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Graphene quantum dot nanosensors for food safety monitoring: A comprehensive review of synthesis, surface functionalization, and emerging diagnostic platforms

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Abstract
Ensuring the safety and integrity of the global food supply is a critical challenge in an era of interconnected agricultural, industrial, and environmental systems. Food products are increasingly susceptible to contamination by pesticide residues, antibiotics, heavy metals, mycotoxins, microplastics, and other chemical hazards, all of which pose serious risks to human health. Conventional analytical techniques, including chromatography, mass spectrometry, and immunoassays, are highly accurate but often suffer from high costs, complex sample pre-processing, and unsuitability for rapid, on-site, real-time screening. To overcome these barriers, nanotechnology-based sensing platforms have emerged as highly promising alternatives. Among these, Graphene Quantum Dots (GQDs)—zero-dimensional carbonaceous nanomaterials —have attracted significant attention owing to their exceptional photoluminescence, large surface-to-volume ratio, chemical stability, superior biocompatibility, low toxicity, and ease of functionalization. This review provides a comprehensive, high-density analytical overview of GQD-based nanosensors for food safety monitoring. We dissect the structural, optical, and physicochemical properties of GQDs, contrasting the electronic behaviors of zigzag and armchair edge configurations and core-state vs. surface-state emissions. Furthermore, we evaluate top-down and bottom-up synthetic strategies, highlighting the sustainability and circularity of green biomass-derived synthesis. Advanced surface engineering techniques, including heteroatom doping (N, S, B, P) and bioconjugation with antibodies, aptamers, and molecularly imprinted polymers, are systematically discussed. We present a highly detailed, grounded performance matrix compiling limits of detection, food matrices, and detection mechanisms for major food contaminants. Finally, current challenges relating to reproducibility, matrix-induced quenching, and toxicity are evaluated alongside emerging point-of-care, smartphone-integrated, and intelligent packaging platforms, establishing a technical roadmap for the practical translation of GQDs from the laboratory to the industrial supply chain.

Keywords: Graphene Quantum Dots (GQDs), food safety, chemical contaminants, nanosensors, photoluminescence, green nanotechnology, ratiometric sensing

Introduction

Ensuring the safety and integrity of the global food supply is a paramount challenge in an era of interconnected agricultural, industrial, and environmental systems (C. Li, 2025) [58]. The rapid development of agricultural and industrial technology has led to an increasing diversity of food products available to the market (Saud *et al*., 2023) [36]. However, with the marked improvement of consumers' requirements for food quality and purity, food safety has become a central focus of society, government regulators, and international health organizations (Y. X. Li *et al*., 2022). Food safety issues have emerged and multiplied due to the escalating complexity of modern food production, processing, transport, and storage, which makes analytical testing and detection a complex and urgent challenge (Chu *et al*., 2020) [51].

Globally, food safety is a major public health concern. Contamination of food systems by biological, chemical, and physical agents leads to millions of foodborne illnesses each year, causing significant morbidity, mortality, and an immense global disease burden caused by foodborne hazards (Havelaar *et al*., 2015) [33]. As food safety problems continue to rise, securing food quality that is completely free from chemical residues and contaminants has become an important concern that highlights the real, everyday threat to human health (Alam *et al*., 2026) [9].

Within this complex contamination network, chemical contaminants comprise a massive group of more than 3,000 compounds and their derivatives. These include pesticides, fertilizers, veterinary drugs, heavy metals, microplastics, pharmaceutically active compounds (including antibiotics), personal care products, and natural and synthetic hormones (Al-Momani *et al*., 2026) [8]. These hazardous compounds quietly and persistently permeate both the source and the final stages of the food chain through diverse and complex channels. These channels include intensive agricultural practices, industrial environmental pollution, improper municipal waste disposal, chemical by-products formed during high-temperature food processing, and toxic components leaching from food packaging materials (Kannan & Guo, 2020) [40]. In livestock husbandry, antibiotics are introduced as infection-preventing or infection-treating agents, as growth promoters, and as pest and disease controllers in animal farming (Kannan & Guo, 2020) [40]. Naturally occurring mycotoxins, together with intentional, profit-driven food adulteration through illegal additives (such as melamine, urea, and synthetic dyes), further complicate and expand this network of food contamination sources (C. Li, 2025) [7].

Table 1: Major Categories of Food Contaminants, Representative Examples, Traditional Detection Techniques, and Key Limitations.

Contaminant Category	Contaminants	Traditional Technique(s)	Limitations of Traditional Methods	References
Pesticide residues	Organophosphates, carbamates, organochlorines	HPLC; GC-MS/MS; LC-MS/MS; GC	High solvent consumption and long run times. Matrix effects cause ion suppression. Unsuitable for polar/thermally labile pesticides.	Jan *et al*. (2025) [5]; Hakeem *et al*. (2026)
Antibiotic / veterinary residues	Tetracyclines, beta-lactams, aminoglycosides, sulfonamides	HPLC; LC-MS/MS; LC-HRMS; ELISA	Immunoassays: cross-reactivity and false positives. LC-MS/MS: expensive isotope standards needed. Matrix effects persist.	Khalifa *et al*. (2024); Amelin *et al*. (2024); Tao *et al*. (2025) [5, 10]
Heavy metals	Hg, Pb, Cd, As, Cr, Ni, Cu, Zn	AAS; ICP-OES/ICP-AES; ICP-MS	AAS: single-element sequential analysis. ICP-MS: spectral interference. Harsh acid digestion required. Cannot differentiate species easily.	Zhao *et al*. (2024); Si *et al*. (2024); Li *et al*. (2025) [69]
Mycotoxins	Aflatoxins, ochratoxin A, fumonisins, zearalenone	HPLC/UPLC; LC-MS/MS; ELISA; GC-MS	ELISA: high false-positive rate. GC-MS: derivatization needed. LC-MS/MS: ion suppression. Lengthy cleanup steps required.	Chen *et al*. (2023); Gherbawy *et al*. (2023); Zhang *et al*. (2024) [21, 28]
Adulterants / synthetic dyes	Melamine, urea, synthetic dyes	HPLC; LC-MS/MS; CE; SERS; UV-Vis	CE: poor reproducibility. UV-Vis: lacks specificity. SERS: expensive substrates with poor reproducibility. HPLC: extensive gradient needs.	Seo *et al*. (2024); El-Tahlawy *et al*. (2026)
Microplastics / other pollutants	Microplastics, PAHs, phenolic compounds	FTIR; Raman spectroscopy; Py-GC-MS; HPLC	FTIR/Raman: diffraction-limited. Raman: fluorescence interference. Py-GC-MS: destructive. Lengthy density separation.	Zhang *et al*. (2023); Food Bioscience (2026) [9, 55]

To prevent emerging food safety problems and protect public health, there is an urgent, non-negotiable requirement to strengthen food testing and quality monitoring frameworks (Chu *et al*., 2020) [40]. Nanotechnology-based sensing platforms, or nanosensors, have emerged as an exceptionally effective tool for resolving these challenges. Nanosensing platforms offer numerous advantages over conventional bulk sensors, including being highly cost-effective, sensitive, selective, capable of real-time detection, efficient, and highly portable (Kannan & Guo, 2020) [40]. Among these platforms, Graphene Quantum Dots (GQDs) have emerged as a highly promising, zero-dimensional addition to the carbon nanomaterials family, possessing remarkable electrical and optical properties (Li *et al*., 2018).

Definition, Structural Architecture, and Fundamental Properties of GQDs

1. Defining GQDs: Distinction from Graphene and Carbon Dots

Graphene quantum dots (GQDs) are a distinct carbon-based class of zero-dimensional (0D) quantum dots, consisting of nanometer-sized graphene sheets (typically less than 10 nm in lateral dimensions) with single- or few-layer structures (Li *et al*., 2018; Campbell *et al*., 2021) [19]. They inherit the planar sp² honeycomb carbon structure of bulk graphene while exhibiting powerful quantum confinement and edge effects similar to conventional semiconductor quantum dots (Ponomarenko *et al*., 2008; Zhu *et al*., 2018). It is crucial to distinguish GQDs from other carbonaceous nanomaterials such as carbon nanodots (CDs) or carbon quantum dots (CQDs) as summarized in Table 2.

Table 2: Key Differences Between Carbon Dots (CDs), Carbon Quantum Dots (CQDs), and Graphene Quantum Dots (GQDs).

Feature	CDs / CNDs	CQDs	GQDs
Structure	Amorphous carbon core	Quasi-spherical carbon nanodots with crystalline domains	Single/few-layer graphene fragments
Hybridization	Mixed sp² / sp³	Mainly sp² with some sp³	Predominantly sp²
Shape	Spherical	Spherical	Planar / disk-like
Size	~2-8 nm	~2-10 nm	~2-20 nm
Quantum confinement	Weak / limited	Present	Strong
PL origin	Mainly surface states	Core + surface states	Core, edge, and surface states
Charge mobility	Low	Moderate	High
Main advantage	Easy synthesis	Good fluorescence	Better electronic and sensing performance

2. Structural Architecture: Lattice, Edges, and HOMO-LUMO Gap

At the atomic scale, the core of a GQD consists of a single or few layers (typically one to five) of sp²-hybridized carbon atoms arranged in a planar honeycomb lattice, supporting a highly delocalized π-electron system. This conjugated carbon core is primarily responsible for the material's structural integrity, high electrical conductivity, and optical absorption features (Medina *et al*., 2023; Huang *et al*., 2014). Single-layer structures exhibit stronger quantum confinement effects and higher quantum yields, whereas few-layer structures provide enhanced physical stability (Vercelli, 2021; Bae *et al*., 2024) [13].

Due to their extremely small lateral dimensions, a large proportion of GQD atoms are located at the boundaries, making the edge configuration a major driver of their electronic and optical properties (Nsibande *et al*., 2020) [51]. Edge configurations are classified as zigzag or armchair configurations. Zigzag edges are characterized by triangular morphologies and often generate localized electronic states near the Fermi level, which significantly reduces the energy bandgap and creates zero-energy states (Cho *et al*., 2024; Rasheed *et al*., 2024) [13, 57]. This localized edge-state electronic density substantially enhances electron transfer kinetics and molecular adsorption, making zigzag-edged GQDs highly suitable for electrochemical and catalytic sensing systems (Tian *et al*., 2018). In contrast, armchair edges, typical of hexagonal GQDs, exhibit greater structural and chemical stability, a larger bandgap, and a more uniform distribution of the Highest Occupied Molecular Orbital (HOMO) over the planar surface (Rasheed *et al*., 2024; Abdelsalam *et al*., 2018) [3, 57].

3. Size-Dependent Bandgap Tuning and Quantum Confinement

The unique properties of GQDs, particularly their excitation-dependent photoluminescence and high quantum yields, arise from the quantum confinement effect (Zhang *et al*., 2025) [67]. When the lateral size of the GQD approaches the de Broglie wavelength of charge carriers, electron motion becomes spatially restricted, causing the continuous energy bands of bulk graphene to split into discrete, size-dependent energy levels (Soni *et al*., 2025; Sarkar *et al*., 2025) [5]. As a result, as the physical size of a GQD decreases, its bandgap increases, causing the emitted photoluminescence to shift toward shorter wavelengths (higher energy), such as blue or violet. Conversely, larger GQDs exhibit a smaller bandgap, shifting emission toward longer wavelengths (lower energy) like green, yellow, orange, or red (Lai *et al*., 2020).

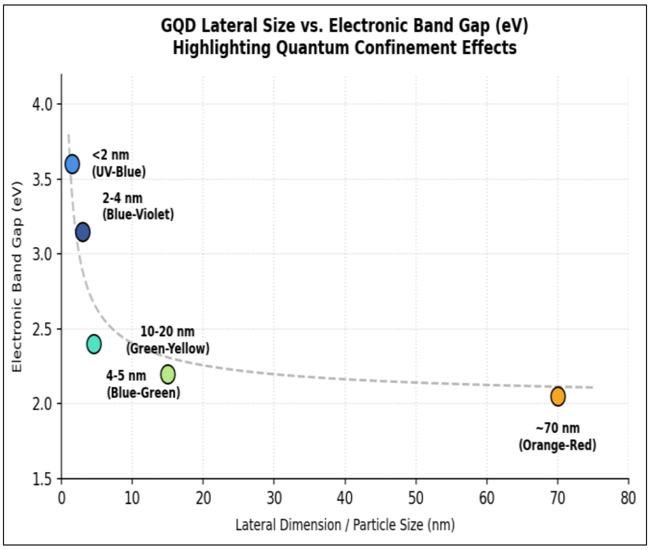

Fig 1: Relationship between GQD lateral core size (nm) and electronic band gap (eV). Plot constructed from reported literature benchmarks, showing how severe quantum confinement in sub-5 nm dots dramatically broadens the band gap, shifting emission from orange-red to high-energy UV-blue.

This size-dependent emission tuning represents a massive advantage for optical diagnostic design, allowing scientists to optimize GQD probes to minimize sample autofluorescence by shifting emission wavelengths or developing multiplexed arrays (Maali *et al*., 2025) [5]. The structural size and the corresponding bandgaps are summarized in Table 3.

Table 3: GQD Size, Electronic Bandgap, and Peak Emissive Properties.

Size Category	Band Gap (eV)	Emission Color	Key Optical Observation	References
~70 nm	2.05 eV	Orange–Red	Larger dimensions yield a smaller band gap; weak confinement	Joshi *et al.* (2021) [38]
10–20 nm	2.1–2.3 eV	Green–Yellow	Moderate confinement effects suitable for down-conversion	Campbell *et al.* (2021) [19]
4–5 nm	~2.4 eV	Blue–Green	Strong quantum confinement regime; highly luminescent	Joshi *et al.* (2021) [38]
2–4 nm	2.8–3.5 eV	Blue–Violet	High-energy emission; strong boundary effects	Campbell *et al.* (2021) [19]
<2 nm	0.1–0.6 eV*	UV–Blue	Strong quantum effects; exciton binding dominates	Ji *et al.* (2018)

4. Surface Chemistry and Abundant Functional Groups

The surface of a GQD is chemically rich, largely due to its high edge-to-core ratio, edge defects, and the oxidation of precursors during synthesis. Common functional groups include carboxyl (–COOH), carbonyl (C=O), hydroxyl (–OH), amino (–NH_2), aldehyde (–CHO), and nitro (–NO_2) groups (Zeng *et al*., 2025; Fan *et al*., 2024) [28, 68]. These groups do not merely act as passive structural endpoints; they actively modify surface charge, water solubility, and emission characteristics. For example, carboxyl groups increase the dipole moment and reduce the core bandgap, promoting stable, green-shifted emission (Zeng *et al*., 2025) [68],

whereas hydroxyl-dominated surfaces are linked with high-energy blue emission and reduced non-radiative energy loss (Fan *et al*., 2024) [28]. Amino groups are highly valued for bioconjugation, serving as primary targets for carbodiimide-mediated coupling (EDC/NHS chemistry) to attach antibodies and aptamers (Lee *et al*., 2024) [10].

Synthetic Strategies for Graphene Quantum Dots

The synthesis strategy plays a central, defining role in determining the lateral size, thickness, core crystallinity, surface defects, and photoluminescence characteristics of GQDs. Since these physical and chemical parameters directly control the sensor's limit of detection and selectivity, selecting a highly robust and reproducible synthesis route is a critical factor in analytical design (Raza *et al*., 2025) [58]. Synthetic strategies are classified into top-down cutting and bottom-up molecular carbonization routes.

1. Top-Down Cutting Approaches

Top-down methods produce GQDs by the physical, chemical, or electrochemical cleavage of bulk graphitic carbon precursors, such as graphite flakes, graphene oxide, carbon fibers, carbon black, or coke (Manjubaashini *et al*., 2024) [57]. These cleavage reactions typically progress along defect sites, grain boundaries, or highly oxidized carbon-carbon bonds. Common top-down routes include oxidative cutting (using strong acids such as HNO3/H2SO4 and oxidants like H2O2), hydrothermal or solvothermal cleavage under elevated temperature and pressure, and electrochemical exfoliation (Jing *et al*., 2025; Sun *et al*., 2023) [36, 37]. A major advantage of electrochemical exfoliation is that it does not require corrosive liquid oxidants; applying an electrical potential drives electrolyte-ion intercalation and anodic oxidation, producing highly water-dispersible GQDs with reduced chemical waste (Yang *et al*., 2020; Danial *et al*., 2021) [1, 25]. While top-down methods are direct and effectively preserve the high sp² crystallinity of the parent graphitic material, they are frequently limited by broader size distributions and the requirement for extensive dialysis (Manjubaashini *et al*., 2024).

2. Bottom-Up Molecular Carbonization Approaches

In contrast, bottom-up methods synthesize GQDs by the thermal, pyrolytic, or microwave conversion of small organic molecules, such as citric acid, glucose, sucrose, or amino acids, into graphitic nanodomains (Shi *et al*., 2023) [36]. This conversion proceeds via a cascade of chemical reactions, including dehydration, condensation, molecular polymerization, aromatization, and solid-state carbonization/nucleation. Pyrolysis refers to broader thermochemical decomposition under anoxygen-deficient conditions, typically at temperatures ranging from 300°C to 800°C, while carbonization/nucleation is focused on solid-phase graphitic domain ordering at milder temperatures (300°C to 450°C) (Montilla *et al*., 2025; Dong *et al*., 2025). Microwave-assisted synthesis utilizes dielectric heating to achieve rapid, uniform molecular carbonization, allowing highly luminescent GQDs to be synthesized within minutes (Salah, 2025; Adhikari *et al*., 2026) [4, 5]. Bottom-up approaches are widely favored in sensor development because they offer superior, precise control over particle lateral size, edge configuration, heteroatom doping efficiency, and surface functional groups, yielding uniform particles with extremely high fluorescence quantum yields (Liu *et al*., 2022).

Table 4: Comparative Evaluation of Top-Down Cutting and Bottom-Up Molecular Carbonization Strategies.

Feature / Parameter	Top-Down Synthesis Route	Bottom-Up Synthesis Route
Starting Materials	Bulk carbon: graphite, graphene oxide, carbon fibers, coke	Small molecules: organic acids, simple sugars, amino acids, urea
Cleavage Mechanism	Physical, chemical, or electrochemical fragmentation of sp² sheets	Thermal dehydration, condensation, polymerization, and carbonization
Size Distribution	Broad size distribution; typically requires lengthy dialysis	Narrow and highly uniform size distribution; highly reproducible
Surface Chemistry	Highly oxidized; abundant oxygen groups; difficult to control density	Highly tunable; precursor composition controls functional groups directly
Quantum Yield	Moderate (typically < 10% without surface passivation)	High (frequently exceeds 20–50% due to precise doping)
Heteroatom Doping	Requires harsh, multi-step post-synthesis chemical treatments	Achieved in a single, rapid step by co-introducing N, S, B precursors
Representative Methods	Acid oxidative cutting, hydrothermal cutting, electrochemical exfoliation	Pyrolysis, microwave carbonization, solvothermal carbonization

Green and Biomass-Derived Synthesis of GQDs

In recent years, the green, sustainable, and biomass-derived synthesis of Graphene Quantum Dots (GQDs) has emerged as a major research frontier in green nanotechnology (Moradialvand *et al*., 2025) [2]. Conventional synthetic routes often utilize concentrated, highly corrosive mineral acids (such as HNO_3, H_2SO_4), toxic oxidizing agents (such as $KMnO_4$), and extensive post-treatment purification cycles, which generate substantial chemical waste and raise severe environmental concerns (Rafique *et al*., 2023) [56]. To establish sustainable GQD production, researchers have turned to green chemistry principles, emphasizing the use of safe reagents, benign solvents (primarily water), low energy inputs, and renewable precursors (Ncube *et al*., 2023).

A major breakthrough in this domain is the valorization of abundant, carbon-rich agricultural and industrial food waste, such as fruit peels, crop residues, spent tea leaves, coffee grounds, and food processing by-products (Usman *et al*., 2024) [26]. These precursors are highly sustainable, inexpensive, and contain organic molecules (such as cellulose, hemicellulose, lignin, polyphenols, and amino acids) that act as natural carbon, nitrogen, and oxygen sources. For instance, mango peel can be hydrothermally converted in a water solvent at 180°C to yield GQDs with a 28% quantum yield (Asri *et al*., 2026) [12]. Spent tea leaves yield Hg^{2+}-sensitive GQDs with a 22% quantum yield (Qrtulen *et al*., 2023) [56], and rice husk can be converted via rapid microwave treatment within 5 minutes to produce highly active metal sensors with a 35% quantum yield (Rocha *et al*., 2026).

Table 5: Green and Sustainable Biomass-Derived Precursors, Synthesis Conditions, and Sensing Applications for GQDs.

Biomass Precursor	Synthesis Method	Reaction Conditions	QY (%)	Food Safety Sensing Application	Reference
Mango peel	Hydrothermal	180°C, 6 h, water solvent	28	Diazinon pesticide sensing; cell imaging	Asri *et al*. (2026) [12]
Rice husk	Microwave	800 W, 5 min, NH4OH	35	Heavy metal ion sensing	Rocha *et al*. (2026)
Spent tea leaves	Hydrothermal	180°C, 12 h, water	22	Selective Hg^{2+} sensing in water and tea	Qurtulen *et al*. (2023) [56]
Spent coffee grounds	One-step Hydrothermal	180°C, 8 h, water	~12	Fe^{3+} / Ce^{4+} and phosphate ion detection	Zhao *et al*. (2025) [69]
Jackfruit seed starch	One-step Hydrothermal	180°C, water	NR	Antioxidant, antibacterial CuO composite	Le *et al*. (2025) [5]
Paddy straw	Hydrothermal	180°C, 6 h, autoclave	NR	Bilirubin detection in clinical and milk samples	Isha *et al*. (2025) [34]
Pineapple leaf fiber	Hydrothermal	Ethylenediamine dopant	NR	Hg^{2+} ion detection in river water	Xiong *et al*. (2022) [66]

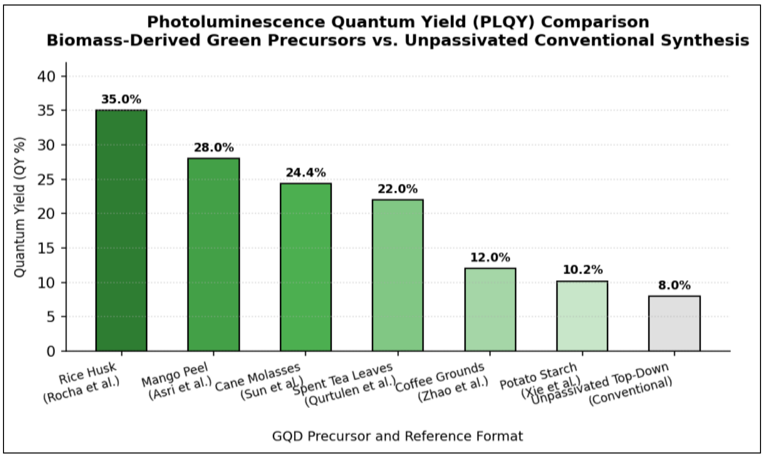

Fig 2: Photoluminescence Quantum Yield (PLQY %) of representative biomass-derived Graphene Quantum Dots vs. conventional unpassivated cutting methods. The comparison underscores that green synthesis routes can match or exceed standard laboratory precursors while implementing a circular bioeconomy

Key optimization parameters for green synthesis include reaction temperature, duration, biomass concentration, and solvent choice. Reaction temperature influences the degree of carbonization and crystalline graphitic domain formation. Reaction duration must be carefully optimized to prevent particle aggregation, while the use of membrane filters (e.g., 0.22 µm) and dialysis against water is crucial to achieve high purity and photoluminescence stability (Zhao *et al*., 2025 [69]; Rocha *et al*., 2026).

Surface Engineering and Functionalization of GQDs

While pristine GQDs possess excellent intrinsic optical and electronic properties, their analytical performance can be significantly enhanced through surface engineering and chemical functionalization, particularly for food sensing applications where complex sample matrices demand extremely high sensitivity and selectivity (Sharma *et al*., 2025; Behjatmanesh *et al*., 2025). Surface engineering is broadly classified into heteroatom doping, covalent conjugation, and non-covalent functionalization.

1. Heteroatom Doping (N, S, B, P)

Heteroatom doping involves incorporating non-carbon elements directly into the sp^2 carbon framework of the GQD core or edges (Permatasari *et al*., 2024; Bhaloo *et al*., 2023) [17]. Doping reconstructs GQD properties by introducing elements with different electronegativities and atomic sizes. Nitrogen (N) has an atomic size similar to carbon but possesses an extra valence electron, acting as an n-type electron donor, shifting HOMO/LUMO levels, and drastically increasing photoluminescence quantum yields (PLQY) and electron transfer kinetics (Behjatmanesh *et al*., 2025).

Sulfur (S) doping increases surface polarity, electrochemical activity, and local lattice distortion, while Boron (B) acts as a p-type dopant introducing electron-deficient sites. Phosphorus (P) enhances surface reactivity and compatibility (Qin *et al*., 2023; Juang *et al*., 2021) [39, 55]. Co-doping strategies, such as N,S- or N,P-co-doping, generate powerful synergistic effects, increasing the PLQY and creating highly specific coordination sites for target analytes (Qin *et al*., 2023) [55].

2. Covalent and Non-Covalent Functionalization

Covalent functionalization utilizes active surface groups (such as –COOH, –OH, $–NH_2$) to attach biomolecular recognition elements—such as specific DNA aptamers, antibodies, enzymes, or Molecularly Imprinted Polymers (MIPs)—via stable amide or ester bonds (EDC/NHS chemistry), providing high selectivity toward specific toxins, pathogens, or antibiotic residues (Nsibande & Forbes, 2020) [51]. Non-covalent functionalization relies on weaker, non-destructive physical interactions, such as π–π stacking, electrostatic force, hydrophobic interaction, and hydrogen bonding. This approach successfully preserves the native fluorescence and charge transport characteristics of GQDs, making it highly useful for creating hybrid nanocomposites, such as GQD-AuNP or GQD-MWCNT conjugates (Nsibande & Forbes, 2020) [51]. GQD surface modification strategies are summarized in **Table 6**.

Table 6: GQD Surface Engineering and Functionalization Strategies in Food Safety Sensing Systems.

Type	Specific Modification	Main Physicochemical Effect	Sensing Target / Application
N-doping	Nitrogen incorporation	Enhances PL intensity and charge transfer kinetics; provides electron-donor sites.	Sensing, bioimaging, pathogen capture
S-doping	Sulfur incorporation	Increases surface polarity, local lattice defects, and electrochemical activity.	Pesticide sensing, metal ion coordination
B-doping	Boron incorporation	Introduces electron-deficient sites; shifts HOMO/LUMO levels.	Optoelectronic and fluorescent sensing
P-doping	Phosphorus incorporation	Alters electronic band gaps, surface reactivity, and compatibility.	Fluorescent pesticide sensing
Co-doping	Two heteroatoms (N,S or N,P)	Synergistic charge redistribution; creates highly active specific binding pockets.	Advanced ratiometric and dual-mode sensing
Covalent	EDC/NHS coupling (antibodies/aptamers)	Establishes highly stable, specific bio-recognition sites.	Toxins, foodborne pathogens, and residues
Non-covalent	pi-pi stacking / electrostatics	Preserves pristine optical/conductive properties of carbon core.	Metallic nanoparticle hybrids (AgNPs/AuNPs)

Characterization Techniques for Sensing Verification

Following synthesis and functionalization, comprehensive characterization of GQDs is essential to establish reliable structure-property relationships. Due to their nanoscale dimensions and complex emissive pathways, a multi-technique characterization approach is required to verify morphological, chemical, optical, and electrochemical features (Balkanloo *et al*., 2023 [15]; Rabeya *et al*., 2022). Structural and morphological properties are commonly analyzed using Transmission Electron Microscopy (TEM/HR-TEM) to measure core lateral size and lattice fringes, which confirm graphitic crystallinity, and Atomic Force Microscopy (AFM) to measure topographic height/thickness and distinguish single-layer from few-layer structures. Dynamic Light Scattering (DLS) is employed to evaluate hydrodynamic size distribution and colloidal stability in aqueous food matrices, while X-ray Photoelectron Spectroscopy (XPS) determines precise elemental composition, oxidation states, and heteroatom bonding configurations (Mousavi *et al*., 2022).

Fourier-Transform Infrared Spectroscopy (FTIR) identifies specific functional groups supporting target binding, while Raman spectroscopy and X-ray Diffraction (XRD) assess graphitic structural order (via the ID/IG ratio) and crystalline interlayer spacing, respectively (Choppadandi *et al*., 2021) [24]. Finally, UV-Vis and Photoluminescence (PL) spectroscopy reveal electronic transitions and photoluminescence quantum yields, while Time-Correlated Single-Photon Counting (TCSPC) studies excited-state dynamics, and Cyclic Voltammetry (CV) or Electrochemical Impedance Spectroscopy (EIS) evaluates modified electrode charge-transfer kinetics (Balkanloo *et al*., 2023) [15]. Key techniques are summarized in Table 7.

Table 7: Common Characterization Techniques Used for Graphene Quantum Dots and Sensing Relevance.

Category	Technique	Key Information Obtained & Sensing Relevance	Reference
Structural	TEM / HR-TEM	Measures core lateral size and shape; lattice fringes confirm core graphitic crystallinity.	Mousavi *et al*., 2022 [66]
Structural	AFM	Measures topographic height/thickness; distinguishes single-layer from few-layer structures.	Rabeya *et al*., 2022 [66]
Structural	DLS	Measures hydrodynamic size and colloidal size distribution in aqueous media.	Balkanloo *et al*., 2023 [15]
Chemical	XPS	Determines precise elemental composition, oxidation states, and heteroatom bonding states.	Balkanloo *et al*., 2023 [15]
Chemical	FTIR	Identifies specific surface functional groups (–COOH, –OH, $–NH_2$) supporting target binding.	Mousavi *et al*., 2022 [66]
Chemical	Raman / XRD	Assess graphitic structural order (ID/IG ratio) and crystalline interlayer spacing.	Choppadandi *et al*., 2021 [24]
Optical	UV-Vis / PL	Reveals electronic transitions, absorption peaks, emission wavelengths, and PL quantum yield.	Rabeya *et al*., 2022 [66]
Electrochemical	CV / EIS	Evaluates interfacial electron-transfer kinetics and modified electrode resistance.	Balkanloo *et al*., 2023 [15]

GQD-Based Nanosensing Applications in Food Safety

Graphene quantum dots (GQDs) have emerged as highly promising nanomaterials for food safety applications due to their exceptional photoluminescence properties, tunable surface chemistry, high aqueous dispersibility, low toxicity, excellent biocompatibility, and ease of functionalization (Anjusha *et al*., 2024) [11]. Compared with conventional nanomaterials and sensing probes, GQDs offer significant advantages including high sensitivity, rapid signal response, strong fluorescence stability, and compatibility with biomolecular recognition systems (Jia *et al*., 2023) [36]. These properties have enabled the development of next-generation fluorescence, electrochemical, ratiometric, and dual-mode sensing platforms for detecting a wide variety of food contaminants.

GQD nanosensors operate across diverse optical and electrochemical mechanisms. In fluorescence-based systems, sensing typically relies on Förster Resonance Energy Transfer (FRET), Photoinduced Electron Transfer (PET), or Inner Filter Effect (IFE), which generally produce signal quenching (Turn-OFF). Conversely, target recognition by aptamers or molecularly imprinted polymers can restore fluorescence (Turn-ON) or cause a ratiometric color shift. Surface-Enhanced Raman Spectroscopy (SERS) relies on enhanced Raman scattering from GQD–gold/silver nanoparticle hybrids, while electrochemical systems detect changes in cyclic voltammetry (CV) currents or interfacial impedance (EIS) on modified working electrodes (Anjusha *et al*., 2024; Savas & Gharibzahedi, 2025) [11, 59].

1. Detection of Pesticide Residues

Pesticide contamination is a significant concern in fruits, vegetables, cereals, and dairy products associated with agricultural runoff. GQD-based nanosensors have been designed for organophosphates, carbamates, and organochlorines, including chlorpyrifos, malathion, dimethoate, profenofos, and carbaryl (Wang *et al*., 2023) [60]. Detection mechanisms frequently operate via acetylcholinesterase (AChE) enzyme inhibition. In these formats, AChE hydrolyzes acetylthiocholine to produce thiocholine, which can quench GQD fluorescence or modulate electrochemical currents. When organophosphate pesticides are introduced, they inhibit AChE, reducing thiocholine production and restoring GQD fluorescence (Mahajan & Patil, 2022) [50]. For example, N-doped GQDs integrated with an AChE inhibition assay achieved a malathion detection limit of 0.02 ng/mL in apples and tomatoes (Mahajan & Patil, 2022) [50], while N,S-co-doped GQDs modified on electrodes facilitated electrochemical detection of chlorpyrifos down to 0.01 ng/mL in grapes and strawberries (Ahmed & Hassan, 2023) [6].

2. Detection of Antibiotic and Veterinary Drug Residues

The widespread misuse of antibiotics in livestock production and poultry farming has resulted in residue accumulation in milk, meat, eggs, and environmental wastewater, accelerating selection pressure for antimicrobial resistance (AMR) under a One Health framework (Habiba *et al*., 2023) [31]. Tetracyclines (such as doxycycline, oxytetracycline) and beta-lactams (such as amoxicillin, penicillin) are among the most commonly abused drug classes (Goswami *et al*., 2023) [29]. GQD surfaces engineered with specific DNA aptamers or molecularly imprinted polymers (MIPs) enable highly selective antibiotic detection. For instance, N-doped GQDs coupled with MIPs (N-GQDs-MIP) demonstrated fluorescence turn-off detection of tetracyclines in milk and honey with a limit of detection of 0.003 µM (Li *et al*., 2025). GQD-gold nanoparticle (GQD-AuNP) composites utilizing Surface-Enhanced Raman Spectroscopy (SERS) achieved an ultra-sensitive detection limit of 0.001 µM for amoxicillin in dairy products (Wang & Liu, 2025) [22].

3. Detection of Toxic Metal Ions

Heavy metal contamination (including Hg^{2+}, Pb^{2+}, Cd^{2+}, As^{3+}, Cr^{6+}) in seafood, rice, and water represents a severe public health threat due to their high toxicity, persistence, and bioaccumulation potential (Zhao *et al*., 2024). GQDs are highly effective for metal-ion sensing due to the abundance of oxygen-containing surface functional groups (such as carboxyl and hydroxyl groups) that promote coordination interactions and surface charge-induced fluorescence quenching (Xiong *et al*., 2022) [66]. Glutathione-functionalized GQDs achieved a detection limit of 0.02 ppb for Mercury (Hg^{2+}) in fish and water samples via specific metal-ligand coordination (Kumar *et al*., 2024) [42]. EDTA-functionalized GQDs demonstrated turn-on fluorescence detection of Lead (Pb^{2+}) and Cadmium (Cd^{2+}) in rice and seafood down to 0.05 ppb (Patel *et al*., 2024) [26].

4. Detection of Foodborne Pathogens and Mycotoxins

Foodborne pathogens (such as E. coli O157:H7, Salmonella spp., S. aureus) and toxic secondary fungal metabolites (such as aflatoxins, ochratoxin A, fumonisins) require highly sensitive and rapid surveillance tools. Functionalization of GQDs with specific antibodies or aptamers enables rapid cell and toxin capture. For example, aptamer-functionalized GQDs integrated with an artificial intelligence array demonstrated Salmonella detection down to 35.6 CFU/mL in milk (Kumaragurubaran *et al*., 2023), while a MXene@GQDs hybrid array discriminated six foodborne pathogens within 3 minutes with 100% identification accuracy (Zhang *et al*., 2026) [9]. Antibody-conjugated GQDs utilizing FRET-based immunoassay achieved a sub-picogram detection limit of 0.01 ng/mL for Aflatoxin B1 in corn and peanut matrices (Li *et al*., 2023).

5. Food Authenticity, Adulteration, and Quality Indicators

GQD platforms have been successfully deployed to detect food fraud and spoilage-related chemical changes. This includes detecting melamine and urea in milk powder (Chen *et al*., 2023) [21], vegetable oil adulteration in olive oil and ghee (Sharma & Gupta, 2024) [42], and microplastics (PS, PE, PET) in bottled water (Wang *et al*., 2024) [62]. Furthermore, quality indicators such as biogenic amines (histamine, cadaverine, putrescine) generated during protein food spoilage are rapidly monitored through GQD fluorescence quenching or aggregation-induced emission, enabling precise shelf-life assessment (Jia *et al*., 2023) [36]. Selected nanosensors and their analytical parameters are compiled in Table 8.

Table 8: Analytical Performance Matrix of GQD-Based Nanosensors for Key Food Contaminants.

Target Contaminant	Food Sample Matrix	GQD Nanosensor Format	Limit of Detection (LOD)	Reference
Malathion & Paraoxon	Apple, Tomato, Tea	N-GQDs / AChE inhibition assay	0.02 ng/mL	Mahajan & Patil, 2022 [50]
Carbaryl (Carbamate)	Rice, Wheat, Veg.	S-GQDs / FRET aptasensor	0.15 ng/mL	Kurniawan *et al*., 2022 [44]
Chlorpyrifos	Grapes, Strawberries	N, S-doped GQDs / Electrochemical	0.01 ng/mL	Ahmed & Hassan, 2023 [6]
Chlorpyrifos	Spinach, Lettuce	N-GQDs-AuNPs / AChE electrochemical	0.005 ng/mL	Zhang *et al*., 2025 [67]
Profenofos	Apple, Grapes	N, S-doped GQDs / Electrochemical	0.004 ng/mL	Ahmed & Hassan, 2025

		(EIS)		[7]
Tetracyclines	Milk, Honey	N-GQDs-MIP / Fluorescence turn-off	0.003 uM	Li *et al*., 2025 [5]
Tetracyclines	Milk, Cheese	GQDs-AuNPs / SERS sensor	0.001 uM	Wang *et al*., 2025 [22]
Amoxicillin (beta-lactam)	Milk, Meat	Aptamer-GQDs / Turn-off	0.004 uM	Goswami *et al*., 2025 [30]
Amoxicillin (beta-lactam)	Milk, Cheese	GQDs-AgNPs / SERS sensor	0.001 uM	Wang & Liu, 2025 [22]
Mercury (Hg^{2+})	Fish, Water	Glutathione-GQDs / Quenching	0.02 ppb	Kumar *et al*., 2024 [42]
Lead (Pb^{2+}), Cd^{2+}	Rice, Seafood	EDTA-GQDs / Turn-on fluorescence	0.05 ppb	Patel *et al*., 2024
Aflatoxin B1 (AFB1)	Corn, Peanuts	Antibody-conjugated GQDs / FRET	0.01 ng/mL	Li *et al*., 2023
Ochratoxin A (OTA)	Coffee, Grains	Aptamer-GQDs / Electrochemical (EIS)	0.05 ng/mL	Li *et al*., 2023
Melamine	Milk Powder	SERS-active GQDs / Raman	0.005 uM	Chen *et al*., 2023 [21]
Microplastics (PS, PE)	Bottled Water	Hydrophobic GQDs / Quenching	0.5 ug/L	Wang *et al*., 2024 [62]

Emerging Practical Platforms and Future Outlook

1. Active and Intelligent Food Packaging Systems

An emerging and highly innovative application of GQDs is their incorporation into active and intelligent food packaging systems. Due to their highly responsive fluorescence, inherent antioxidant activity, and antimicrobial properties, GQDs can be successfully embedded into starch, gelatin, or synthetic polymer bio-films to create packaging materials that monitor food freshness in real time (Bakeshlouy *et al*., 2024) [14]. These systems act as non-destructive freshness indicators, visual leak detectors, oxygen-sensitive films, and time-temperature indicators (TTIs), which undergo a dramatic, visible fluorescence color change upon contact with volatile biogenic amines (such as histamine or cadaverine) generated during protein food spoilage. This enables real-time monitoring of meat and seafood spoilage directly inside the package without opening it, thereby reducing food waste and improving consumer safety (Bakeshlouy *et al*., 2024) [14].

2. Smartphone-Based and Point-of-Care Testing (POCT)

For practical, field-based food safety monitoring, there is substantial research interest in portable, user-friendly, and field-deployable point-of-care testing (POCT) platforms. GQDs are uniquely suited for POCT because their fluorescent signals can be easily visualized under portable, low-cost handheld UV lamps and quantitatively analyzed using smartphone cameras and customized colorimetric applications (Savas *et al*., 2025) [59]. When a contaminant is present, the glow changes from yellow-green to blue, or undergoes a FRET-induced quenching. By capturing a photo with a smartphone camera, a custom-designed app can read the blue (B) and green (G) color values. The B/G ratio compares the two colors, which dramatically reduces environmental and lighting errors (ratiometric sensing), delivering accurate results in under 5 minutes without requiring laboratory instrumentation (Savas *et al*., 2025) [59]. Recent advancements have successfully delivered paper-based GQD sensor strips, portable pesticide testing cards, and smartphone-assisted microfluidic kits that enable rapid, on-site screening of raw milk, river water, and crops (Savas *et al*., 2025) [59].

3. Critical Research Challenges and Roadblocks

Despite their extraordinary promise, several critical challenges and research gaps must be resolved before practical industrial translation can be achieved (Sharma *et al*., 2021; Hashim *et al*., 2022) [32]. First, the lack of reproducibility in synthesis represents a major roadblock.

Slight variations in hydrothermal heating rates, precursors, or oxidation durations can lead to significant batch-to-batch variations in GQD size, edge structures, and photoluminescence quantum yields, hindering commercial standardization (Jing *et al*., 2025) [37]. Second, signal interference remains an issue. Real food matrices contain fats, proteins, carbohydrates, and natural pigments that cause auto-fluorescence or non-specific quenching, reducing overall sensor selectivity (Sharma *et al*., 2021). Third, long-term colloidal and optical stability, comprehensive *in vivo* toxicity profiles, and a lack of large-scale validation in commercial food supply chains remain unresolved (Sharma *et al*., 2021). Future research must focus on establishing standardized, automated synthesis protocols, utilizing AI-driven machine-learning algorithms to deconvolve multi-contaminant signals, and integrating GQD-POCT devices with IoT-enabled supply chain tracking systems (Hashim *et al*., 2022) [32].

Conclusion

Overall, Graphene Quantum Dots (GQDs) have demonstrated extraordinary versatility and functionality in food safety applications. Unlike conventional sensing materials, GQDs can operate across multiple sensing mechanisms including fluorescence-based, electrochemical, SERS, ratiometric, and portable point-of-care devices (Ren *et al*., 2025; Savas *et al*., 2025) [53, 59]. Their tunable optical properties, ease of functionalization, compatibility with biomolecular recognition elements, low toxicity, and suitability for low-cost, green fabrication strongly support their future role in advanced food diagnostics and intelligent packaging technologies. While critical challenges relating to synthetic reproducibility and matrix interference must still be addressed, continued progress in green synthesis routes and smartphone-assisted readouts is expected to accelerate their transition from laboratory research to commercial food industry applications, ensuring global supply chain safety and public health protection.

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