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Review

Advances in Fluorescent Sensing Carbon Dots: An Account of Food Analysis

Jixiang Tian, Minmei An, Xiaoang Zhao, Yun Wang,* and Murtaza Hasan*

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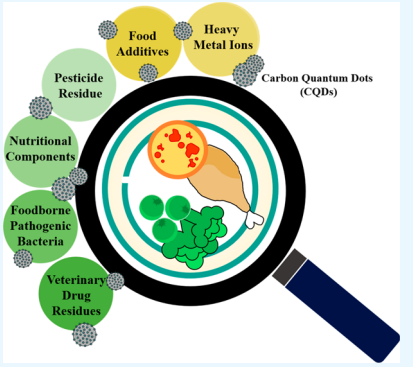
ABSTRACT: Illuminating the use of nanomaterials, carbon quantum dots (CQDs) have transfigured the food safety arena because of their bright luminescence, optical properties, low toxicity, and enhanced biocompatibility. Therefore, fluorescent resonance energy transfer, photoinduced electron transfer, and an internal filtering effect mechanism allow precise detection of food additives, heavy metal ions, pathogenic bacteria, veterinary drug residues, and food nutrients. In this review, we describe the primal mechanism of CQD-based fluorescence sensors for food safety inspection. This is an abridged description of the nanodesign and future perspectives of more advanced CQD-based sensors for food safety analysis.



1. INTRODUCTION

The emergence of nanotechnology is a revolutionary step in all area of research materials, particularly carbon quantum dots (CQDs), a form of carbon dot (CD), as a new type of fluorescent carbon nanomaterial that comprises of oxygen/nitrogen organic functional groups.[1] It was first discovered by Xu's group in 2004 through the purification of single-walled carbon nanotubes fragments.[2] For the last 5−10 years, researchers have been working on many aspects of nanomaterials and carbon dots such as synthetic approaches and their their characteristics, and most important are their prominent applications in the field of biomedical science and industrial uses.[3,4] Recently, CQDs have received enormous attention for their high fluorescence intensity, resistance to photobleaching, good light stability and biocompatibility,[5,6] and wide use in biological imaging,[7,8] biochemical analysis,[9] photoelectric catalysis,[10−12] food analysis,[13−17] and other fields.

This review is focused on the detection mechanism of CQD fluorescent sensors and their key application in food detection that chiefly includes heavy metal ions, food additives, foodborne pathogenic bacteria, agricultural and veterinary drug residues, and nutrient composition detection (Figure 1). The upcoming challenges of CQDs in all groups of science are also discussed.

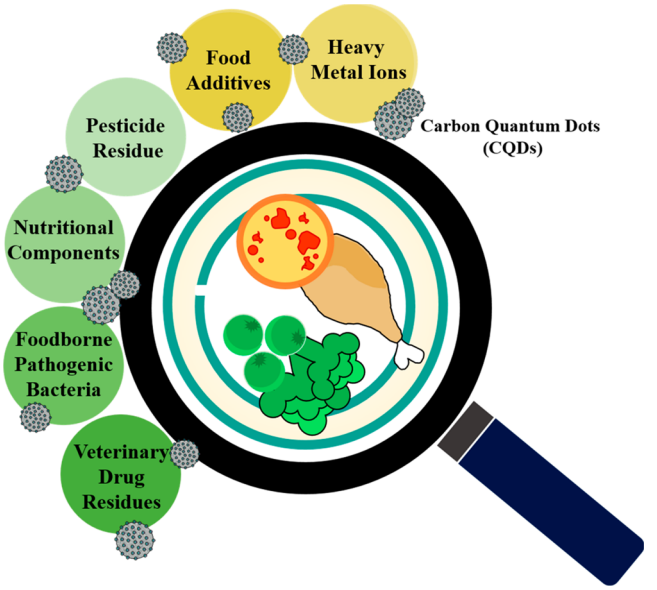


Figure 1. Overview of carbon dot nanomaterial-based biosensor for food analysis.

2. FLUORESCENCE PROPERTIES AND DETECTION MECHANISM OF CQDS

Photoluminescence is one of the important optical properties of CQDs. The reported luminous mechanisms of CQDs majorly include bandgap transitions of conjugated π-

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domains,[18,19] surface defection state,[20,21] and effects of fluorescents or the other fluorophores.[22,23] Due to the wide range of synthetic raw materials, diverse preparation methods, and a variety of complex components (including nitrogen and nitrogen morphology, nitrogen, and sulfur, etc.),[24,25] it is difficult to form a unified theory by comparing the results in the literature. Therefore, the fluorescence mechanism of CQDs needs further study.

CQDs have remarkable fluorescence stability and stable fluorescence emission under continuous long-time excitation light.[26] In addition, CQDs have low toxicity, low cost, easy functionalization, and good biocompatibility. Based on such premium properties, CQD fluorescent sensors have attracted intense attention for food analysis applications. The fluorescence sensor of CQDs is mainly created on the principle of fluorescence quenching (on−off)[27] or fluorescence enhancement (on−off−on).[28] The mechanism of fluorescence quenching or enhancement primarily includes fluorescence resonance energy transfer (FRET), photoinduced electron transfer (PET), and their internal filtering effect (IFE).

2.1. Fluorescent Resonance Energy Transfer. FRET is a technology to determine the distance between the binary molecules that is based on the resettlement of the energy from a fluorescent donor to a fluorescent receptor in a narrow distance.[29,30] Based on this principle, a new fluorescent molecule for quantitative detection of L-cysteine (L-Cys) was established.[31] The system consists of positively charged CDs and negatively charged *N*-acetyl-L-cysteine-capped gold nanoparticles (NAC AuNPs) to form the FRET module. The fluorescence of CDs was highly reduced by NAC-AuNPs (Figure 2). Tian et al.[32] designed a FRET ratiometric adapter

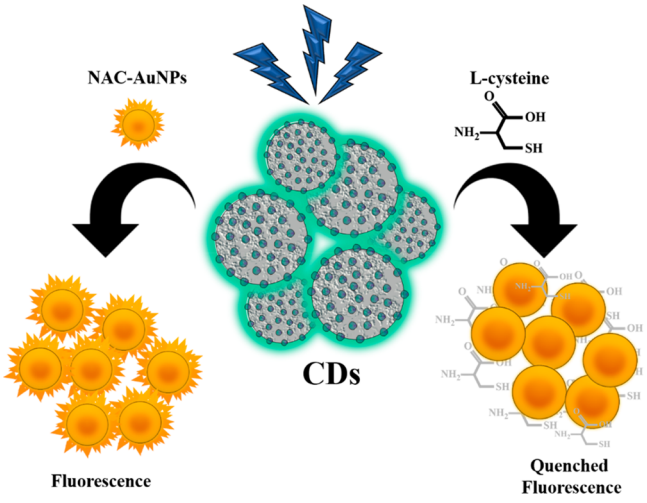

Figure 2. Schematic illustration of ratiometric detection of L-cysteine using a FRET system of CDs and NAC-AuNPs by far-red fluorescent sensing.

sensor that uses cerium oxide nanoparticles as donors and graphene quantum dots as acceptors (GQDs) to sense ochratoxin A in feed and food chains where the detection range was about 0.01−20 ng/mL with a maximum limit of detection of 2.5 pg/mL.

2.2. Photoinduced Electron Transfer. PET refers to an electron transferral process where an excited electron is shifted from one donor to the fluorophore, quenching the fluorescence.[33,34] A typical PET molecule usually consists of a fluorophore acceptor, receptor (donor or quencher), and spacer. Based on this mechanism, Hu et al.[35] prepared a unique raspberry-like γ-Fe_2o_3@CD nanocatalyst that has a proficient visible-light photocatalyst in PET-RAFT polymerization because of the oxidative quenching among the photoexcited γ-Fe2O3@CDs and RAFT agent in the PET development.

2.3. Internal Filtering Effect. IFE refers to the where the the fluorescence decreases owing to the absorber gripping the excitation and emission light of the fluorophore. Compared with FRET and other technologies, IFE avoids many tedious labeling processes and has the benefits of extraordinary sensitivity, good discrimination, and a simple and flexible procedure. The absorber and the fluorophore are the two main units of the IFE sensing system, and their optical characteristics and spectral overlap directly affect the quenching efficiency of IFE.[36]

Based on this principle, Gao et al. successfully fabricated potent N/S/P-codoped carbon dots (N/S/P-CDs) for the recognition of tetracycline in milk by an IFE.[37] Cui et al. had designed a nanomaterial-based point of care testing (POCT) device composed of a ratio fluorescence test strip, a sample slot, and a smartphone along with an UV lamp for the specific detection of tetracycline. The ratio fluorescence test strips were made from nitrogen and sulfur codoped CDs (N,S-CDs) and Eu^{3+} placed onto filter paper. N,S-CDs/Eu^{3+}, as a fluorescent absorber, can efficiently obstruct the fluorescence of N,S-CDs through IFE, resulting in fluorescence reduction.[38] Li et al. developed a dual-signal parathion methyl nanomaterial which combines fluorescence through UV−vis spectrophotometry to evaluate organophosphorus pesticides (Ops) using silver nanoparticles (AgNPs) enhanced with graphic carbon nitride (g-C_3N_4). The design of silver nanoparticles decreased the fluorescence strength of the g-C_3N_4 duo to IFE[39] (Figure 3).

2.4. Other Detection Mechanisms. In addition to the above three common detection mechanisms, the detection mechanism of a fluorescence sensor based on CQDs in food analysis also includes the reaction of CQDs with the analyte to shape a ground-state complex that can detect the analyte based on static quenching. The fluorescence quenching is roughly divided into three types: dynamic quenching, static quenching, and an amalgamation of the two. Vibrant quenching is due to collisions between the fluorophore and the specific quencher in an excited state, while static quenching is from the formed complex between the quencher and fluorophore.[40−42]

Xu et al. had shown the ability to dissolve hydrophilic luminous CQDs in water via a hydrothermal method using aloe as the carbon source to detect tartrazine. The interface between tartrazine and CQDs forms a ground-state complex, and the detection of tartrazine is achieved by static quenching with the detection range of 0.25−32.5 μM; the detection limit is 73 nM.[43−45]

Aggregation-induced quenching is also one of the common fluorescence detection mechanisms. Zhou et al. developed a dosage-sensitive fluorescent colorimetry test paper using glutathione- and dithiothreitol-modified red quantum dots (CdTe QDs) combined with cyan carbon dots to detect arsenic ions As(III). The detection mechanism realizes the ophthalmic detection of As(III) by inducing the aggregation of CdTe QDs, thereby quenching the red fluorescence of CdTe QDs.[46]

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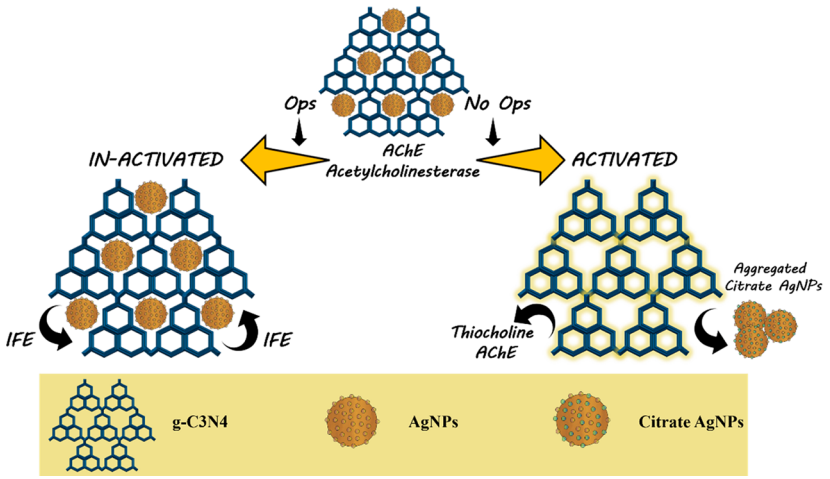

Figure 3. Mechanism of organophosphorus pesticide detection using g-C_3N_4/AgNPs.

Table 1. Biosensors for the Detection of Food Flavorings Agents and Additives

Analytes	Biosensors	Nanomaterials	LOD	Detection range	Real Samples	Ref
Tannic acid	Fluorescent	BPEI-CDs	36.8 nm	0.1−5 μM	lake water and white wine	51
Rhodamine 6G	MIP	CDs-PMO-MIS	−[a]	4−7 μg/L	water	52
Clenbuterol	SERS/RRS dual-spectroscopic immunosensor	$CD_{N/Ag}$	0.68 pg	−[a]	pork liver	53
Tartrazine	Fluorescent	N,Cl-FCDs	48 nM	0.1−30 μM	beverages	54
Tartrazine	Fluorescent	CDs	73 nM	0.25−32.5 μM	candy, steamed buns made of corn and honey	43
Melamine	Fluorescent	Au@CQDs	12 nM	1−10 μM	milk	55

[a]—: not mentioned.

3. APPLICATION OF CQDS IN FOOD ANALYSIS

3.1. Food Additives. Food ingredients and condiments are extensively used in the production of high-quality materials to improve the look, surface, and preservation of food.[44,47−49] Excessive use of food flavorings agents has caused a major risk to human health and food security, such as chronic intestinal inflammation, carcinogenesis, and metabolic syndrome.[50] Therefore, it is important to introduce an efficient method for the detection of food contaminants in the form of additives. A huge variety of nanomaterial-based biosensors have been fabricated, designed, and commercially industrialized (Table 1).

Tannic acid (TA), as a food additive, plays an important part in the flavor and quality of beverages and wines. TA has certain benefits to the human body, but a high content of TA in food will have adverse effects on the human body and may lead to poor taste and lower product quality. Yang et al.[51] developed a polyamine-functionalized CQD from precursors containing renewable xylans and branched polyethylene imines (BPEI) using a naive and proficient microwave-assisted method for detection of TA in white wine. The concentrations of TA in the water and ethanol solutions for optimum conditions are often in the 0.1−5 μM range with detection limits of 36.8 and 44.9 nM, respectively.

Rhodamine 6G (R6G) is a cationic dye that is prohibited from use in the course of high-quality food manufacture. Cui et al.[52] presented a molecularly imprinted fluorescent sensor with carbon dot-embedded periodic mesoporous organosilica (PMO) as a support via a one-pot self-assembly process for extremely sensitive detection of R6G. The detection concentration of R6G ranges from 4 to 7 μg/L.

Clenbuterol (Clen), also known as bony meat powder, has been banned in most countries. However, it is still illegally added to animal meat. Thus, Yao et al.[53] synthesized a multifunctional nitrogen/silver-codoped CD (CDN/Ag) by a microwave method and constructed a dual-spectroscopic immunosensor based on surface-enhanced Raman scattering (SERS)/resonance Rayleigh scattering to detect Clen. The advantage of this immunosensor was that no fluorescent labeling steps were required and the lowest detection limit was about 0.68 pg·mL^{-1}.

Water-soluble tartrazine, also called lemon yellow, is a kind of artificial pigment which is extensively used as a food additive in foods such as sweets and beverages.[56] However, several studies have shown that people who consume an excess of foods containing pigments (such as lemon yellow) may suffer from diarrhea and allergy.[57] Thus, there is an urgent need to develop a proficient, economical, and informal method to detect tartrazine in foods. Therefore, Yang et al.[54] used urea as source of nitrogen with $FeCl_3·6H_2O$ as the chlorine source to prepare N, Cl codoped fluorescent CDs (N, Cl FCDs) by a hydrothermal method, which can be used to detect tartaric acid. The detection range was 48 nmol·L^{-1}.

Melamine is commonly used as a feedstock to produce plastics, coatings, leather, paints, laminates, etc. Due to its high nitrogen concentration (66%), it is used to illegally supplement dairy products to increase the clear protein content.[58] Gold nanoparticle@CD nanocomposites (Au@CQDs) were synthesized with AuNPs and CQDs for visual analysis of melamine in milk. The fluorescent radiation of Au@CQDs increased with increasing concentration of melamine. The detection range was 1−10 μmol·L^{-1}, and the degree of quantification was 12 nmol·

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Table 2. Biosensors in Heavy Metal Detection

Analytes	Biosensors	Nanomaterials	LOD	Detection range	Real Samples	Ref
Pb^{2+}	Fluorescent	CuNCs-CNQDs	0.0031 mg/L	0.010−2.5 mg·L^{-1}	porphyra	61
Cr^{6+}	Fluorescent	CDs	10−5 M	0−0.1 M	water	62
Hg^{2+}	Fluorescent	CDs	3.3 nM	0.01−10 μM	lake water	63

Table 3. Biosensors for the Detection of Pesticide Residue

Analytes	Biosensors	Nanomaterials	LOD	Detection range	Real Samples	Ref
Thiophanate Methyl	Fluorescent	CD/CU	2.90 × 10^6 μM	0.1−20 μM	soil	70
Methyl-Parathion	Fluorescent	N-CDs	13 ppb	0.02−20 ppm	tap water and food samples	71
OrganophosphOrus Pesticides	Fluorescence/UV−vis	g-C3N4/AgNPs	0.0324 μg·L^{-1}	0.1−1.0 μg·L^{-1}	lake water, apple, carrot	39

L^{-1}.[55] As a novel carbon-based nanomaterial, CD fluorescence sensing probes alone or in combination with fluorescence spectrometry have a wide application panorama in the determination of food additives.

3.2. Heavy Metal Ion. Heavy metal toxicity is counted as a major threat to human health and food security. Certain heavy metal ions including Pb^{2+}, Cd^{2+}, Cr^{6+}, Hg^{2+}, As^{3+}, and radioactive metals are considered important polluters of water and the environment that are easy to accumulate in the food chain and body.[49,59,60] The traditional methods for detecting heavy metal ions have many disadvantages, such as being time-consuming and requiring complex operation and expensive large instruments. In contrast, CQDs fluorescent sensors have high sensitivity, good selectivity, and simple operation. So, the interaction between CQDs and some metal ions can cause the fluorescence quenching of CQDs, which are helpful in detecting heavy metal ions. Based on the IFE, various biosensing nanomaterial have been developed (Table 2)

Li et al.[61] tailored a unique, simple, and ratiometric fluorescence probe using copper nanoclusters and nitrogen-doped CQDs (CuNCs-CNQDs) for quick detection of lead(II) ions (Pb^{2+}) in porphyra. Over the IFE, the acquired CuNCs-CNQDs demonstrated a worthy fluorescent response to the Pb^{2+} with a detection margin of 0.0031 mg·L^{-1} (range 0.010−2.5 mg·L^{-1}). The study provided an intuitive, stable, and sensitive method for the detection of Pb^{2+} in porphyra. Yang et al.[62] prepared hydrophilic CDs by a one-step hydrothermal carbonization of ethylene diamine tetraacetic acid (EDTA) salt to construct fluorescent test papers for sensitive detection of Cr^{6+}, whereas Hou et al.[63] prepared water-soluble CDs with the help of electrochemical carbonization of sodium citrate and urea to diagnose Hg^{2+} based on fluorescence quenching of Hg^{2+}. It is also used as unique without any labeling process to probe for selective detection of Hg^{2+} with a wide-ranging concentration of 0.01−10 μM and detection control of 3.3 nM. Because different CQDs have different surface functional groups and different metal ions interact with CQDs in different ways, it is essential to select more suitable CQDs for heavy metal ion detection.

3.3. Foodborne Pathogens. Foodborne pathogens that use food as a carrier are one of the main factors causing foodborne illnesses. Enteropathogenic *Escherichia coli*, *Staphylococcus aureus*, *Salmonella*, and *Campylobacter jejuni* are common foodborne pathogens.[64,65] Foodborne pathogens are a growing threat to public health, and their detection is of global significance for food safety and foodborne disease prevention.[66] Recently, nanomaterial-based biosensors have been applied to detect foodborne pathogens.

Escherichia coli often remains in uncooked sausage or milk, lettuce, apple juice, and other foods that have not been sterilized at high temperature. If eaten by people, it may cause gastroenteritis and may also cause bloody colitis or hemolytic uremic syndrome and renal failure. Ahmadian-Fard-Fini et al.[67] prepared a new magnetic and photoluminescence nanocomposite (Fe_3O_4−CQDs) for identification of *E. coli* bacteria that required two steps for the synthesis of Fe_3O_4−CQDs: blue CQDs were synthesized (i) using a one-pot hydrothermal method with lemon and grape fruit extracts and (ii) in combination with Fe_3O_4-modified nanoparticles. The results showed that the fluorescence of blue CQDs was steadily quenched with the increase in *E. coli*. The quenching intensity had a good linear correlation with the concentration of *E. coli*, and the concentration range for detecting *E. coli* is 0−9 × 10^7 CFU/mL.

Similarly, Choi et al.[68] constructed a nanosensor with diol-modified fluorescent probe (DYE) and phenylboronic acid functionalized fluorescent CQD (FCQD) for detecting of *E. coli* and *S. aureus*. When they exist in food, the glycol group of polysaccharides on the bacterial cell surface forms a new cyclic borate ester bond with FCQDs, which replaced the dye molecules. The DYE molecules were released into the solution, causing the recovery of the fluorescence of FCQD. Although the fluorescence sensor based on CQDs had the advantages of high sensitivity and short time consumption in detecting foodborne pathogens, most methods can only detect a single pathogen. Therefore, it is essential to establish the most efficient and fast formula that can be used for simultaneous detection of multiple foodborne pathogens is the future research direction.

3.4. Pesticide Residue. Excessive or unreasonable use of pesticides will lead to pesticide residues, posing a serious threat to the ecological environment. Pesticides left in crops such as grain will further affect food quality, thereby affecting human health. The traditional methods for detecting pesticide residues are chromatography and chromatography−mass spectrometry. Although they are highly sensitive and accurate, they are complex and time-consuming. The fluorescence analysis method based on CQDs can overcome the above shortcomings when used to detect pesticide residues in food.[69] Numerous nanometric biosensors have been designed and developed (Table 3)

Thiophanate methyl (TM) is commonly used for the treatment and control of various diseases of crops and the storage of grain after harvest. However, long-term exposure to TM[70] may cause teratogenesis, cancer, and other risks, and it has been banned in the United States. Han et al.[72] have developed a ratiometric fluorescence sensor for ultrasensitive

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Table 4. Biosensors for the detection of veterinary drug residue

Analytes	Biosensors	Nanomaterials	LOD	Detection range	Real Samples	Ref
Tetracycline	Fluorescent	S,N-CQDs	0.56 μM	1.88−60 μM	milk, honey, tap water	80
Tetracycline	Fluorescent	CDs	5.18 nM	15.5−6 μM	tobacco	81
Ooxytetracycline	Fluorescent	CDs	6.06 nM	20 nM−2 μM	tobacco	81
Oxytetracycline	UV	CDs-Fe^{3+}	22.8 nM	0.1−2.7 μM	milk	82
Chlorotetracycline	Fluorescence/UV−vis	CDs	14 nM	20 nM−0.2 μM	tobacco	81
Ampicillin	UV	CDs-Fe^{3+}	0.70 μM	0−150 μM	river water	83
Kanamycin	Immune	AuNPS-CDs	18 nM	0.04−0.24 μM	milk	84
Kanamycin	Electrochemiluminecence (ECL)	MIL-53(Fe)@CdS-PEI	1.7×10^{-11} M	1.0×10^{-10}−1.0×10^{-6} M	milk and honey sample	85
Neocycin	ElectrochemilUminecence (ECL)	MIL-53(Fe)@CdS-PEI	3.5×10^{-10} M	1.0×10^{-9}−1.0×10^{-5} M	milk and honey sample	85

detection of TM using copper ion (Cu^{2+}) triggered double emission carbon dots (CD/Cu) with a detection range of 0.1−20 μmol·L^{-1}, and the detection limit is 2.90×10^6 μmol·L^{-1}. The sensor has good precision for everyday applications with recoveries of 88.33−101.09% and RSD of 1.61−5.06% and can be used for ultrasensitive detection of TM residues in complex matrices.

Organophosphorus pesticides (OPPSs) were broadly used in agricultural production for their robust effect and broad spectrum.[73] OPPSs may inhibit the activity of acetylcholine esterase, and its obvious accumulation may lead to organ failure and endanger the health of humans.[74] Huang et al.[75] prepared an extremely sensitive ratiometric fluorescent probe for the detection of OPPSs in normal tap water and food based on the inner filter effect between nitrogen-doped CDs and 2,3-diaminophenazine. The detection limit of methylparathion is 13 ppb. The experimental results further verified the detection effect of a ratiometric fluorescent probe on OPPs in food samples, which correlated with GC−MS results. Yan et al.[76] prepared a novel manganese dioxide (MnO_2) nanosheet-CD sensing platform for the detection of organophosphorus pesticides. The detection range was 0.05−5 ng·mL-1 with a detection limit of 0.015 ng·mL^{-1}. For the detection of triazophos in cucumber samples, Wu et al.[77] developed a magnetic, molecularly imprinted polymeric mocrosphere (MMIP) sensor comprising MMIPS and vinyl phosphate-modified CDs (CDs@VPA). The system presented a good liner relationship from the concentration range of 0.0035−0.20 mmol/L, and the LOD limitation was 0.0015 nmol·L^{-1}. Lan et al.[78] developed a fluorescent biosensor for indirectly measuring methyl parathion (MP) using N-doped carbon dots based on alkaline-induced hydrolysis. The fluorescence sensor displayed enhanced fluorescence responses to MP in a dose-dependent manner in a concentration range of 0.075−15 ppm.

As we compared the traditional single emission fluorescent probes with composites nanomaterials this ratiometric probe can eliminate the limitations of experimental conditions including light source, probe concentration, and background interference effects to achieve higher anti-interference performance in pesticide residue detection. Therefore, the ratiometric fluorescent sensor based on CQDs has a good development prospect.

3.5. Veterinary Drug Residue. Antibiotics, as commonly used veterinary drugs, are widely used to treat bacterial infections in all form of populations and communities on earth. Long-term overuse of antibiotics will lead to the accumulation of antibiotics in animals, thus affecting food quality and safety.[79] At present, it is difficult for the traditional detection methods to meet the requirements of rapid and highly sensitive detection of antibiotic residues in food. Thus, the improvement of highly sensitive and trustworthy analytical methods for the detection of antibiotic residues in animal-derived foods has become the focus of research. Many nanomaterial-based biosensors for veterinary drug residues have been developed (Table 4)

Tetracycline antibiotics (TCs) have been used to treat a great variety of bacterial infections by either Gram-positive and Gram-negative bacteria. It has been observed that TCs remain in foods, as honey and milk obtained from animals will lead to adverse allergic reactions, gastrointestinal disorders, and hepatotoxicity and promote bacterial resistance to antibiotics. Fan et al.[80] designed a novel fluorescent sensor based on S,N-doped CQDs (S,N-CQDs) for efficient detection of TCs. From 1.88 to 60 μmol·L^{-1} of TC concentration, the plot made between fluorescence intensity and TC concentration showed good linearity, and the detection limit for TC is 0.56 μmol·L^{-1}. Miao et al. used tobacco as a carbon source to synthesize bright-blue fluorescent CQDs (QY nearly 27.9%) by hydrothermal method to fabricate a fluorescence sensor for sensitive detection of three different types of tetracyclines (tetracycline, oxytetracycline, and chlorotetracycline). The overall detection ranges for tetracycline, oxytetracycline, and chlorotetracycline are 5.18, 6.06, and 14 nmol·L^{-1}, respectively.[81]

Aminoglycoside antibiotics including kanamycin, neomycin, amikacin, and tobramycin are common antibacterial agents used to treat diseases produced by Gram-negative and Gram-positive bacteria.[86] Although effective, the use of aminoglycoside antibiotics has declined over the years due to serious side effects, including nephrotoxicity and ototoxicity.[87]

It has been reported that Fe^{3+} has a fluorescence quenching effect on CDs. With the intensification of Fe^{3+} concentration, the fluorescence emission of CDs gradually decreases; based on this, Fu et al.[83] synthesized a blue fluorescence CD combined with Fe^{3+} to build a nonfluorescent system for detection of ampicillin with a limit detection of 0.70 μM. However, the fluorescence sensor based on CQDs has many advantages in the detection of antibiotics, such as being highly sensitive, fast, and simple, but many antibiotics have fluorescence characteristics that may affect the detection of CQDs. Therefore, the anti-interference ability of CQDs in antibiotic detection should be further improved.

3.6. Nutritional Composition. The interaction between some metal ions and CQDs can cause the fluorescence of CQDs to be quenched, while many nutrients have metal chelating ability. Adding them to the CQD solution containing these metal ions can restore the fluorescence of CQDs.

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Therefore, this principle can be used to build a fluorescence enhanced sensor for detecting nutrients in food.

Vitamin C, namely ascorbic acid (AA), is a water-soluble vitamin that can promote the formation of collagen, cure scurvy, prevent gum bleeding, etc., but excessive intake will also bring harm to human health. Li et al.[88] had developed a very smart care point (SPOC) sensor which consists of a fluorescent paper chip, 3D printed-accessories, and a smartphone for efficient sensitive and form-based quantitative detection of AA. Fluorescent paper chips were made by drawing silicon-doped carbon dots (SiCDs)−Fe^{3+} as "ink" onto filter paper, where SiCDs emitted a strong fluorescence signal quenched by Fe^{3+} and then were recycled by AA due to the release of $-NH_2$/−OH and the introduction of defects on SiCDs. The SPOC exhibited high sensitivity and a detection range as low as 18.12 nM. Integration of a portable sensing platform via fluorescent sensors and smartphone devices will be conducive to the super sensitivity and on-site detection of AA.

Glutathione (GSH) is an endogenous antioxidant and a free radical scavenger that can associate with free radicals and heavy metals to transform harmful substances into harmless substances that excrete out from the body.[89] Aberrant levels of GSH have been related to numerous diseases, such as Alzheimer's disease, cancer, cardiovascular disease, etc. Zhang et al.[90] used glucose and polyethylenimine as raw materials to synthesize branched polyethylenimine-functionalized CQDs (PEI-CQDs) by a hydrothermal method. Since the fluorescence of PEI-CQDs can be effectively quenched by Cu^{2+}, the addition of GSH can restore the fluorescence of the above system. On this basis, a "turn-on" fluorescence probe for detection of GSH detection was developed using PEI-CQDS-Cu^{2+}system. The low concentration detection range of GSH is 0−80 μM, the detection range for high concentration is 0−1400 μM, and the corresponding detections are 0.33 and 9.49 μM, respectively. Compared with the traditional GSH detection probe, the PEI-CQDS-Cu^{2+} system has a significant advantage in that it can be used to detect both low concentration and high concentration GSH. Due to the complexity of food ingredients, the accuracy of the test results will be affected when actual samples are tested. Therefore, it is necessary to select appropriate sample pretreatment methods and CQDs with better stability and selectivity.

4. CONCLUSIONS

Therefore, based on their excellent performance, the fluorescence sensors based on CQDs have great prospects in food detection. However, there are still several problems that need to be addressed for the practical application of food detection. Current methods for CQDs can often detect only one class of analytes. Therefore, development of nanosensors based on CQDs that can simultaneously detect multiple analytes is an important direction for future work. In addition, fluorescence sensors based on CQDs mostly use single fluorescence intensity as the response signal, which is prone to influence by various factors including instrument error, solvent, and other experimental factors. Different from the fluorescent sensor with a single signal, the ratiometric fluorescent sensor can greatly reduce the above interference, achieve higher analysis accuracy through the self-calibration of two fluorescence intensities, and the ratiometric fluorescent method is usually accompanied by visible color changes, which can be used for rapid visual identification and detection. In the future, based on the application research of CQDs in food detection, we will focus on the development of multi-component visual portable detection technology.

AUTHOR INFORMATION

Corresponding Authors

Yun Wang − *Institute of Chinese Materia Medica, Academy of Chinese Medical Sciences, Beijing 100700, China*; Email: ywang@icmm.ac.cn

Murtaza Hasan − *Faculty of Biological and Chemical Sciences, Department of Biotechnology, The Islamia University of Bahawalpur, Bahawalpur 63100, Pakistan; School of Chemistry and Chemical Engineering, Zhongkai University of Agriculture and Engineering, Guangzhou 510225, China*; orcid.org/0000-0001-7715-9173; Email: murtaza@iub.edu.pk

Authors

Jixiang Tian − *Institute of Chinese Materia Medica, Academy of Chinese Medical Sciences, Beijing 100700, China*

Minmei An − *Taian Traditional Chinese Medicine Hospital, Taian 271000, China*

Xiaoang Zhao − *Institute of Chinese Materia Medica, Academy of Chinese Medical Sciences, Beijing 100700, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c07986

Author Contributions

Jixiang Tian: formal analysis; Yun Wang: data curation, writing—review and editing, supervision; Minmei An: data collection; Xiaoang Zhao: data collection; Murtaza Hasan: final editing, English writing, and correction. All authors have read and agreed to the published version of the manuscript.

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Notes

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REFERENCES

(1) Sun, Y. P.; Zhou, B.; Lin, Y.; Wang, W.; Fernando, K. A. S.; Pathak, P.; Meziani, M. J.; Harruff, B. A.; Wang, X.; Wang, H.; Luo, P. G.; Yang, H.; Kose, M. E.; Chen, B.; Veca, L. M.; Xie, S. Y. Quantum-sized carbon dots for bright and colorful photoluminescence. *J. Am. Chem. Soc.* **2006**, *128*, 7756.

(2) Xu, X.; Ray, R.; Gu, Y.; Ploehn, H. J.; Gearheart, L.; Raker, K.; Scrivens, W. A. Electrophoretic analysis and purification of fluorescent single-walled carbon nanotube fragments. *J. Am. Chem. Soc.* **2004**, *126*, 12736.

(3) Qiao, L.; Qian, S.; Wang, Y.; Yan, S.; Lin, H. Carbon-Dots-Based Lab-On-a-Nanoparticle Approach for the Detection and Differentiation of Antibiotics. *Chem.—Eur. J.* **2018**, *24*, 4703.

(4) Hasan, M.; Ullah, I.; Zulfiqar, H.; Naeem, K.; Iqbal, A.; Gul, H.; Ashfaq, M.; Mahmood, N. Biological entities as chemical reactors for synthesis of nanomaterials: Progress, challenges and future perspective. *Mater. Today Chem.* **2018**, *8*, 13.

(5) Hasan, M.; Yang, W.; Ju, Y.; Chu, X.; Wang, Y.; Deng, Y.; Mahmood, N.; Hou, Y. Biocompatibility of iron carbide and detection of metals ions signaling proteomic analysis via HPLC/ESI-Orbitrap. *Nano Res.* **2017**, *10*, 1912.

(6) Li, J.; Tang, K.; Yu, J.; Wang, H.; Tu, M.; Wang, X. Nitrogen and chlorine co-doped carbon dots as probe for sensing and imaging in biological samples. *R Soc. Open Sci.* **2019**, *6*, 181557.

(7) Sun, Z.; Zhou, Y.; Zhou, W.; Luo, J.; Liu, R.; Zhang, X.; Zhou, L.; Pang, Q. Pb(ii) detection and versatile bio-imaging of green-emitting carbon dots with excellent stability and bright fluorescence. *Nanoscale* **2021**, *13*, 2472.
(8) Hasan, M.; Sajjad, M.; Zafar, A.; Hussain, R.; Anjum, S. I.; Zia, M.; Ihsan, Z.; Shu, X. Blueprinting morpho-anatomical episodes via green silver nanoparticles foliation. *Green Processing and Synthesis* **2022**, *11*, 697−708.
(9) Gong, L.; Zhao, L.; Tan, M.; Pan, T.; He, H.; Wang, Y.; He, X.; Li, W.; Tang, L.; Nie, L. Two-Photon Fluorescent Nanomaterials and Their Applications in Biomedicine. *J. Biomed Nanotechnol* **2021**, *17*, 509.
(10) Geng, H.; Jiang, N.; Li, C.; Zhu, X.; Qiao, Y.; Cai, Q. Efficient photocatalytic inactivation of E. coli by Mn-CdS/ZnCuInSe/CuInS2quantum dots-sensitized TiO2nanowires. *Nanotechnology* **2020**, *31*, 395602.
(11) Batool, S.; Hasan, M.; Dilshad, M.; Zafar, A.; Tariq, T.; Wu, Z.; Chen, R.; Gul Hassan, S.; Munawar, T.; Iqbal, F.; Saqib Saif, M.; Waqas, M.; Shu, X. Green synthesis of Cordia myxa incubated ZnO, Fe2O3, and Co3O4 nanoparticle: Characterization, and their response as biological and photocatalytic agent. *Advanced Powder Technology* **2022**, *33*, 103780.
(12) Manzoor, Y.; Hasan, M.; Zafar, A.; Dilshad, M.; Ahmed, M. M.; Tariq, T.; Hassan, S. G.; Hassan, S. G.; Shaheen, A.; Caprioli, G.; Shu, X. Incubating Green Synthesized Iron Oxide Nanorods for Proteomics-Derived Motif Exploration: A Fusion to Deep Learning Oncogenesis. *ACS Omega* **2022**, *7*, 47996.
(13) Jia, J.; Lu, W.; Cui, S.; Dong, C.; Shuang, S. Preparation of yellow-emitting carbon dots and their bifunctional detection of tetracyclines and Al3+ in food and living cells. *Microchimica Acta* **2021**, DOI: 10.1007/s00604-021-05078-4.
(14) Long, D.; Peng, J.; Peng, H.; Xian, H.; Li, S.; Wang, X.; Chen, J.; Zhang, Z.; Ni, R. A quadruple-channel fluorescent sensor array based on label-free carbon dots for sensitive detection of tetracyclines. *Analyst* **2019**, *144*, 3307.
(15) Liu, Y.; Liu, B.; Huang, P.; Wu, F. Y.; Ma, L. Concentration-dependent photoluminescence carbon dots for visual recognition and detection of three tetracyclines. *Anal Bioanal Chem.* **2021**, *413*, 2565.
(16) Hasan, M.; Zafar, A.; Jabbar, M.; Tariq, T.; Manzoor, Y.; Ahmed, M. M.; Hassan, S. G.; Shu, X.; Mahmood, N. Trident Nano-Indexing the Proteomics Table: Next-Version Clustering of Iron Carbide NPs and Protein Corona. *Molecules* **2022**, *27*, 5754.
(17) Hussain, R.; Zafar, A.; Hasan, M.; Tariq, T.; Saif, M. S.; Waqas, M.; Tariq, F.; Anum, M.; Anjum, S. I.; Shu, X. Casting Zinc Oxide Nanoparticles Using Fagonia Blend Microbial Arrest. *Appl. Biochem. Biotechnol.* **2023**, *195*, 264.
(18) Yuan, F.; Wang, Z.; Li, X.; Li, Y.; Tan, Z.; Fan, L.; Yang, S. Bright Multicolor Bandgap Fluorescent Carbon Quantum Dots for Electroluminescent Light-Emitting Diodes. *Adv. Mater.* **2017**, *29*, 1604436.
(19) Shen, J.; Zhu, Y.; Yang, X.; Zong, J.; Zhang, J.; Li, C. One-pot hydrothermal synthesis of graphene quantum dots surface-passivated by polyethylene glycol and their photoelectric conversion under near-infrared light. *New J. Chem.* **2012**, *36*, 97.
(20) Ding, H.; Yu, S. B.; Wei, J. S.; Xiong, H. M. Full-color light-emitting carbon dots with a surface-state-controlled luminescence mechanism. *ACS Nano* **2016**, *10*, 484.
(21) Yuan, B.; Guan, S.; Sun, X.; Li, X.; Zeng, H.; Xie, Z.; Chen, P.; Zhou, S. Highly Efficient Carbon Dots with Reversibly Switchable Green-Red Emissions for Trichromatic White Light-Emitting Diodes. *ACS Appl. Mater. Interfaces* **2018**, *10*, 16005.
(22) Gude, V.; Das, A.; Chatterjee, T.; Mandal, P. K. Molecular origin of photoluminescence of carbon dots: Aggregation-induced orange-red emission. *Phys. Chem. Chem. Phys.* **2016**, *18*, 28274.
(23) Guo, L.; Ge, J.; Liu, W.; Niu, G.; Jia, Q.; Wang, H.; Wang, P. Tunable multicolor carbon dots prepared from well-defined polythiophene derivatives and their emission mechanism. *Nanoscale* **2016**, *8*, 729.
(24) Zhang, H. Y.; Wang, Y.; Xiao, S.; Wang, H.; Wang, J. H.; Feng, L. Rapid detection of Cr(VI) ions based on cobalt(II)-doped carbon dots. *Biosens Bioelectron* **2017**, *87*, 46.
(25) Wu, W.; Zhan, L.; Fan, W.; Song, J.; Li, X.; Li, Z.; Wang, R.; Zhang, J.; Zheng, J.; Wu, M.; Zeng, H. Cu-N dopants boost electron transfer and photooxidation reactions of carbon dots. *Angewandte Chemie - International Edition* **2015**, *54*, 6540.
(26) Chen, X.; Mei, Q.; Yu, L.; Ge, H.; Yue, J.; Zhang, K.; Hayat, T.; Alsaedi, A.; Wang, S. Rapid and On-Site Detection of Uranyl Ions via Ratiometric Fluorescence Signals Based on a Smartphone Platform. *ACS Appl. Mater. Interfaces* **2018**, *10*, 42225.
(27) Luo, L.; Song, T.; Wang, H.; Yuan, Q.; Zhou, S. A highly selective fluorescence sensing platform for nanomolar Hg(II) detection based on cytosine derived quantum dot. *Spectrochim Acta A Mol. Biomol Spectrosc* **2018**, *193*, 95.
(28) Lin, Q. Y.; Li, Z.; Brown, K. A.; O'Brien, M. N.; Ross, M. B.; Zhou, Y.; Butun, S.; Chen, P. C.; Schatz, G. C.; Dravid, V. P.; Aydin, K.; Mirkin, C. A. Strong Coupling between Plasmonic Gap Modes and Photonic Lattice Modes in DNA-Assembled Gold Nanocube Arrays. *Nano Lett.* **2015**, *15*, 4699.
(29) Aoki, K.; Kamioka, Y.; Matsuda, M. Fluorescence resonance energy transfer imaging of cell signaling from in vitro to in vivo: Basis of biosensor construction, live imaging, and image processing. *Dev Growth Differ* **2013**, *55*, 515.
(30) Manzoor, Y.; Dilshad, M.; Hassan, S. G.; Hasan, M.; Nasir, M.; Tariq, T.; Zafar, A.; Israr, S.; Tariq, F.; Haq, A. Blueprinting in Coherence to Diagnostic Momentum: On Account of Cancer Detection in Bahawalpur Community. *Pakistan Journal of Biochemistry and Biotechnology* **2022**, *3*, 64−79.
(31) Dong, W.; Wang, R.; Gong, X.; Liang, W.; Dong, C. A far-red FRET fluorescent probe for ratiometric detection of L-cysteine based on carbon dots and N-acetyl-L-cysteine-capped gold nanoparticles. *Spectrochim Acta A Mol. Biomol Spectrosc* **2019**, *213*, 90.
(32) Tian, J.; Wei, W.; Wang, J.; Ji, S.; Chen, G.; Lu, J. Fluorescence resonance energy transfer aptasensor between nanoceria and graphene quantum dots for the determination of ochratoxin A. *Anal. Chim. Acta* **2018**, *1000*, 265.
(33) Peng, H. L.; Callender, R. Mechanism for Fluorescence Quenching of Tryptophan by Oxamate and Pyruvate: Conjugation and Solvation-Induced Photoinduced Electron Transfer. *J. Phys. Chem. B* **2018**, *122*, 6483.
(34) Zhu, J. L.; Xu, L.; Ren, Y. Y.; Zhang, Y.; Liu, X.; Yin, G. Q.; Sun, B.; Cao, X.; Chen, Z.; Zhao, X. L.; Tan, H.; Chen, J.; Li, X.; Yang, H. B. Switchable organoplatinum metallacycles with high quantum yields and tunable fluorescence wavelengths. *Nat. Commun.* **2019**, *10*, 4285 DOI: 10.1038/s41467-019-12204-7.
(35) Hu, L.; Wang, Q.; Zhang, X.; Zhao, H.; Cui, Z.; Fu, P.; Liu, M.; Liu, N.; He, S.; Pang, X.; Qiao, X. Light and magnetism dual-gated photoinduced electron transfer-reversible addition-fragmentation chain transfer (PET-RAFT) polymerization. *RSC Adv.* **2020**, *10*, 6850.
(36) Carstea, E. M.; Bridgeman, J.; Baker, A.; Reynolds, D. M. Fluorescence spectroscopy for wastewater monitoring: A review. *Water Res.* **2016**, *95*, 205.
(37) Gao, Z.; Liu, M.; Xu, K.; Tang, M.; Lin, X.; Hu, S.; Ren, X. Facile fabrication of N/S/P tri-doped carbon dots for tetracycline detection by an internal filtering effect of a two-way matching strategy. *Analytical Methods* **2020**, *12*, 2551.
(38) Goral, A. Assessment of a markerless optical tracking technique for computer-assisted hip surgery. *IST 2018 - IEEE International Conference on Imaging Systems and Techniques* **2018**, DOI: 10.1109/IST.2018.8577079.
(39) Li, Y.; Wan, M.; Yan, G.; Qiu, P.; Wang, X. A dual-signal sensor for the analysis of parathion-methyl using silver nanoparticles modified with graphitic carbon nitride. *J. Pharm. Anal* **2021**, *11*, 183.
(40) Wani, T. A.; Bakheit, A. H.; Ansari, M. N.; Al-Majed, A. R. A.; Al-Qahtani, B. M.; Zargar, S. Spectroscopic and molecular modeling studies of binding interaction between bovine serum albumin and roflumilast. *Drug Des Devel Ther* **2018**, *12*, 2627.

https://doi.org/10.1021/acsomega.2c07986
ACS Omega 2023, 8, 9031−9039

(41) Zafar, A.; Hasan, M.; Tariq, T.; Dai, Z. Enhancing Cancer Immunotherapeutic Efficacy with Sonotheranostic Strategies. *Bioconjug Chem.* **2022**, *33*, 1011.
(42) Huang, L.; Chen, R.; Luo, J.; Hasan, M.; Shu, X. Synthesis of phytonic silver nanoparticles as bacterial and ATP energy silencer. *J. Inorg. Biochem* **2022**, *231*, 111802.
(43) Xu, H.; Yang, X.; Li, G.; Zhao, C.; Liao, X. Green Synthesis of Fluorescent Carbon Dots for Selective Detection of Tartrazine in Food Samples. *J. Agric. Food Chem.* **2015**, *63*, 6707.
(44) Luo, F.; Wang, W.; Chen, M.; Zheng, Z.; Zeng, D.; Hasan, M.; Fu, Z.; Shu, X. Synthesis and efficacy of the n-carbamoyl-methionine copper on the growth performance, tissue mineralization, immunity, and enzymatic antioxidant capacity of nile tilapia (oreochromis niloticus). *ACS Omega* **2020**, *5*, 22578.
(45) Athar, M.; Fiaz, M.; Farid, M. A.; Tahir, M.; Asghar, M. A.; Ul Hassan, S.; Hasan, M. Iron and Manganese Codoped Cobalt Tungstates Co1-(x+ y)Fe xMn yWO4as Efficient Photoelectrocatalysts for Oxygen Evolution Reaction. *ACS Omega* **2021**, *6*, 7334.
(46) Zhou, Y.; Huang, X.; Liu, C.; Zhang, R.; Gu, X.; Guan, G.; Jiang, C.; Zhang, L.; Du, S.; Liu, B.; Han, M. Y.; Zhang, Z. Color-Multiplexing-Based Fluorescent Test Paper: Dosage-Sensitive Visualization of Arsenic(III) with Discernable Scale as Low as 5 ppb. *Anal. Chem.* **2016**, *88*, 6105.
(47) Pinget, G.; Tan, J.; Janac, B.; Kaakoush, N. O.; Angelatos, A. S.; O'Sullivan, J.; Koay, Y. C.; Sierro, F.; Davis, J.; Divakarla, S. K.; Khanal, D.; Moore, R. J.; Stanley, D.; Chrzanowski, W.; Macia, L. Impact of the food additive titanium dioxide (e171) on gut microbiota-host interaction. *Front Nutr* **2019**, DOI: 10.3389/fnut.2019.00057.
(48) Luo, F.; Zeng, D.; Chen, R.; Zafar, A.; Weng, L.; Wang, W.; Tian, Y.; Hasan, M.; Shu, X. PEGylated dihydromyricetin-loaded nanoliposomes coated with tea saponin inhibit bacterial oxidative respiration and energy metabolism. *Food Funct* **2021**, *12*, 9007.
(49) Luo, F.; Wang, M.; Huang, L.; Wu, Z.; Wang, W.; Zafar, A.; Tian, Y.; Hasan, M.; Shu, X. Synthesis of Zinc Oxide Eudragit FS30D Nanohybrids: Structure, Characterization, and Their Application as an Intestinal Drug Delivery System. *ACS Omega* **2020**, *5*, 11799.
(50) Lv, M.; Liu, Y.; Geng, J.; Kou, X.; Xin, Z.; Yang, D. Engineering nanomaterials-based biosensors for food safety detection. *Biosens Bioelectron* **2018**, *106*, 122.
(51) Yang, P.; Zhu, Z.; Chen, M.; Zhou, X.; Chen, W. Microwave-assisted synthesis of polyamine-functionalized carbon dots from xylan and their use for the detection of tannic acid. *Spectrochim Acta A Mol. Biomol Spectrosc* **2019**, *213*, 301.
(52) Cui, C.; Lei, J.; Yang, L.; Shen, B.; Wang, L.; Zhang, J. Carbon-dot-encapsulated molecularly imprinted mesoporous organosilica for fluorescent sensing of rhodamine 6G. *Res. Chem. Intermed.* **2018**, *44*, 4633−4640.
(53) Yao, D.; Li, C.; Wen, G.; Liang, A.; Jiang, Z. A highly sensitive and accurate SERS/RRS dual-spectroscopic immunosensor for clenbuterol based on nitrogen/silver-codoped carbon dots catalytic amplification. *Talanta* **2020**, *209*, 120529.
(54) Yang, X.; Xu, J.; Luo, N.; Tang, F.; Zhang, M.; Zhao, B. N,Cl co-doped fluorescent carbon dots as nanoprobe for detection of tartrazine in beverages. *Food Chem.* **2020**, *310*, 125832.
(55) Hu, X.; Shi, J.; Shi, Y.; Zou, X.; Arslan, M.; Zhang, W.; Huang, X.; Li, Z.; Xu, Y. Use of a smartphone for visual detection of melamine in milk based on Au@Carbon quantum dots nanocomposites. *Food Chem.* **2019**, *272*, 58.
(56) Madej, M.; Fendrych, K.; Porada, R.; Flacha, M.; Kochana, J.; Baś, B. Application of Fe(III)-exchanged clinoptilolite/graphite nanocomposite for electrochemical sensing of amitriptyline. *Microchemical Journal* **2021**, *160*, 105648.
(57) Rovina, K.; Acung, L. A.; Siddiquee, S.; Akanda, J. H.; Shaarani, S. M. Extraction and Analytical Methods for Determination of Sunset Yellow (E110)—a Review. *Food Anal Methods* **2017**, *10*, 773.
(58) Li, Q.; Song, P.; Wen, J. Melamine and food safety: a 10-year review. *Curr. Opin Food Sci.* **2019**, *30*, 79.
(59) Baby, R.; Saifullah, B.; Hussein, M. Z. Carbon Nanomaterials for the Treatment of Heavy Metal-Contaminated Water and Environmental Remediation. *Nanoscale Res. Lett.* **2019**, *14*, 341 DOI: 10.1186/s11671-019-3167-8.
(60) Wu, Z.; Ren, Y.; Liang, Y.; Huang, L.; Yang, Y.; Zafar, A.; Hasan, M.; Yang, F.; Shu, X. Synthesis, Characterization, Immune Regulation, and Antioxidative Assessment of Yeast-Derived Selenium Nanoparticles in Cyclophosphamide-Induced Rats. *ACS Omega* **2021**, *6*, 24585−24594.
(61) Li, W.; Hu, X.; Li, Q.; Shi, Y.; Zhai, X.; Xu, Y.; Li, Z.; Huang, X.; Wang, X.; Shi, J.; Zou, X.; Kang, S. Copper nanoclusters @ nitrogen-doped carbon quantum dots-based ratiometric fluorescence probe for lead (II) ions detection in porphyra. *Food Chem.* **2020**, *320*, 126623.
(62) Yang, Y.; Chen, X.; Wang, Y.; Wu, M.; Ma, Y.; Yang, X. A Novel Fluorescent Test Papers Based on Carbon Dots for Selective and Sensitive Detection of Cr (VI). *Front Chem.* **2020**, DOI: 10.3389/fchem.2020.595628.
(63) Hou, Y.; Lu, Q.; Deng, J.; Li, H.; Zhang, Y. One-pot electrochemical synthesis of functionalized fluorescent carbon dots and their selective sensing for mercury ion. *Anal. Chim. Acta* **2015**, *866*, 69.
(64) Alreshidi, M. M. Selected Metabolites Profiling of Staphylococcus aureus Following Exposure to Low Temperature and Elevated Sodium Chloride. *Front Microbiol* **2020**, DOI: 10.3389/fmicb.2020.00834.
(65) Konkel, M. E.; Talukdar, P. K.; Negretti, N. M.; Klappenbach, C. M. Taking Control: Campylobacter jejuni Binding to Fibronectin Sets the Stage for Cellular Adherence and Invasion. *Front Microbiol* **2020**, DOI: 10.3389/fmicb.2020.00564.
(66) Tian, K.; Chen, X.; Luan, B.; Singh, P.; Yang, Z.; Gates, K. S.; Lin, M.; Mustapha, A.; Gu, L. Q. Single Locked Nucleic Acid-Enhanced Nanopore Genetic Discrimination of Pathogenic Serotypes and Cancer Driver Mutations. *ACS Nano* **2018**, *12*, 4194.
(67) Ahmadian-Fard-Fini, S.; Salavati-Niasari, M.; Ghanbari, D. Hydrothermal green synthesis of magnetic Fe3O4-carbon dots by lemon and grape fruit extracts and as a photoluminescence sensor for detecting of E. coli bacteria. *Spectrochim Acta A Mol. Biomol Spectrosc* **2018**, *203*, 481.
(68) Choi, C. A.; Mazrad, Z. A. I. M.; Lee, G.; In, I.; Lee, K. D.; Park, S. Y. Boronate-based fluorescent carbon dot for rapid and selectively bacterial sensing by luminescence off/on system. *J. Pharm. Biomed Anal* **2018**, *159*, 1.
(69) Alavanja, M. C. R.; Hoppin, J. A.; Kamel, F. Health effects of chronic pesticide exposure: Cancer and neurotoxicity. *Annu. Rev. Public Health* **2004**, *25*, 155.
(70) Costa, I. M.; Codognoto, L.; Valle, E. M. A. Voltammetric and spectroscopic studies of the interaction between copper (II) ions with the pesticide carbendazim and its effect in the soil. *J. Solid State Electrochem.* **2018**, *22*, 1563.
(71) Huang, S.; Yao, J.; Chu, X.; Liu, Y.; Xiao, Q.; Zhang, Y. 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.* **2019**, *67*, 11244.
(72) Han, Y.; Yang, W.; Luo, X.; He, X.; Yu, Y.; Li, C.; Tang, W.; Yue, T.; Li, Z. Cu2+-Triggered Carbon Dots with Synchronous Response of Dual Emission for Ultrasensitive Ratiometric Fluorescence Determination of Thiophanate-Methyl Residues. *J. Agric. Food Chem.* **2019**, *67*, 12576.
(73) Zou, R.; Chang, Y.; Zhang, T.; Si, F.; Liu, Y.; Zhao, Y.; Liu, Y.; Zhang, M.; Yu, X.; Qiao, X.; Zhu, G.; Guo, Y. Up-converting nanoparticle-based immunochromatographic strip for multi-residue detection of three organophosphorus pesticides in food. *Front Chem.* **2019**, DOI: 10.3389/fchem.2019.00018.
(74) Rezg, R.; Mornagui, B.; El-Fazaa, S.; Gharbi, N. Organophosphorus pesticides as food chain contaminants and type 2 diabetes: A review. *Trends Food Sci. Technol.* **2010**, *21*, 345.

https://doi.org/10.1021/acsomega.2c07986
ACS Omega 2023, 8, 9031−9039

(75) Huang, S.; Yao, J. D.; Chu, X.; Liu, Y.; Xiao, Q.; Zhang, Y. 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.* **2019**, *67*, 11244.
(76) Yan, X.; Song, Y.; Zhu, C. Z.; Li, H. X.; Du, D.; Su, X. G.; Lin, Y. MnO2 Nanosheet-Carbon Dots Sensing Platform for sensitive Detection of Organophosphorus Pesticides. *Anal. Chem.* **2018**, *90*, 2618.
(77) Wu, M.; Fan, Y. J.; Li, J. W.; Lu, D. Q.; Guo, Y. P.; Xie, L. W.; Wu, Y. Q. Vinyl Phosphate-Functionalized, Magnetic, Molecularly-Imprinted Polymeric Microspheres' Enrichment and Carbon Dots' Fluorescence-Detection of Organophosphorus Pesticide Residues. *Polymers (Basel)* **2019**, *11*, 1770.
(78) Lan, S. Y.; Wang, X. F.; Liu, Q. Y.; Jing, B.; Yang, M.; Fa, H. B.; Hou, C. J.; Huo, D. Q. Fluorescent sensor for indirect measurement of methyl parathion based on alkaline-induced hydrolysis using N-doped carbon dots. *Talanta* **2019**, *192*, 368.
(79) Baynes, R. E.; Dedonder, K.; Kissell, L.; Mzyk, D.; Marmulak, T.; Smith, G.; Tell, L.; Gehring, R.; Davis, J.; Riviere, J. E. Health concerns and management of select veterinary drug residues. *Food Chem. Toxicol.* **2016**, *88*, 112.
(80) Fan, Y.; Qiao, W.; Long, W.; Chen, H.; Fu, H.; Zhou, C.; She, Y. Detection of tetracycline antibiotics using fluorescent "Turn-off" sensor based on S, N-doped carbon quantum dots. *Spectrochim Acta A Mol. Biomol Spectrosc* **2022**, *274*, 121033.
(81) Miao, H.; Wang, Y.; Yang, X. Carbon dots derived from tobacco for visually distinguishing and detecting three kinds of tetracyclines. *Nanoscale* **2018**, *10*, 8139.
(82) An, X.; Zhuo, S.; Zhang, P.; Zhu, C. Carbon dots based turn-on fluorescent probes for oxytetracycline hydrochloride sensing. *RSC Adv.* **2015**, *5*, 19853.
(83) Fu, Y.; Zhao, S.; Wu, S.; Huang, L.; Xu, T.; Xing, X.; Lan, M.; Song, X. A carbon dots-based fluorescent probe for turn-on sensing of ampicillin. *Dyes Pigm.* **2020**, *172*, 107846.
(84) Wang, J.; Lu, T.; Hu, Y.; Wang, X.; Wu, Y. A label-free and carbon dots based fluorescent aptasensor for the detection of kanamycin in milk. *Spectrochim Acta A Mol. Biomol Spectrosc* **2020**, *226*, 117651.
(85) Feng, D.; Tan, X.; Wu, Y.; Ai, C.; Luo, Y.; Chen, Q.; Han, H. Electrochemiluminecence nanogears aptasensor based on MIL-53(Fe)@CdS for multiplexed detection of kanamycin and neomycin. *Biosens Bioelectron* **2019**, *129*, 100.
(86) Moazed, D.; Noller, H. F. Interaction of antibiotics with functional sites in 16S ribosomal RNA. *Nature* **1987**, *327*, 389.
(87) Veal, G. J.; Amankwatia, E. B.; Paludetto, M. N.; Möcklinghoff, T.; Thomson, F.; André, N.; Ciccolini, J.; Chatelut, E. Pharmacodynamic therapeutic drug monitoring for cancer: Challenges, advances, and future opportunities. *Ther Drug Monit* **2019**, *41*, 142.
(88) Chu, S.; Wang, H.; Du, Y.; Yang, F.; Yang, L.; Jiang, C. Portable Smartphone Platform Integrated with a Nanoprobe-Based Fluorescent Paper Strip: Visual Monitoring of Glutathione in Human Serum for Health Prognosis. *ACS Sustain Chem. Eng.* **2020**, *8*, 8175.
(89) Drechsel, D. A.; Liang, L. P.; Patel, M. 1-Methyl-4-phenylpyridinium-induced alterations of glutathione status in immortalized rat dopaminergic neurons. *Toxicol. Appl. Pharmacol.* **2007**, *220*, 341.
(90) Zhang, B.; Duan, Q.; Li, Y.; Zhang, Y.; Che, M.; Zhang, W.; Sang, S. A "turn-on" fluorescent probe for glutathione detection based on the polyethylenimine-carbon dots-Cu2+ system. *J. Photochem. Photobiol. B* **2019**, *197*, 111532.

https://doi.org/10.1021/acsomega.2c07986
ACS Omega 2023, 8, 9031−9039