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Wood-derived carbon quantum dots for food sensing applications

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Abstract

Carbon quantum dots (CQDs) have emerged as a prominent class of carbon-based nanomaterials owing to their remarkable photoluminescence, chemical stability, low toxicity, and tunable surface chemistry. In recent years, increasing emphasis has been placed on the sustainable synthesis of CQDs from renewable biomass resources, particularly wood and wood-derived wastes. Wood-derived carbon quantum dots (W-CQDs) combine the intrinsic advantages of biomass precursors—abundance, low cost, and environmental friendliness—with excellent optical and sensing properties. These features make W-CQDs especially attractive for applications in food safety and quality monitoring, where rapid, sensitive, and portable analytical tools are urgently needed. This review provides a comprehensive overview of the synthesis, physicochemical properties, photoluminescence mechanisms, and sensing behaviors of W-CQDs, with a particular focus on their application as fluorescent sensors for food additives, nutrients, heavy metals, pesticides, and spoilage indicators. Detailed discussions are provided on synthesis strategies, surface functionalization, structure–property relationships, and fluorescence sensing mechanisms. Challenges related to reproducibility, selectivity, toxicity, and commercialization are critically analyzed, and future research directions are proposed. This article aims to serve as a detailed reference for researchers in nanomaterials, food science, and analytical chemistry.

Keywords: Carbon quantum dots (CQDs), wood-derived carbon quantum dots (W-CQDS), biomass-based nanomaterials, sustainable synthesis

Introduction

Food safety and quality assurance have become critical global issues due to population growth, industrialization, and the globalization of food supply chains. Modern food systems are increasingly complex, involving long transportation routes, extended storage times, and extensive use of additives and preservatives. As a result, food products are vulnerable to contamination by chemical additives, pesticide residues, heavy metals, and microbial spoilage byproducts, which can pose serious health risks to consumers. Conventional analytical methods such as high-performance liquid chromatography (HPLC), gas chromatography–mass spectrometry (GC–MS), inductively coupled plasma mass spectrometry (ICP–MS), and atomic absorption spectroscopy (AAS) are widely used for food analysis due to their high accuracy and reliability. However, these techniques often require expensive instrumentation, skilled personnel, and labor-intensive sample preparation, making them unsuitable for rapid, on-site, or real-time monitoring [1, 2].

In this context, nanomaterial-based sensors have gained increasing attention as promising alternatives for food analysis. Among various nanomaterials, carbon quantum dots (CQDs) stand out due to their unique optical properties, excellent water solubility, resistance to photobleaching, and favorable biocompatibility [2, 3]. CQDs are zero-dimensional carbon nanomaterials with sizes typically below 10 nm and exhibit strong and tunable photoluminescence. Unlike traditional semiconductor quantum dots containing toxic heavy metals, CQDs are composed primarily of carbon, making them environmentally benign and suitable for applications involving food and biological systems [3]. An important recent trend in CQD research is the development of sustainable synthesis routes using renewable biomass precursors. Biomass-derived CQDs not only reduce reliance on fossil-based carbon sources but also contribute to waste valorization and circular economy strategies [6]. Among various biomass resources, wood represents one of the most abundant and renewable lignocellulosic materials on Earth. Wood and wood-processing wastes such as sawdust, bark, and lignin-rich residues are inexpensive, widely available, and rich in carbon content, making them ideal precursors for CQD synthesis [8, 9]. Wood-derived carbon quantum dots (W-CQDs) have demonstrated excellent fluorescence properties and high sensitivity toward various food-related analytes. This review aims to provide a comprehensive and in-depth analysis of W-CQDs and their applications in food sensing. The article systematically discusses the fundamentals of CQDs, the advantages of wood as a precursor, synthesis strategies, optical and sensing mechanisms, and representative applications in food safety and quality monitoring. Key challenges and future perspectives are also highlighted.

Fundamentals of Carbon Quantum Dots

1. Definition and Classification

Carbon quantum dots are quasi-spherical, zero-dimensional nanomaterials with diameters generally ranging from 2 to 10 nm. They consist primarily of carbon atoms arranged in a combination of sp2- and sp3-hybridized domains. Depending on their structure and synthesis route, carbon-based fluorescent nanodots are often classified into carbon quantum dots (CQDs), graphene quantum dots (GQDs), and carbon nanodots (CNDs). CQDs typically possess a crystalline or semi-crystalline carbon core, whereas CNDs are more amorphous in nature [3]. In practice, the term “CQDs” is frequently used as a broad designation encompassing various types of fluorescent carbon nanodots.

2. Structural Characteristics

The internal structure of CQDs usually consists of small graphitic domains embedded within an amorphous carbon matrix. High-resolution transmission electron microscopy (HRTEM) often reveals lattice fringes with interplanar spacings corresponding to graphitic carbon, while X-ray diffraction (XRD) patterns show broad diffraction peaks indicative of nanoscale carbon structures [4]. The surface of CQDs is rich in functional groups such as hydroxyl (–OH), carboxyl (–COOH), carbonyl (C=O), and amino (–NH2) groups, particularly for biomass-derived CQDs [6]. These surface functionalities play a crucial role in determining water solubility, chemical reactivity, and sensing behavior.

3. Optical Properties and Photoluminescence Mechanisms

One of the most distinctive features of CQDs is their strong photoluminescence (PL), which can be excited by ultraviolet or visible light. CQDs often exhibit excitation-dependent emission behavior, where the emission wavelength shifts with changing excitation wavelength. Several mechanisms have been proposed to explain CQD photoluminescence, including quantum confinement effects, surface state emission, and molecular fluorophore-related emission [4, 9]. Among these, surface state emission is widely accepted as the dominant mechanism for biomass-derived CQDs, as their rich surface chemistry creates multiple emissive traps. CQDs also exhibit excellent photostability and resistance to photobleaching, which are essential for long-term sensing applications. Their fluorescence intensity remains stable under prolonged illumination, making them suitable for repeated or continuous measurements in food analysis [2].

4. Biocompatibility and Environmental Safety

Compared with conventional semiconductor quantum dots containing cadmium or lead, CQDs exhibit significantly lower toxicity. Numerous studies have demonstrated low cytotoxicity and minimal environmental impact of CQDs at concentrations relevant for sensing applications [7]. These characteristics make CQDs particularly attractive for applications in food systems, where safety considerations are paramount.

Wood as a Sustainable Precursor for Carbon Quantum Dots

1. Chemical Composition of Wood Biomass

Wood is a natural composite material composed primarily of cellulose (40–50%), hemicellulose (20–30%), and lignin (20–30%), along with small amounts of extractives and inorganic minerals. Cellulose and hemicellulose are polysaccharides rich in hydroxyl groups, while lignin is an aromatic polymer containing phenylpropane units. The high carbon content and diverse functional groups present in these components make wood an excellent precursor for carbon nanomaterial synthesis [6, 8].

2. Advantages of Wood-Derived Precursors

The use of wood as a CQD precursor offers several advantages. First, wood is abundant, renewable, and widely available worldwide. Second, wood-processing industries generate large quantities of waste materials that are often underutilized or discarded. Converting these wastes into high-value CQDs adds economic value and reduces environmental burden [8]. Third, wood-derived CQDs inherently possess oxygen-rich surface functional groups, which enhance water solubility and facilitate interactions with analytes in sensing applications.

3. Sustainability and Green Chemistry Considerations

Wood-based CQD synthesis aligns well with the principles of green chemistry, including the use of renewable feedstocks, reduction of hazardous reagents, and energy-efficient processes. Many reported methods employ water as a solvent and avoid strong acids or toxic chemicals, making the process environmentally benign and scalable [6].

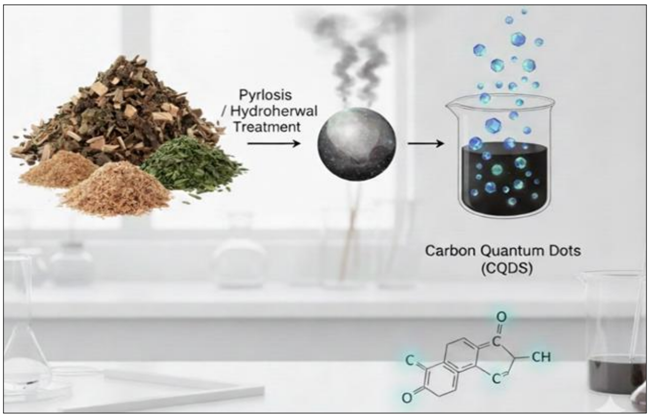

Fig 1: Wood biomass as carbon precursors for CQDs [4-8]

Synthesis Strategies for Wood-Derived Carbon Quantum Dots

1. Bottom-Up Synthesis Methods

Bottom-up synthesis involves the carbonization of small organic molecules or biomass precursors under controlled conditions. Hydrothermal and solvothermal methods are the most widely used approaches for synthesizing W-CQDs. In a typical hydrothermal process, wood powder, sawdust, or lignin is dispersed in water and heated in a sealed autoclave at temperatures between 180 and 250 °C. Under these conditions, dehydration, polymerization, aromatization, and carbonization reactions occur, leading to the formation of nanoscale carbon dots [8, 9]. Reaction parameters such as temperature, time, pH, and precursor concentration strongly influence the size, surface chemistry, and quantum yield of the resulting CQDs. Higher temperatures generally promote graphitization and increase fluorescence intensity, while longer reaction times may lead to aggregation or reduced yield.

2. Top-Down Synthesis Methods

Top-down approaches involve breaking down bulk carbon materials into nanoscale dots. Techniques such as chemical oxidation, laser ablation, and electrochemical exfoliation have been explored. For wood-derived materials, top-down methods are typically applied to carbonized wood or biochar. Chemical oxidation using strong acids can produce CQDs with high oxygen content, although environmental and safety concerns limit their large-scale application [3].

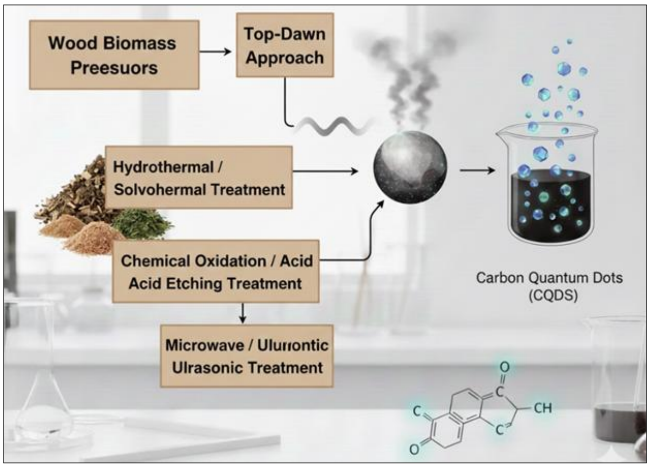

Fig 2: Synthesis strategies for wood-derived carbon quantum dots [5-9]

3. Heteroatom Doping and Surface Functionalization

Heteroatom doping and surface functionalization are among the most powerful strategies for tailoring the physicochemical properties of wood-derived carbon quantum dots (W-CQDs) toward high-performance food sensing applications. Owing to the intrinsic chemical heterogeneity of lignocellulosic biomass, pristine W-CQDs inherently possess abundant oxygen-containing functional groups such as hydroxyl (–OH), carboxyl (–COOH), carbonyl (–C=O), and ether (–C–O–C) moieties. These surface functionalities originate mainly from cellulose, hemicellulose, and lignin components and provide a chemically active interface for further modification and analyte interaction [6, 9]. Among various doping strategies, nitrogen doping has been most extensively investigated due to its pronounced effect on electronic structure and photoluminescence behavior. Nitrogen atoms can be incorporated into the carbon framework in several bonding configurations, including pyridinic N, pyrrolic N, and graphitic N. Pyridinic and pyrrolic nitrogen species are typically associated with edge defects and surface states, which introduce localized energy levels within the bandgap and act as emissive centers. Graphitic nitrogen, in contrast, substitutes carbon atoms within the sp^2 lattice and enhances electron delocalization, thereby improving electrical conductivity and charge transfer efficiency [3, 4]. In wood-derived systems, nitrogen doping is commonly achieved through hydrothermal or solvothermal treatment in the presence of nitrogen-rich precursors such as urea, ethylenediamine, ammonia, or amino acids. Numerous studies have demonstrated that N-doped W-CQDs exhibit significantly higher quantum yields and stronger fluorescence intensity compared to undoped counterparts. More importantly, nitrogen doping enhances the affinity of W-CQDs toward electron-deficient analytes, including transition metal ions and nitrite species, leading to improved sensitivity and lower detection limits in food sensing applications [9, 12]. Beyond nitrogen, sulfur and phosphorus doping have emerged as effective approaches to further tune the sensing performance of W-CQDs. Sulfur doping introduces thiol, sulfoxide, or sulfonate groups onto the CQD surface, which act as soft Lewis base sites and show strong coordination affinity toward soft metal ions such as Hg^{2+} and Ag^+. This property is particularly advantageous for detecting trace levels of mercury contamination in seafood and aquatic products [6, 9]. Phosphorus doping, on the other hand, modifies surface charge distribution and electron density, facilitating photoinduced electron transfer (PET) processes and enhancing fluorescence response toward redox-active analytes. Co-doping strategies, especially N, S- and N, P-co-doping, have attracted increasing interest due to synergistic effects that cannot be achieved by single-element doping alone. Co-doped W-CQDs often display broader excitation-dependent emission ranges, higher photoluminescence stability, and improved selectivity for specific food contaminants. These advantages arise from the combined modulation of surface states, band structure, and interfacial charge transfer pathways [6]. Surface functionalization provides an additional level of control over analyte recognition and sensor selectivity. Post-synthetic modification techniques, such as covalent grafting or noncovalent adsorption of functional molecules, enable the introduction of specific recognition elements onto the CQD surface. Functionalization with polymers, chelating agents, enzymes, or biomolecules has been shown to significantly reduce matrix interference from proteins, fats, and carbohydrates commonly present in food samples. As a result, functionalized W-CQDs demonstrate improved analytical accuracy and robustness in real food matrices compared with bare CQDs [10].

Optical and Sensing Mechanisms of Wood-Derived Carbon Quantum Dots

The sensing performance of wood-derived carbon quantum dots is fundamentally governed by their optical properties, particularly photoluminescence (PL) behavior. Unlike traditional semiconductor quantum dots, where emission is primarily dictated by size-dependent quantum confinement, the PL of W-CQDs is dominated by surface states associated with functional groups, defects, and heteroatom dopants. This surface-state-driven emission mechanism renders W-CQDs highly sensitive to their chemical environment, making them exceptionally suitable for fluorescence-based sensing applications [4, 6]. A characteristic feature of W-CQDs is excitation-dependent emission, whereby the emission peak shifts to longer wavelengths as the excitation wavelength increases. This phenomenon is generally attributed to the presence of multiple emissive traps with different energy levels on the CQD surface. From a sensing perspective, excitation-dependent emission offers practical advantages, including flexible excitation strategies and the possibility of ratiometric or multichannel detection in complex food systems. Fluorescence quenching is the most widely exploited sensing mechanism in W-CQD-based food sensors. Quenching processes can be broadly classified into static quenching, dynamic (collisional) quenching, photoinduced electron transfer (PET), Förster resonance energy transfer (FRET), and the inner filter effect (IFE). In many reported systems, PET is the dominant mechanism, particularly for the detection of metal ions and oxidizing species. When an analyte with suitable redox potential interacts with the surface of W-CQDs, electrons can be transferred from the excited CQD to the analyte, resulting in nonradiative recombination and fluorescence suppression [9, 12]. Metal ions such as Fe^{3+}, Cu^{2+}, and Hg^{2+} are among the most frequently targeted analytes in food safety monitoring. These ions exhibit strong coordination with oxygen- and nitrogen-containing functional groups on the CQD surface, which facilitates efficient PET and leads to pronounced fluorescence quenching. The relationship between quencher concentration and fluorescence intensity is commonly described by the Stern–Volmer equation. Linear Stern–

Volmer behavior suggests a single dominant quenching pathway, whereas nonlinear behavior indicates the coexistence of multiple mechanisms, such as combined static and dynamic quenching. The inner filter effect represents another important sensing mechanism, particularly for colored food additives and dyes. IFE occurs when the absorption spectrum of an analyte overlaps with the excitation or emission spectrum of the CQDs, resulting in an apparent decrease in fluorescence intensity without direct interaction between the CQD and analyte. This mechanism has been widely applied for detecting synthetic food colorants such as tartrazine and sunset yellow in beverages and confectionery products [11]. In contrast to quenching-based sensors, fluorescence enhancement or “turn-on” sensing strategies have gained increasing attention due to their higher signal-to-noise ratios. In W-CQDs, turn-on responses may arise from passivation of surface defects, suppression of nonradiative recombination pathways, or disruption of aggregation-induced quenching upon analyte binding. Antioxidants, polyphenols, and certain vitamins can act as reducing agents or surface passivators, leading to fluorescence enhancement and enabling sensitive detection in food samples [10, 11]. Overall, the rich surface chemistry and tunable optical properties of wood-derived carbon quantum dots enable multiple sensing mechanisms to coexist within a single system. Understanding and controlling these mechanisms is essential for rational sensor design, accurate quantification, and reliable application in real food matrices.

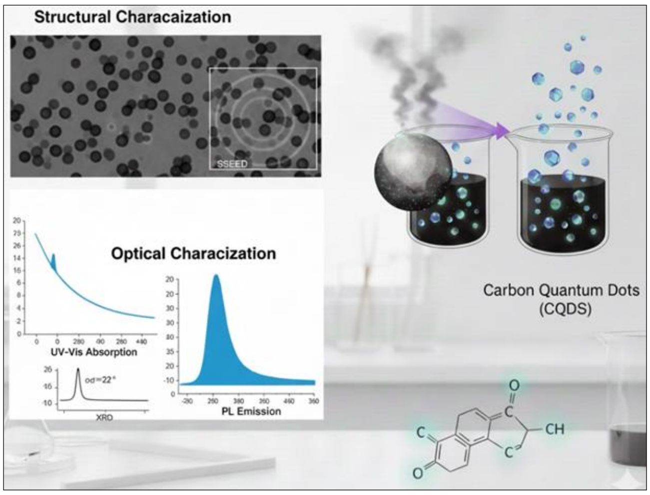

Fig 3: Structural and optical characterization of wood-derived CQDs [9-11]

Applications of Wood-Derived Carbon Quantum Dots in Food Safety and Quality Monitoring

Wood-derived carbon quantum dots have been extensively explored for food-related sensing applications due to their strong fluorescence, tunable surface chemistry, low toxicity, and sustainable origin. Their applicability spans multiple domains of food safety and quality control, including the detection of additives, nutrients, heavy metals, pesticide residues, and food spoilage indicators. One of the most widely reported applications of W-CQDs is the detection of food additives, particularly nitrites and sulfites. Nitrites are commonly used as preservatives in processed meat products but can form carcinogenic nitrosamines when present in excessive amounts. W-CQD-based fluorescent sensors enable sensitive and rapid nitrite detection, typically through fluorescence quenching mechanisms involving oxidation reactions or photoinduced electron transfer. Detection limits reported in the literature are often well below regulatory limits, demonstrating the suitability of W-CQDs for practical food monitoring [11]. Synthetic food colorants, such as tartrazine, sunset yellow, and allura red, represent another important class of analytes. These dyes exhibit strong absorption bands that overlap with the excitation or emission spectra of CQDs, making the inner filter effect a dominant sensing mechanism. W-CQDs have been successfully applied to quantify these additives in beverages, candies, and dairy products with high selectivity and minimal sample pretreatment [11]. In addition to additives, W-CQDs have shown considerable promise in the detection of nutrients and bioactive compounds. Lignin-derived CQDs, in particular, possess aromatic structures that facilitate π–π interactions and hydrogen bonding with phenolic compounds. This property has been exploited for the detection of polyphenols, flavonoids, and antioxidants in food matrices such as tea, wine, and fruit juices. Fluorescence enhancement or quenching responses enable quantitative analysis of antioxidant capacity and nutritional quality [10]. Heavy metal contamination remains one of the most critical food safety issues worldwide. Toxic metal ions such as Pb^{2+}, Hg^{2+}, Cd^{2+}, and As^{3+} can enter the food chain through contaminated water, soil, and agricultural practices. Due to the abundance of oxygen-, nitrogen-, and sulfur-containing functional groups on their surface, W-CQDs exhibit strong chelation ability toward metal ions. Numerous studies have reported nanomolar-level detection limits for heavy metals using W-CQD-based sensors, with good agreement between laboratory results and real food sample analysis [9, 12]. Emerging applications of W-CQDs include pesticide residue detection and food spoilage monitoring. Functionalized W-CQDs have been employed to detect organophosphorus and carbamate pesticides through enzyme-assisted sensing or direct interaction mechanisms. Although this research area is still in its early stages, preliminary results indicate that W-CQDs can serve as low-cost and portable alternatives to conventional chromatographic techniques. Food spoilage monitoring represents one of the most promising directions for practical deployment. During spoilage, volatile amines and organic acids are generated, leading to changes in pH and chemical composition. W-CQDs incorporated into polymer films or hydrogels can respond to these changes through fluorescence variation or visible color shifts, enabling real-time freshness indicators for meat, fish, and seafood products [12-14].

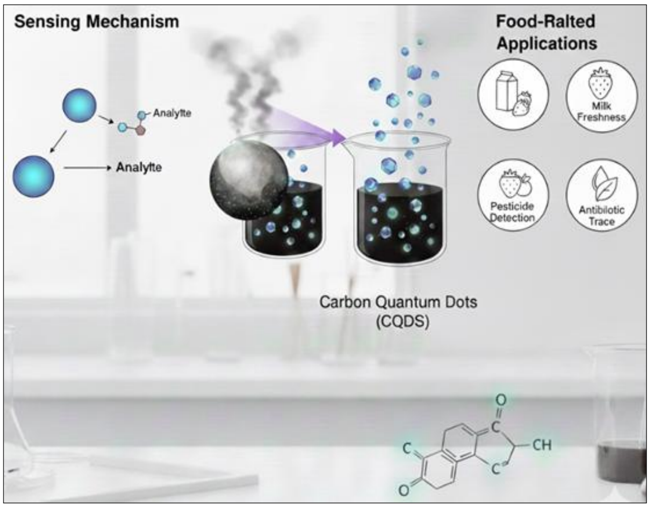

Fig 4: Optical sensing mechanisms and food-related applications [9-13]

Integration of W-CQDs into Practical Sensor Platforms

For real-world implementation, W-CQDs must be integrated into robust, user-friendly sensing platforms. While solution-based fluorescent probes remain valuable for laboratory analysis, solid-state and portable sensor formats are increasingly favored for on-site food monitoring.

Paper-based sensors are among the most attractive platforms due to their low cost, ease of fabrication, and disposability. W-CQDs can be readily immobilized onto cellulose-based substrates through physical adsorption or chemical bonding, forming fluorescent test strips that respond rapidly to target analytes. These sensors are particularly suitable for point-of-care applications and field testing [13]. Polymer-based composites and hydrogel systems offer additional advantages, including mechanical stability and compatibility with food packaging materials. Embedding W-CQDs into polymer matrices enables the fabrication of intelligent packaging systems capable of continuous freshness monitoring. Furthermore, integration with smartphone-based fluorescence detection systems allows quantitative analysis through image processing, significantly enhancing accessibility and practicality.

Toxicity, Safety, and Regulatory Considerations

Although wood-derived carbon quantum dots are generally considered low-toxicity materials, comprehensive safety evaluation is essential for food-related applications. Most *in vitro* cytotoxicity studies report minimal adverse effects of W-CQDs on mammalian cells at concentrations relevant for sensing. Their favorable biocompatibility is largely attributed to the absence of heavy metals and the use of renewable biomass precursors [7]. However, several safety concerns remain insufficiently addressed. Long-term exposure effects, bioaccumulation behavior, and interactions with biological systems require further investigation. When W-CQDs are incorporated into food packaging materials, the potential migration of nanoparticles into food products under various storage conditions must be carefully assessed. From a regulatory perspective, commercialization of W-CQD-based sensors will require compliance with food contact material regulations established by authorities such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA). Standardized synthesis protocols, reproducible material properties, and robust toxicological data will be critical for regulatory approval.

Challenges and Future Perspectives

Despite substantial progress, several challenges hinder the large-scale adoption of wood-derived carbon quantum dots in food sensing applications. One major challenge is the reproducibility of W-CQD synthesis. Variations in wood species, biomass composition, and processing conditions often lead to significant batch-to-batch variability in optical and sensing performance. Developing standardized and scalable synthesis methods remains a key research priority. Another critical challenge lies in the incomplete understanding of photoluminescence mechanisms. Although surface-state emission is widely accepted as the dominant mechanism, the precise roles of specific functional groups, defect structures, and heteroatom dopants remain unclear. Advanced spectroscopic studies and theoretical modeling will be essential to establish structure–property–function relationships. Future research should also focus on multi-analyte sensing platforms capable of simultaneous detection of multiple contaminants in complex food matrices. Integration with digital technologies, such as smartphone readout, machine learning-assisted data analysis, and wireless communication, is expected to further enhance the practicality and impact of W-CQD-based sensors.

Conclusion

Wood-derived carbon quantum dots represent a highly promising class of sustainable nanomaterials for food safety and quality monitoring. Their green synthesis from renewable wood biomass, combined with tunable photoluminescence properties, rich surface chemistry, and favorable biocompatibility, enables diverse sensing applications ranging from additive and heavy metal detection to food freshness monitoring and intelligent packaging. Although challenges remain in terms of synthesis reproducibility, mechanistic understanding, and regulatory approval, continued advances in material design, surface functionalization, and sensor integration are expected to accelerate the practical deployment of W-CQD-based sensors. With sustained interdisciplinary research and standardization efforts, wood-derived carbon quantum dots are poised to play a significant role in next-generation food sensing technologies.

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