotochem.2020.112724

Liu Y-Y, Yu N-Y, Fang W-D, Tan Q-G, Ji R, Yang L-Y, Wei S, Zhang X-W, Miao A-J (2021) Photodegradation of carbon dots cause cytotoxicity. Nat Commun 12(1):812. https://doi.org/10.1038/s41467-021-21080-z

Liu Y, Qiao W, Fan X, Wang L, Wang M, Liu X, Jia Y, Liu D, Liu T, Zang M (2024) Rapid detection of nitrite in food by multi-colorimetric and fluorescence dual-mode based on crystal violet modulated carbon dots. Microchem J 200:110334. https://doi.org/10.1016/j.microc.2024.110334

Lu G, Jia Z, Yu M, Zhang M, Xu C (2023) A ratiometric fluorescent sensor based on chelation-enhanced fluorescence of carbon dots for zinc ion detection. Molecules 28(23):7818. https://doi.org/10.3390/molecules28237818

Ma Z, Ma Y, Gu M, Huo X, Ma S, Lu Y, Ning Y, Zhang X, Tian B, Feng Z (2020) Carbon dots derived from the maillard reaction for Ph sensors and Cr(VI) detection. Nanomaterials 10(10):1924. https://doi.org/10.3390/nano10101924

Mao L, Zuo J, Liu Y, Zheng B, Dai X, Bai Z, Liu Y, Yao J (2023) Alginate based films integrated with nitrogen-functionalized carbon dots and layered clay for active food packaging applications. Int J Biol Macromol 253:126653. https://doi.org/10.1016/j.ijbiomac.2023.126653

Meng L, Wu H (2024) Preparation of carbon quantum dots and their application in the detection of vitamin B2. RSC Adv 14(22):15499–15506. https://doi.org/10.1039/D4RA01388C

Min S, Ezati P, Yoon KS, Rhim J-W (2023) Gelatin/poly(vinyl alcohol)-based functional films integrated with spent coffee ground-derived carbon dots and grapefruit seed extract for active packaging application. Int J Biol Macromol 231:123493. https://doi.org/10.1016/j.ijbiomac.2023.123493

Mintz KJ, Mercado G, Zhou Y, Ji Y, Hettiarachchi SD, Liyanage PY, Pandey RR, Chusuei CC, Dallman J, Leblanc RM (2019) Tryptophan carbon dots and their ability to cross the blood-brain barrier. Colloids Surf B 176:488–493. https://doi.org/10.1016/j.colsurfb.2019.01.031

Mukherjee P, Chakraborty A, Chakraborty M, Mukhopadhyay G (2022) Carbon dot–an updated review. Int J Pharm Investig 12(2):136–140. https://doi.org/10.5530/ijpi.2022.2.25

Nethaji P, Revathi P, Kumar PS, Logesh M, Rajabathar JR, Al-Lohedan H, Arokiyaraj S, Rangasamy G (2024) Fluorescence enhancing and quenching signal based on new approach for selective detection of multiple organochlorine pesticides using blue emissive-carbon dot. Environ Pollut 345:123418. https://doi.org/10.1016/j.envpol.2024.123418

Nguyen DH, Muthu A, El-Ramady H, Daróczi L, Nagy L, Kéki S, Béni Á, Csarnovics I, Prokisch J (2024) Optimization of extraction conditions to synthesize green carbon nanodots using the maillard reaction. Mater Adv 5(8):3499–3505. https://doi.org/10.1039/D4MA00037D

Nie H, Li M, Li Q, Liang S, Tan Y, Sheng L, Shi W, Zhang SX-A (2014) Carbon dots with continuously tunable full-color emission and their application in ratiometric ph sensing. Chem Mater 26(10):3104–3112. https://doi.org/10.1021/cm5003669

Njoagwuani EI, Onyeaka H, Mazi IM, Akegbe H, Oladunjoye IO, Ochulor CE, Omotosho AD, Odeyemi OA, Nwaiwu O, Tamasiga P (2023) Food safety in vulnerable populations: a perspective on the challenges and solutions. FASEB J 37(5):e22872. https://doi.org/10.1096/fj.202201713R

Nobel-Prize (2023) The nobel prize in chemistry. NobelPrize.org. Retrieved November 01 from https://www.nobelprize.org/prizes/chemistry/2023/summary/

Nygård J, Cobden DH, Lindelof PE (2000) Kondo physics in carbon nanotubes. Nature 408(6810):342–346. https://doi.org/10.1038/35042545

Omer KM, Al-Hashimi B, Mohammadi S, Salimi A, Salih YM, Hassan AQ, Aziz KHH, Mohammad SJ (2022) Carbon nanodots as sensitive and selective nanomaterials in pharmaceutical analysis. J Mater Sci 57(30):14217–14245. https://doi.org/10.1007/s10853-022-07531-y

Otten M, Hildebrandt M, Kühnemuth R, Karg M (2022) Pyrolysis and solvothermal synthesis for carbon dots: role of purification and molecular fluorophores. Langmuir 38(19):6148–6157. https://doi.org/10.1021/acs.langmuir.2c00508

Pajewska-Szmyt M, Buszewski B, Gadzała-Kopciuch R (2020) Carbon dots as rapid assays for detection of mercury (II) ions based on turn-off mode and breast milk. Spectrochim Acta A 236:118320. https://doi.org/10.1016/j.saa.2020.118320

Pan M, Xie X, Liu K, Yang J, Hong L, Wang S (2020) Fluorescent carbon quantum dots—synthesis, functionalization and sensing application in food analysis. Nanomaterials 10(5):930. https://doi.org/10.3390/nano10050930

Pandey SC, Kumar A, Sahu SK (2020) Single step green synthesis of carbon dots from murraya koenigii leaves; a unique turn-off fluorescent contrivance for selective sensing of Cd (II) ion. J Photochem Photobiol A 400:112620. https://doi.org/10.1016/j.jphotochem.2020.112620

Park Y, Yoo J, Lim B, Kwon W, Rhee SW (2016) Improving the functionality of carbon nanodots: doping and surface functionalization. J Mater Chem A 4(30):11582–11603. https://doi.org/10.1039/C6TA04813G

Pathak A, Venugopal P, Nair BG, Suneesh PV, Satheesh Babu TG (2020) Facile ph-sensitive optical detection of pathogenic bacteria and cell imaging using multi-emissive nitrogen-doped carbon dots. Microchem J 159:105324. https://doi.org/10.1016/j.microc.2020.105324

Pelaz B, Alexiou C, Alvarez-Puebla RA, Alves F, Andrews AM, Ashraf S, Balogh LP, Ballerini L, Bestetti A, Brendel C, Bosi S, Carril M, Chan WCW, Chen C, Chen X, Chen X, Cheng Z, Cui D, Du J, Dullin C, Escudero A, Feliu N, Gao M, George M, Gogotsi Y, Grünweller A, Gu Z, Halas NJ, Hampp N, Hartmann RK, Hersam MC, Hunziker P, Jian J, Jiang X, Jungebluth P, Kadhiresan P, Kataoka K, Khademhosseini A, Kopeček J, Kotov NA, Krug HF, Lee DS, Lehr C-M, Leong KW, Liang X-J, Ling Lim M, Liz-Marzán LM, Ma X, Macchiarini P, Meng H, Möhwald H, Mulvaney P, Nel AE, Nie S, Nordlander P, Okano T, Oliveira J, Park TH, Penner RM, Prato M, Puntes V, Rotello VM, Samarakoon A, Schaak RE, Shen Y, Sjöqvist S, Skirtach AG, Soliman MG, Stevens MM, Sung H-W, Tang BZ, Tietze R, Udugama BN, VanEpps JS, Weil T, Weiss PS, Willner I, Wu Y, Yang L, Yue Z, Zhang Q, Zhang Q, Zhang X-E, Zhao Y, Zhou X, Parak WJ (2017) Diverse applications of nanomedicine. ACS Nano 11(3):2313–2381. https://doi.org/10.1021/acsnano.6b06040

Peng H, Li Y, Jiang C, Luo C, Qi R, Huang R, Duan C-G, Travas-Sejdic J (2016) Tuning the properties of luminescent nitrogen-doped carbon dots by reaction precursors. Carbon 100:386–394. https://doi.org/10.1016/j.carbon.2016.01.029

Prathumsuwan T, Jaiyong P, In I, Paoprasert P (2019) Label-free carbon dots from water hyacinth leaves as a highly fluorescent probe for selective and sensitive detection of borax. Sens Actuators B 299:126936. https://doi.org/10.1016/j.snb.2019.126936

Qu J, Zhang X, Liu Y, Xie Y, Cai J, Zha G, Jing S (2020) N, p-co-doped carbon dots as a dual-mode colorimetric/ratiometric fluorescent sensor for formaldehyde and cell imaging via an aminal reaction-induced aggregation process. Microchim Acta 187(6):355. https://doi.org/10.1007/s00604-020-04337-0

Ramoğlu B, Gümrükçüoğlu A, Çekirge E, Ocak M, Ocak Ü (2021) One spot microwave synthesis and characterization of nitrogen-doped carbon dots with high oxygen content for fluorometric determination of banned sudan II dye in spice samples. J Fluoresc 31(6):1587–1598. https://doi.org/10.1007/s10895-021-02795-0

Rodríguez-Varillas S, Fontanil T, Obaya ÁJ, Fernández-González A, Murru C, Badía-Laíño R (2022) Biocompatibility and antioxidant capabilities of carbon dots obtained from tomato (*solanum lycopersicum*). Appl Sci 12(2):773. https://doi.org/10.3390/app12020773

Rossini EL, Milani MI, Pezza HR (2019) Green synthesis of fluorescent carbon dots for determination of glucose in biofluids using a paper platform. Talanta 201:503–510. https://doi.org/10.1016/j.talanta.2019.04.045

Rossini EL, Milani MI, Lima LS, Pezza HR (2021) Paper microfluidic device using carbon dots to detect glucose and lactate in saliva samples. Spectrochim Acta A 248:119285. https://doi.org/10.1016/j.saa.2020.119285

Sahu V, Khan F (2020) Synthesis of bovine serum albumin capped boron-doped carbon dots for sensitive and selective detection of Pb (II) ion. Heliyon 6(5):e03957. https://doi.org/10.1016/j.heliyon.2020.e03957

Sahu S, Behera B, Maiti TK, Mohapatra S (2012) Simple one-step synthesis of highly luminescent carbon dots from orange juice: application as excellent bio-imaging agents. Chem Commun 48(70):8835. https://doi.org/10.1039/c2cc33796g

Saraswat V, Yadav M (2020) Carbon dots as green corrosion inhibitor for mild steel in HCl solution. Chem Select 5(25):7347–7357. https://doi.org/10.1002/slct.202000625

Sasikumar K, Rajamanikandan R, Ju H (2023) Nitrogen-and sulfur-codoped strong green fluorescent carbon dots for the highly specific quantification of quercetin in food samples. Mater 16(24):7686. https://doi.org/10.3390/ma16247686

Sato K, Katakami R, Iso Y, Isobe T (2022) Surface-modified carbon dots with improved photoluminescence quantum yield for color conversion in white-light-emitting diodes. ACS Appl Nano Mater 5(6):7664–7669. https://doi.org/10.1021/acsanm.2c01868

Sawant VJ, Bamane SR, Kanase DG, Patil SB, Ghosh J (2016) Encapsulation of curcumin over carbon dot coated TiO_2 nanoparticles for ph sensitive enhancement of anticancer and anti-psoriatic

potential. RSC Adv 6(71):66745–66755. https://doi.org/10.1039/C6RA13851A

Shabbir H, Wojtaszek K, Rutkowski B, Csapó E, Bednarski M, Adamiec A, Głuch-Lutwin M, Mordyl B, Druciarek J, Kotańska M, Ozga P, Wojnicki M (2022) Milk-derived carbon quantum dots: study of biological and chemical properties provides evidence of toxicity. Molecules 27(24):8728. https://doi.org/10.3390/molecules27248728

Sharma V, Tiwari P, Kaur N, Mobin SM (2021) Optical nanosensors based on fluorescent carbon dots for the detection of water contaminants: A review. Environ Chem Lett 19:3229–3241

Shen P, Xia Y (2014) Synthesis-modification integration: one-step fabrication of boronic acid functionalized carbon dots for fluorescent blood sugar sensing. Anal Chem 86(11):5323–5329. https://doi.org/10.1021/ac5001338

Shi X, Wei W, Fu Z, Gao W, Zhang C, Zhao Q, Deng F, Lu X (2019) Review on carbon dots in food safety applications. Talanta 194:809–821. https://doi.org/10.1016/j.talanta.2018.11.005

Shin Y, Park J, Hyun D, Yang J, Lee J-H, Kim J-H, Lee H (2015) Acid-free and oxone oxidant-assisted solvothermal synthesis of graphene quantum dots using various natural carbon materials as resources. Nanoscale 7(13):5633–5637. https://doi.org/10.1039/C5NR00814J

Song X, Wang H, Zhang R, Yu C, Tan M (2018) Bio-distribution and interaction with dopamine of fluorescent nanodots from roasted chicken. Food Funct 9(12):6227–6235. https://doi.org/10.1039/C8FO01159A

Su K, Xiang G, Jin X, Wang X, Jiang X, He L, Zhao W, Sun Y, Cui C (2022) Gram-scale synthesis of nitrogen-doped carbon dots from locusts for selective determination of sunset yellow in food samples. Luminescence 37(1):118–126. https://doi.org/10.1002/bio.4152

Sun L, Liu Y, Wang Y, Xu J, Xiong Z, Zhao X, Xia Y (2021) Nitrogen and sulfur co-doped carbon dots as selective and visual sensors for monitoring cobalt ions. Opt Mater 112:110787. https://doi.org/10.1016/j.optmat.2020.110787

Tabaraki R, Abdi O (2019) Microwave assisted synthesis of n-doped carbon dots: an easy, fast and cheap sensor for determination of aspartic acid in sport supplements. J Fluoresc 29(3):751–756. https://doi.org/10.1007/s10895-019-02387-z

Tammina SK, Rhim J-W (2023) Carboxymethylcellulose/agar-based functional film incorporated with nitrogen-doped polyethylene glycol-derived carbon dots for active packaging applications. Chemosphere 313:137627. https://doi.org/10.1016/j.chemosphere.2022.137627

Tang D, Lin Y, Zhou Q (2018) Carbon dots prepared from litchi chinensis and modified with manganese dioxide nanosheets for use in a competitive fluorometric immunoassay for aflatoxin B1. Microchim Acta 185(10):476. https://doi.org/10.1007/s00604-018-3012-2

Vadia FY, Ghosh S, Mehta VN, Jha S, Malek NI, Park TJ, Kailasa SK (2023) Fluorescence "turn off-on" detection of Fe^{3+} and propiconazole pesticide using blue emissive carbon dots from lemon peel. Food Chem 428:136796. https://doi.org/10.1016/j.foodchem.2023.136796

Vijeata A, Chaudhary S, Chaudhary GR (2022) Fluorescent carbon dots from indian bael patra as effective sensing tool to detect perilous food colorant. Food Chem 373:131492. https://doi.org/10.1016/j.foodchem.2021.131492

Wagh RV, Khan A, Priyadarshi R, Ezati P, Rhim J-W (2023) Cellulose nanofiber-based multifunctional films integrated with carbon dots and anthocyanins from brassica oleracea for active and intelligent food packaging applications. Int J Biol Macromol 233:123567. https://doi.org/10.1016/j.ijbiomac.2023.123567

Wang Y, Anilkumar P, Cao L, Liu J-H, Luo PG, Tackett KN, Sahu S, Wang P, Wang X, Sun Y-P (2011) Carbon dots of different composition and surface functionalization: cytotoxicity issues relevant to fluorescence cell imaging. Exp Biol Med 236(11):1231–1238. https://doi.org/10.1258/ebm.2011.011132

Wang L, Yin Y, Jain A, Zhou HS (2014) Aqueous phase synthesis of highly luminescent, nitrogen-doped carbon dots and their application as bioimaging agents. Langmuir 30(47):14270–14275. https://doi.org/10.1021/la5031813

Wang R, Xu Y, Zhang T, Jiang Y (2015) Rapid and sensitive detection of salmonella typhimurium using aptamer-conjugated carbon dots as fluorescence probe. Anal Methods 7(5):1701–1706. https://doi.org/10.1039/C4AY02880E

Wang H, Xie Y, Liu S, Cong S, Song Y, Xu X, Tan M (2017) Presence of fluorescent carbon nanoparticles in baked lamb: their properties and potential application for sensors. J Agric Food Chem 65(34):7553–7559. https://doi.org/10.1021/acs.jafc.7b02913

Wang H, Liu S, Song Y, Zhu B-W, Tan M (2019) Universal existence of fluorescent carbon dots in beer and assessment of their potential toxicity. Nanotoxicology 13(2):160–173. https://doi.org/10.1080/17435390.2018.1530394

Wang BJ, Xu ZY, Sun Z, Li ZQ, Luo YH, Luo HQ, Li NB (2023) A wide-range ratiometric sensor mediating fluorescence and scattering based on carbon dots/metal–organic framework composites for the detection of bisulfite/sulfite in sugar. Anal Bioanal Chem 415(19):4639–4647. https://doi.org/10.1007/s00216-023-04763-y

Wang Y, Ma Y, Wang H, Shang F, Yang B, Han Y (2024) Smartphone-assisted carbon dots fluorescent sensing platform for visual detection of thiophanate-methyl in fruits and vegetables. Food Chem 441:138413. https://doi.org/10.1016/j.foodchem.2024.138413

Wei Q, Liu T, Pu H, Sun DW (2020) Development of a fluorescent microwave-assisted synthesized carbon dots/Cu^{2+} probe for rapid detection of tea polyphenols. J Food Process Eng 43(7):e13419. https://doi.org/10.1111/jfpe.13419

WHO (2022, 2022/05/19/) Food safety fact sheet. World Health Organization. Retrieved November 01 from https://www.who.int/news-room/fact-sheets/detail/food-safety

Wise JP, Young JL, Cai J, Cai L (2022) Current understanding of hexavalent chromium [Cr(VI)] neurotoxicity and new perspectives. Environ Int 158:106877. https://doi.org/10.1016/j.envint.2021.106877

Wu Y, Li C, Van Der Mei HC, Busscher HJ, Ren Y (2021) Carbon quantum dots derived from different carbon sources for antibacterial applications. Antibiotics 10(6):623. https://doi.org/10.3390/antibiotics10060623

Wu J, Chen T, Ge S, Fan W, Wang H, Zhang Z, Lichtfouse E, Van Tran T, Liew RK, Rezakazemi M (2023) Synthesis and applications of carbon quantum dots derived from biomass waste: a review. Environmental Chemistry Letters 21(6):3393–3424

Xu X, Ray R, Gu Y, Ploehn HJ, Gearheart L, Raker K, Scrivens WA (2004) Electrophoretic analysis and purification of fluorescent single-walled carbon nanotube fragments. J Am Chem Soc 126(40):12736–12737. https://doi.org/10.1021/ja040082h

Xu M, Li X, Liu P, Liu J, Han X, Chai G, Zhong S, Yang B, Cui L (2024) A novel and visible ratiometric fluorescence determination of carbaryl based on red emissive carbon dots by a solvent-free method. Chin Chem Lett. https://doi.org/10.1016/j.cclet.2024.109860

Yang S, Cao L, Luo PG, Lu F, Wang X, Wang H, Meziani MJ, Liu Y, Qi G, Sun Y-P (2009a) Carbon dots for optical imaging in vivo. J Am Chem Soc 131(32):11308–11309. https://doi.org/10.1021/ja904843x

Yang S, Wang X, Wang H, Lu F, Luo PG, Cao L, Meziani MJ, Liu J-H, Liu Y, Chen M (2009b) Carbon dots as nontoxic and high-performance fluorescence imaging agents. J Phys Chem C 113(42):18110–18114. https://doi.org/10.1021/jp9085969

Yang X, Xu J, Luo N, Tang F, Zhang M, Zhao B (2020) N, Cl co-doped fluorescent carbon dots as nanoprobe for detection of tartrazine in beverages. Food Chem 310:125832. https://doi.org/10.1016/j.foodchem.2019.125832

Yang Y, Tong X, Chen Y, Zhou R, Cai G, Wang T, Zhang S, Shi S, Guo Y (2023) A dual-emission carbon dots-based nonenzymatic fluorescent sensing platform for simultaneous detection of parathion-methyl and glyphosate. Food Chem 403:134346. https://doi.org/10.1016/j.foodchem.2022.134346

Yao B, Huang H, Liu Y, Kang Z (2019) Carbon dots: a small conundrum. Trends Chem 1(2):235–246. https://doi.org/10.1016/j.trechm.2019.02.003

Yu G, Zheng W, Wang W, Dai F, Zhang Z, Yuan Y, Wang Q (2017) Health risk assessment of chinese consumers to cadmium via dietary intake. J Trace Elements Med Biol 44:137–145. https://doi.org/10.1016/j.jtemb.2017.07.003

Yu Y, Li C, Chen C, Huang H, Liang C, Lou Y, Chen X-B, Shi Z, Feng S (2019) Saccharomyces-derived carbon dots for biosensing ph and vitamin B12. Talanta 195:117–126. https://doi.org/10.1016/j.talanta.2018.11.010

Yuxin X, Laipeng S, Kang L, Haipeng S, Zonghua W, Wenjing W (2022) Metal-doped carbon dots as peroxidase mimic for hydrogen peroxide and glucose detection. Anal Bioanal Chem 414(19):5857–5867. https://doi.org/10.1007/s00216-022-04149-6

Zaidi Z, Maiti N, Ali MI, Sharma G, Moin S, Padhy H, Balaji GL, Sundramurthy VP (2022) Fabrication, characteristics, and therapeutic applications of carbon-based nanodots. J Nanomater 2022:1–12. https://doi.org/10.1155/2022/8031495

Zeng Q, Feng T, Tao S, Zhu S, Yang B (2021) Precursor-dependent structural diversity in luminescent carbonized polymer dots (cpds): the nomenclature. Light Sci Appl 10(1):142. https://doi.org/10.1038/s41377-021-00579-6

Zhang S, Jin L, Liu J, Wang Q, Jiao L (2020) A label-free yellow-emissive carbon dot-based nanosensor for sensitive and selective ratiometric detection of chromium (VI) in environmental water samples. Mater Chem Phys 248:122912. https://doi.org/10.1016/j.matchemphys.2020.122912

Zhang W, Zhong H, Zhao P, Shen A, Li H, Liu X (2022) Carbon quantum dot fluorescent probes for food safety detection: Progress, opportunities and challenges. Food Control 133:108591. https://doi.org/10.1016/j.foodcont.2021.108591

Zhao Y, Ye M, Chao Q, Jia N, Ge Y, Shen H (2009) Simultaneous detection of multifood-borne pathogenic bacteria based on functionalized quantum dots coupled with immunomagnetic separation in food samples. J Agric Food Chem 57(2):517–524. https://doi.org/10.1021/jf802817y

Zhao D, Zhang Z, Liu X, Zhang R, Xiao X (2021a) Rapid and low-temperature synthesis of n, p co-doped yellow emitting carbon dots and their applications as antibacterial agent and detection probe to sudan red I. Mater Sci Eng C 119:111468. https://doi.org/10.1016/j.msec.2020.111468

Zhao P, Jin B, Zhang Q, Peng R (2021b) High-quality carbon nitride quantum dots on photoluminescence: effect of carbon sources. Langmuir 37(5):1760–1767. https://doi.org/10.1021/acs.langmuir.0c02966

Zhao L, Du M, Du W, Guo J, Liao Z, Kang X, Liu Q (2022) Evaluation of the carbon sink capacity of the proposed kunlun mountain national park. Int J Environ Res Public Health 19(16):9887. https://doi.org/10.3390/ijerph19169887