Carbon Quantum Dots from Horticultural Waste: Sustainable Nanotechnology for Food Preservation

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Abstract: Losses of highly perishable fruits and vegetables remain a serious worldwide issue and generate large volumes of carbon-rich waste. This review examines how horticultural by-products, such as peels, pomace, seeds, and stems, can be converted into carbon quantum dots (CQDs) using green, bottom-up synthesis approaches, with particular emphasis on hydrothermal techniques. These methods produce small (2-10 nm), water-dispersible, fluorescent, and low-toxicity nanomaterials bearing abundant surface functional groups that confer strong antioxidant and antimicrobial activities. CQDs exert their effects through mechanisms including reactive oxygen species scavenging, inhibition of free radicals, disruption of microbial membranes, and interference with biofilm formation; these properties can be further tailored by heteroatom or metal doping. When incorporated into edible coatings and biopolymer films, CQDs improve UV shielding, barrier properties, and oxidative stability, which in turn suppresses microbial growth, slows quality deterioration, and extends the shelf life of fresh produce. CQDs also support intelligent packaging by serving as fluorescence-based nano-sensors capable of real-time detection of freshness markers, ethylene, gas composition, and contaminants. By relating the physicochemical features of CQDs to their functional performance, this review underscores their potential role in circular bioeconomy strategies that valorise food and horticultural waste. It also outlines key challenges, such as scale-up, standardisation, safety evaluation, and migration behaviour, that must be addressed for their broader adoption in sustainable food packaging.

1. Introduction

Food loss and waste, especially in short-lived fruits and vegetables, seriously threaten global food security and are linked to major economic and environmental impacts. Within the framework of a circular bioeconomy, it is crucial to both valorise horticultural waste streams and develop advanced systems that prolong the freshness of food [1]. Current estimates suggest that close to one-third of all food produced worldwide never reaches consumption, leading to annual financial losses of about USD 750-940 billion and generating considerable greenhouse gas emissions associated with production, transport, and disposal [2]. Perishable commodities, and particularly fresh fruits and vegetables, are disproportionately affected, often experiencing greater postharvest losses than cereals and other staple foods, with the problem being especially acute in low- and middle-income regions [2], [3], [4]. In India, such losses translate into billions of dollars in unrealized value and represent a missed opportunity to reduce pressure on land and water resources while addressing hunger and malnutrition. Moreover, these losses indicate wastage of embedded inputs such as water, energy, labour, and fertilizers, thereby amplifying the environmental footprint of the food supply chain [5].

Against this backdrop, increasing attention is being directed towards converting horticultural residues and food processing by-products into value-added materials as part of circular bioeconomy strategies [6], [7]. Fruit processing wastes such as peels, pomace, and seeds, along with other agro-industrial residues, are rich in carbon and are being explored as sustainable precursors for nanostructured materials. Such valorisation simultaneously reduces waste and recovers resources, while introducing new functional ingredients for food and packaging systems [8].

Among these, carbon quantum dots (CQDs) have emerged as a promising class of nanomaterials that can be synthesized from renewable biomass and food waste. CQDs produced from these waste materials typically display adjustable photoluminescence, a high density of surface functional groups, excellent dispersibility in water, good biocompatibility, and low toxicity. Their antioxidant, antimicrobial, and UV-blocking characteristics make them strong candidates for use in food preservation [9], [10]. As a result, CQDs derived from biomass are increasingly integrated into biopolymer films and edible coatings and are also applied as fluorescent components in intelligent packaging.

Although several reviews have discussed green or biomass-derived CQDs for uses such as environmental remediation, sensing, bioimaging, and energy storage, relatively few have focused specifically on CQDs obtained from horticultural by-products. Moreover, a comprehensive assessment of their application in edible coatings and smart packaging designed for fresh produce is still missing [11], [12]. This review, therefore, concentrates on horticultural waste as a targeted carbon source and surveys CQD-based active and intelligent preservation strategies along the fresh fruit and vegetable supply chain.

2. Horticultural Waste as a Carbon Source

Horticultural residues including peels, pomace, seeds, and stems are carbon-rich materials composed of carbohydrates, lignocellulosic components, proteins, and polyphenols. Together, these constituents provide both carbon and heteroatoms required for CQD synthesis. CQDs generated from such waste generally show tunable photoluminescence, high water solubility, and low cytotoxicity, which makes them promising candidates for food-contact materials and smart packaging systems [8], [13], [14], [15]. Fruit processing residues from crops such as citrus, grape, mango, and banana are particularly appealing as precursors because they are produced in large volumes at centralized facilities, facilitating efficient collection and processing [16], [17].

An important benefit of using horticultural and food waste is that the resulting CQDs naturally carry surface hydroxyl, carboxyl, and amino groups originating from biomass components such as polysaccharides and proteins [18]. These polar groups improve dispersibility in aqueous media, enable straightforward surface passivation, and support favourable interactions with biological systems and polymer matrices, features that are critical for food-contact applications and sensing devices [19]. Many biomass-derived CQDs have particle sizes of about 2-8 nm, emit strong blue or green fluorescence, and exhibit low cytotoxicity in cell-based or *in vitro* tests. Taken together, these properties make them suitable as biocompatible, low-toxicity nanomaterials for bioimaging, environmental monitoring, and emerging food-related uses [20] (Table 1).

Table 1: Horticultural residues used as precursors for CQD synthesis

Waste-type precursor	**Synthesis method**	**Dominant surface/functional groups**	**Emission characteristics (colour, key λ)**	**References**
Orange peels	Hydrothermal	Carbonyl (C=O), carboxyl (–COOH), hydroxyl (–OH) groups (FTIR, C=O stretch)	Strong blue PL, excitation-dependent; emission ≈419-426 nm at 338-340 nm excitation	[14], [21]
Lemon peels	Bottom-up green (hydrothermal)	–COOH, –OH, C–H, C=O (FTIR, zeta potential)	Blue emission; maximal fluorescence at 365 nm excitation	[22]
Orange juice	Bottom-up green (hydrothermal)	Carboxylic and hydroxyl groups (FTIR)	Indigo emission: maximal fluorescence at 250 nm excitation	[22]
Cassava peels	Hydrothermal	Not detailed; UV-vis shows π–π* (C=C) and n–π* (C=O/C–O) bands	Excitation-dependent PL, QY ≈4.7%; suitable for white-LED application	[23]
Banana peel	Hydrothermal	N- and O-containing groups (–OH, C=O, N-groups)	Intense blue under 365 nm UV; excitation-dependent, QY ≈20%,	[14], [24]
Pineapple peels	Hydrothermal	–OH, –COOH, other oxygenated groups (FTIR, XPS)	Strong blue emission, QY ≈10.7%	[21]
Sugarcane bagasse pulp	Hydrothermal	Hydrophilic –OH, –COOH, $–NH_2$ (FTIR, XPS)	Strong blue/sky-blue emission; QY ≈18%	[25]
Butternut squash peel	Hydrothermal	Surface hydroxyl and carboxyl groups (FTIR)	Bright blue fluorescence; emission at 360 nm excitation, QY 13.5%	[26]
Avocado peels	Hydrothermal (CDs)	Oxygen-rich surface;	Bright blue-green emission	[27], [28]

	or laser-ablation of biocarbon (CNDs)	low graphitization (Raman, FTIR, XPS)	centred at 430 nm (330 nm excitation)	
Plantain peels	Hydrothermal	C=O, C=N, C–O, additional C=C at higher T (FTIR, Raman)	Absorption red-shift 266→283 nm; PL governed by surface states, high QY	[29]
Jackfruit peels	Hydrothermal, N-doped	Oxygen & nitrogen surface groups; N-doping confirmed by XPS	Strong, excitation-dependent, blue emission; QY ≈13%	[30]
Tamarind peels	Hydrothermal, N-doped	Oxygenated and -containing functionalities	Blue emission, excitation-dependent; QY ≈6%	[30]
Okra waste	Hydrothermal	Hydroxyl, carbonyl, ether, alkyl groups (FTIR, XPS)	Strong absorption at 275 & 325 nm; fluorescent CQDs in nanocomposite	[31]
Lemon peels	Hydrothermal (water)	Oxygen-rich surface; 1-3 nm size	Strong PL, QY ≈14%; applied in r Cr(VI) sensing	[32]

3. Synthesis and Characterization

CQDs are zero-dimensional, nearly spherical carbon nanostructures, generally measuring about 1–10 nm. Their intense, often excitation-dependent fluorescence is usually attributed to quantum confinement within the sp^2-rich carbon core together with emission from surface states. Both contributions can be tailored by choosing appropriate precursors and adjusting synthesis parameters [10], [14], [33]. The presence of a condensed π-conjugated core surrounded by numerous functional groups (–OH, –COOH, $–NH_2$, etc.) gives CQDs excellent water dispersibility, good chemical robustness, and makes them well-suited for applications in sensing, packaging, and at biological interfaces [34], [35].

CQD preparation routes are commonly grouped into top-down and bottom-up methods. Top-down techniques such as laser ablation, arc discharge, and electrochemical or chemical oxidation of bulk carbon (e.g., graphite, carbon nanotubes, nanodiamonds) operate by fragmenting larger carbon materials into nanoscale particles. Although these approaches can yield highly uniform CQDs with precise structural control, they usually demand substantial energy input, strong oxidizing agents, and specialized equipment. As a result, their scalability is limited, costs are higher, and there are concerns about environmental sustainability [36], [37].

By contrast, bottom-up strategies, particularly hydrothermal, microwave-assisted, and pyrolytic processes, are more frequently adopted for “green” synthesis of CQDs from fruit residues and other agro-industrial by-products (Table 2). These methods are typically simpler, more sustainable, and compatible with waste valorisation, producing highly luminescent, water-soluble CQDs (≈2-8 nm) enriched with oxygen- and nitrogen-containing surface groups, often without the need for extra passivating agents. Hydrothermal synthesis is flexible and relatively eco-friendly,but can be time-intensive. Microwave-assisted protocols greatly shorten reaction times and can deliver high yields, though they still face challenges related to uniform heating and scale-up. Pyrolysis, on the other hand, is inherently scalable and economically attractive, but tends to give broader size distributions and requires higher processing temperatures and chemical activation, which raise issues around energy demand and effluent handling [19], [38]. More recently, hybrid routes, for example, combining pyrolysis with a subsequent hydrothermal step, have been proposed to improve quantum yields and overall process efficiency [39].

Table 2. Qualitative comparison of main CQD synthesis routes relevant to horticultural waste

Methods	**Typical yield & QY**	**Scalability & time**	**Energy / temperature**	**Environmental & cost aspects**	**References**
Hydrothermal from biomass	Generally moderate yields; QY up to ~95% in optimized systems	Simple batch reactors; typical reaction times 2-12 h	180-200°C; moderate energy input over extended runs	Uses water and biomass; minimal toxic reagents; longer cycles can increase operating cost	[38], [40], [41]

Microwave-assisted from biomass	Very high product yields reported (up to ~84% for biomass CQDs); high QY frequently obtained	Reaction times from a few minutes to <1h; suitable for rapid or semi-continuous processing	High instantaneous power but short duration; efficient volumetric heating	Lower solvent usage and short processing times reduce footprint; specialized equipment influences cost at scale	[40], [41], [42], [43]
Pyrolysis (including microwave pyrolysis)	Typically moderate to high yields; often broader particle size distributions	Simple, robust setups; well adapted to large biomass throughputs	Elevated temperatures; energy demand depends on residence time and activation conditions	Cost-effective and highly scalable; may require corrosive activators and gas treatment, affecting effluent management	[19]
Combined pyrolysis-hydrothermal	Enhanced QY (reported up to ~68%) and shorter total processing time compared with single-step methods	Still primarily batch-oriented, but process integration reduces overall cycle time and can improve productivity	Requires both high-temperature pyrolysis and hydrothermal stages; energy use can be optimized by tuning parameters	Efficient valorisation of waste; reduced additive consumption in optimized schemes can improve environmental and cost profiles	[38]

A wide spectrum of horticultural and agro-industrial residues, including citrus peels, grape pomace, watermelon rinds, corn stalks, nutshells, butternut squash peels, and shrimp shells, have been successfully converted into CQDs *via* these bottom-up methods (Fig. 1). These sustainable syntheses typically yield strongly emissive, water-soluble CQDs with rich surface functionalities derived from inherent biomass components, thereby enabling effective *in-situ* passivation and tunable photoluminescence without additional passivating agents [1].

The functional properties of CQDs, particularly for edible coatings and packaging applications, depend strongly on their physicochemical characteristics, necessitating comprehensive characterization. UV-vis spectroscopy is commonly used to evaluate the UV-shielding capacity of CQD-filled films; for example, incorporation of ~3 wt% CQDs into polymer matrices such as poly(vinyl alcohol) (PVA) or carboxymethyl cellulose (CMC) can yield >99 % UV attenuation while maintaining visible transparency [44], [45], [46]. Thermal properties, including glass transition and degradation behaviour, are assessed using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), revealing the influence of CQDs on polymer stability [47]. X-ray diffraction (XRD) provides insights into crystallinity and structural organization, which are linked to mechanical and barrier properties [48].

Photoluminescence (PL) spectroscopy, including emission profiling and quantum yield determination, is essential for designing CQDs as fluorescent probes in intelligent packaging systems [49], [50]. Mechanical properties of CQD-based films, such as tensile strength, Young's modulus, and elongation at break, are evaluated using universal testing machines, demonstrating their reinforcing effects in biopolymer matrices [45]. Barrier properties, including oxygen transmission rate (OTR) and water vapour transmission rate (WVTR), are critical for food preservation; CQDs can enhance these properties by creating tortuous diffusion pathways that limit gas and moisture permeation [46]. Additionally, transmission electron microscopy (TEM) and high-resolution TEM (HRTEM) provide detailed information on particle size, morphology, dispersion, and crystallinity, which directly influence optical performance and matrix interactions [48], [49]. Overall, these synthesis strategies and characterization techniques provide a comprehensive understanding of how CQDs derived from horticultural waste can be tailored to enhance optical, thermal, mechanical, and barrier properties, enabling their effective application in edible coatings and intelligent packaging for postharvest quality preservation [7], [9].

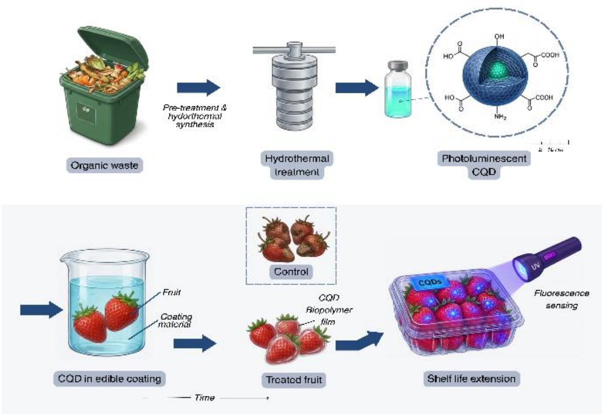

Fig. 1: Schematic of bottom-up synthesis of CQDs from horticultural waste and key characterization outputs.

4. Antioxidant and Antimicrobial Mechanisms

CQDs are attractive in food systems because they quench reactive species that drive oxidative spoilage and inactivate microorganisms responsible for decay. Both functions are strongly influenced by surface chemistry and can be modulated by light [49].

4.1. Antioxidant Mechanisms

The antioxidant behaviour of CQDs is mainly associated with the following:

1. Direct ROS scavenging. CQDs can neutralize reactive oxygen species (ROS) such as •OH, $O_2^{\bullet-}$, and $^1O_2$ via electron transfer or by donating hydrogen atoms from surface –OH, –COOH, and –NH_2 groups, aided by their high specific surface area.

2. Interruption of radical chain reactions. By quenching free radicals, CQDs help slow down chain reactions in lipids, proteins, and pigments, thereby limiting oxidative deterioration in food systems.

3. Metal ion chelation. CQDs can bind transition metals such as Fe^{2+} and Cu^{2+}, thereby inhibiting Fenton-type reactions and lowering the overall oxidative load.

When CQDs are embedded in biopolymer films or edible coatings, they often lead to higher DPPH and ABTS radical-scavenging capacities and can delay browning and pigment loss in fruits and vegetables, including commodities such as asparagus and longan. These beneficial effects are frequently associated with better retention of chlorophyll and phenolic compounds against oxidative degradation [9], [51].

4.2. Antimicrobial Mechanisms

CQDs inhibit foodborne microorganisms through multiple, often synergistic mechanisms that operate at both the cell surface and intracellularly [49].

4.2.1. Electrostatic adhesion and membrane disruption

Positively charged CQDs or those rich in amine groups are drawn electrostatically to the negatively charged bacterial cell envelope and surrounding extracellular polymeric substances (EPS). This close association can disturb membrane integrity, increase permeability, and eventually lead to leakage of cellular contents [52].

4.2.2. ROS-mediated oxidative damage

Many CQDs are capable of generating ROS either inherently or upon exposure to visible or blue light. These ROS species attack membrane lipids, proteins, and nucleic acids, causing pronounced oxidative stress and bacterial death [53]. Photodynamically active systems, for example, turmeric-derived CQDs embedded in chitosan films or CQDs obtained from spent coffee used in wash solutions, show particularly strong antibacterial performance under suitable pH or illumination, effectively inactivating pathogens such as *Staphylococcus aureus* and *Escherichia coli* on food products and contact surfaces [31].

4.2.3. Biofilm inhibition and interference with cellular processes

CQDs can hinder the formation of biofilms or destabilize those already established by penetrating the EPS matrix, competing with natural adhesive molecules, and making bacteria more vulnerable to antimicrobial agents [55]. Experimental studies have also reported changes in bacterial genetic profiles and enhanced leakage of intracellular markers such as proteins and lactate dehydrogenase, suggesting that CQDs cause damage beyond the membrane and affect internal cellular functions [56].

Reported minimum inhibitory concentrations (MICs) for *S. aureus* and *E. coli* range from the low µg/mL level for specifically engineered CQDs (e.g., amine-functionalized or metal-doped) to sub-mg/mL values for less optimized formulations, generally with limited toxicity toward mammalian cells *in vitro* and *in vivo* [57].

Taken together, these observations indicate that CQDs display a dual functional role: in food matrices, they often behave as antioxidants that remove ROS and help maintain quality, whereas in microorganisms they tend to enhance ROS generation and induce membrane and intracellular damage. This functional duality, combined with their tunable surface chemistry, supports growing interest in CQDs as environmentally benign preservatives or co-preservatives in active and intelligent packaging systems [51].

5. CQDs in Edible Coatings

The incorporation of CQDs into edible biopolymer coatings is an emerging approach for protecting fresh and minimally processed produce. By merging the film-forming and barrier attributes of polysaccharides and proteins with the antioxidant,

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antimicrobial, and UV-blocking properties of CQDs, these coatings provide active and, in some configurations, intelligent protection during storage (Table 3).

5.1. Functional Roles of CQDs in Edible Coatings

5.1.1. Antioxidant and antimicrobial activity: Edible films based on guar gum/alginate, carboxymethyl cellulose, starch, pectin, sericin, and chitosan exhibit markedly enhanced radical-scavenging capacity and broad-spectrum inhibition of bacteria and fungi when doped with CQDs [58]. Systems prepared from lemon and coffee husk wastes, chitosan-based CQDs, and carrot-derived CDs can reach >90% DPPH/ABTS scavenging and achieve near-complete inhibition of common foodborne pathogens at suitable CQD contents [59].

5.1.2. UV blocking and barrier enhancement: CQD incorporation significantly increases UV blocking while maintaining visible transparency, thereby limiting the photooxidative degradation of pigments and nutrients [60]. Simultaneously, the nanoscale fillers generate more tortuous diffusion pathways in the coating, lowering water vapour and oxygen transmission rates and helping to slow moisture loss and oxidative reactions [38].

5.2. Physiological and Quality Effects

Across a range of commodities, CQD-containing coatings function as semi-permeable barriers that curb weight loss, softening, and chlorophyll degradation, while better preserving soluble solids, titratable acidity, phenolics, and ascorbic acid [60], [62]. Reduced malondialdehyde accumulation and suppressed activities of oxidative enzymes such as PPO and CAT indicate effective alleviation of oxidative stress. The microbial load on coated produce is consistently and markedly lower than on uncoated controls [63].

5.3. Safety and Prospects:

Across various studies, CQD-based coatings have been found to alleviate oxidative stress in fresh produce, as indicated by reduced malondialdehyde levels and lowered activities of oxidative enzymes such as polyphenol oxidase (PPO) and catalase (CAT). At the same time, coated samples typically show reduced microbial counts compared with untreated controls, underscoring the contribution of CQDs to controlling spoilage and pathogenic microorganisms [41]. These results suggest that CQD-fortified edible coatings could serve as eco-friendly alternatives or supplements to conventional chemical preservatives for postharvest handling of fruits and vegetables.

Biomass-derived CQDs are often described as water-soluble, cyto-compatible, and having low acute toxicity, which has encouraged their use in food-contact applications, including packaging films and edible coatings [9], [64], [65]. Nevertheless, current safety assessments are not yet comprehensive. Major issues include the absence of harmonized regulatory thresholds, limited evidence on the migration of CQDs from coatings into foods, and an incomplete picture of long-term exposure outcomes. Existing analytical and regulatory tools also struggle to clearly differentiate dissolved species from particulate forms, complicating risk evaluation. In addition, the long-term fate, possible bioaccumulation, and metabolic processing of CQDs remain poorly defined, and data on chronic toxicity are still inconclusive [9], [66], [67], [68].

Overall, although available studies generally support the short-term biocompatibility of biomass-derived CQDs, more systematic research is needed before their widespread adoption in food systems. Priority areas include: (i) detailed migration studies under realistic storage conditions, (ii) investigation of bioaccumulation and toxicokinetic in relevant biological models, and (iii) the formulation of clear regulatory guidance for CQDs within existing frameworks governing food-contact materials [49], [67].

Table 3. Quantitative performance of CQD-based coatings and films on different foods

Food/system	CQD source/matrix	Shelf-life extension/storage condition	Microbial inhibition	Antioxidant/quality effects	Reference
Fresh-cut apples with CQD-CMC film	Coffee-husk CQDs in CMC film	Shelf life extended to 7 days at 4°C vs. faster deterioration in control	Slowed surface spoilage and microbial growth	>95% DPPH and ABTS radical scavenging; maintained quality attributes	[49]
Lemons with CQD-based lemon coating	Ascorbic acid/chitosan CQDs in CMC coating	No visible mould for 21 d	Bactericidal against *E. coli* and *L. monocytogenes*	88% DPPH and 100% ABTS scavenging; excellent antioxidant	[49]

Avocados with CQD-chitosan/gelatin coating	Glucose-derived CQDs in chitosan/gelatin matrix	Shelf life extended by >14 d	Effective suppression of mould development	Maintained overall visual quality over the extended storage period	[49]
Berries (goji) with photoactivated CQD coating	PEI-citrate CQD-based photo-responsive coating	Reported extension of storage stability under refrigerated conditions	Light-activated inhibition of spoilage microorganisms	Enhanced antioxidant protection and colour/texture preservation under photo-activation	[69]
Ground beef in CQD-bacterial cellulose membrane	Carbon dots in antibacterial cellulose film	Shelf life up to 9 d at 4°C	Significantly reduced *E. coli* growth	Preserved meat freshness is linked to UV-blocking and antioxidant properties	[67]

6. Smart Packaging Applications

CQDs are also being explored as optical nano-sensors in intelligent packaging. Because of their strong, tunable fluorescence and easily modifiable surfaces [9], [50]. CQDs can be engineered to signal changes in product freshness, headspace gas composition, or contamination. At the same time, their inherent antioxidant and antimicrobial activities add an active protection function to the packaging [60], [70].

6.1. Fluorescent Nano-sensors in Packaging

The combination of bright, photostable emission, relatively low toxicity, and flexible surface chemistry makes CQDs attractive for use in embedded indicators and labels. These systems can respond to gases, pH variations, or specific contaminants through fluorescence quenching or enhancement, or by an apparent colour shift [44]. In many designs, the optical changes are visible to the naked eye or can be quantified using simple cameras or smartphones, enabling convenient, point-of-use monitoring of food quality and safety [70], [72].

6.2. Ethylene and Fruit-Ripening Sensing

Ethylene is the key hormone that drives ripening in most climacteric fruits. "Turn-on" fluorescent carbon-dot sensors with detection limits as low as 0.12 ppm have been reported, allowing fast (≤3 min) and selective measurement of endogenous ethylene release and even spatial mapping of ripening within fruit tissues [73]. More broadly, studies on CQDs in fruit and vegetable systems show that these nanomaterials can function as smart ethylene indicators to help regulate ripening and monitor freshness [74]. For instance, one strategy embeds N-doped CQDs and Cu nanoparticles into agar hydrogels to form dual colorimetric/fluorescent labels whose colour and emission change irreversibly when exposed to ethylene during banana ripening, enabling non-destructive, visual assessment of ripeness in packaged fruits [70].

6.3. Gas, Atmosphere, and Spoilage Indicator

CQD- and carbon-dot-based films have been designed to act as:

- Atmosphere/quality indicators, showing clear, visible changes in response to pH shifts and accumulation of spoilage-related metabolites (CO_2, NH_3, volatile amines) or more general headspace changes, thus supporting modified-atmosphere packaging and seal/integrity monitoring [75].
- CQDs@MOFs hybrid labels, in which CQDs confined within metal-organic frameworks (MOFs) interact with spoilage markers (pH, CO_2, NH_3) and respond via fluorescence or colour changes that track product deterioration [44].

Recent reviews highlight that these systems can simultaneously provide passive or active control over the internal atmosphere (through barrier characteristics) and real-time visual tracking of spoilage development [47].

6.4. Detection of Contaminants and Safety Indicators

Beyond freshness monitoring, CQDs are extensively investigated as fluorescent probes for detecting heavy metals, pesticides, veterinary drug residues, illegal additives, and mycotoxins in food and water. Their sensing performance typically relies on fluorescence quenching or enhancement controlled by FRET, PET, or inner-filter mechanisms [72], [76]. CQDs produced from biomass or juices often exhibit strong affinity and selectivity for Cu^{2+} and other metal ions at low micromolar to nanomolar levels [35], [77]. CQDs@MOFs composites generally further boost sensitivity and selectivity toward metal ions, antibiotics, and aromatic pollutants relevant to food safety. When integrated into films, disposable tags, or wash-water sensors, these materials support rapid, on-site contaminant screening alongside their primary packaging roles.

6.5. Active-Intelligent Integration and Sustainability

CQDs are now widely viewed as versatile nanomaterials that can unify active and intelligent functionalities within a single food-packaging platform. As active components, they supply antioxidant, antimicrobial, and UV-blocking effects, thereby improving product stability and extending shelf life [7]. At the same time, their intrinsic photoluminescence allows their use as fluorescent reporters for real-time tracking of food quality and safety [50]. When CQDs are produced via green synthesis from food and agricultural by-products and incorporated into biodegradable polymers, they support sustainable packaging concepts that merge mechanical protection, quality sensing, and reduced environmental impact along the supply chain [78].

Intelligent packaging based on CQDs has shown particularly strong performance as pH-responsive indicators and fluorescence-based spoilage sensors. Applied studies demonstrate that CQD-containing films can follow quality changes in highly perishable foods such as fish and shrimp through visible colour or fluorescence changes that correlate with spoilage metabolites, enabling rapid, visual evaluation in real time [76], [79]. More generally, CQD-based sensors display high sensitivity, quick response, and low detection limits for contaminants such as heavy metals, pesticides, antibiotics, and foodborne pathogens, largely through fluorescence quenching or enhancement [65]. Despite this progress, most CQD-enabled packaging technologies remain confined to laboratory or early pilot stages. Major obstacles to commercialization include difficulties in scaling up synthesis with consistent quality, maintaining long-term photoluminescence stability, achieving regulatory approval, and ensuring compatibility with existing packaging operations [49], [50], [79].

From a sustainability and scale-up standpoint, several issues still need to be solved. Although agro-industrial residues offer plentiful and renewable carbon feedstocks, their seasonal variation, compositional heterogeneity, and possible contaminants can compromise the reproducibility of CQD properties [80]. Moreover, current synthesis approaches such as hydrothermal and pyrolytic methods face challenges related to yield, energy demand, and process control at industrial scale. Economic viability also hinges on optimizing production costs, including energy use, reactor design, and downstream purification to remove residual reagents and by-products. Comprehensive life-cycle assessments remain scarce, and further work is required to clarify degradation behaviour, migration potential, and end-of-life impacts of CQD-containing materials. Overcoming these hurdles is crucial for moving CQD-based active-intelligent packaging from experimental settings to commercial practice [68].

7. Doping Carbon Quantum Dots for Enhanced Postharvest Applications

The performance of CQDs in both preservation and sensing can be substantially improved by intentionally incorporating non-metal heteroatoms (e.g., N, S, P) or metal ions (e.g., Zn, Fe). Such dopants modify the carbon core and surface electronic structure, thereby tuning optical, redox, and catalytic characteristics that are important for postharvest applications [35] (Table 4).

Introducing heteroatoms creates extra defect sites and new electronic energy levels within the CQD lattice, which promotes charge transfer, adjusts band gaps, and increases surface chemical reactivity [81]. Consequently, doped CQDs usually exhibit higher quantum yields, brighter and more tunable fluorescence, and enhanced radical-scavenging and catalytic activity, leading to stronger antioxidant and antimicrobial effects when they are integrated into films or coatings [82].

Nitrogen-doped CQDs are especially notable: their higher electron density and increased number of surface functional groups improve emission, catalytic behaviour, and antibacterial efficacy. When embedded in biopolymer matrices, these CQDs can couple strong antioxidant capacity with light-activated bactericidal effects against foodborne microorganisms, helping to prolong the shelf life of fish and other easily spoiled foods [41]. Sulphur-containing and N,S co-doped CQDs introduce numerous structural defects and tailored redox properties, giving rise to intense fluorescence and robust antimicrobial activity, and enabling microbe- and pH-responsive films that visibly signal spoilage in products such as tomatoes and green beans [83].

Phosphorus-doped and more complex multi-doped CQDs further alter charge distribution and stabilize reactive intermediates, which in turn reinforces both antioxidant and catalytic functions [34]. Metal-doped and metal/non-metal co-doped systems (e.g., Zn- or Fe-based CQDs) frequently exhibit enhanced fluorescence, catalytic efficiency, and sensing sensitivity. These materials can detect trace levels of small molecules and gases and are attractive building blocks for intelligent packaging and CQD-MOF hybrid sensors aimed at monitoring food quality [85].

Overall, doping provides a versatile strategy to engineer CQDs for particular postharvest problems, including oxidative deterioration, microbial spoilage, and quality decline, supporting the design of highly efficient, multifunctional preservation systems and advanced smart packaging.

Table 4: Doped CQDs in Postharvest Management

Dopant	Enhanced Property	Postharvest Application	Citations
N-doping/N-co-doped CQDs	Higher PL, electron density, ROS generation	Antimicrobial films, sensors	[86]
S-doping/ S-co-doped CQDs	Defect sites, redox tuning, and strong antimicrobial activity	Antifungal / antibacterial smart films	[83]
P-doping/ multi-doped CQDs	Charge modulation, enhanced catalytic activity	Electrocatalysis, sensing	[85]
Metal + non-metal	Strong PL, improved catalytic/sensing performance	Metal-ion and pollutant detection	[85]
N, P, S co-doped CQDs on PP film	High radical scavenging, antifogging behaviour	Antioxidant &shelf-life extension	[82]
Ca-doped CQDs	Strong antioxidant activity, PPO/POD inhibition	Anti-browning	[87]
N-CQDs in KGM/alginate film	>98% bacterial inhibition, extended shelf-life	Antibacterial packaging	[88]
S, N-CQDs in amylopectin or cellulose films	Fluorescence/ colour changes with microbes, pH, Cr (VI)	Spoilage/Cr(VI) sensing	[83]
N-functionalized CQDs	Lemon edible coating, citrus shelf-life	Antifungal and antimicrobial activity	[15]
Zn-doped CQDs (Zn-CQDs)	Longan, mango preservation, active films	Antioxidant, antibacterial, UV shielding; browning and quality inhibition	[89]
CQDs from fruit/vegetable waste	Films/coatings for fruits & vegetables	Antioxidant, antimicrobial, UV shielding	[1], [8], [49]
CQD-MOF hybrids	Agar/gelatin active/ indicator films for tomato storage	Strong antioxidant, antifungal performance	[90]

8. Applications in Fruits, Vegetables, and Flowers

Doped and undoped carbon dots are being evaluated across numerous horticultural commodities: fruits, vegetables, and ornamentals, primarily *via* surface coatings and active packaging films. In these matrices, their antioxidant, antimicrobial, UV-screening, and in some cases ethylene-related functions are central to limiting microbial growth, oxidative damage, and senescence-related quality losses [1].

8.1. Fruits: Decay Control and Browning Inhibition

For climacteric and non-climacteric fruits such as mango, citrus, tangerine, strawberry, and longan, CQD-based coatings and composite films repeatedly demonstrate reductions in fungal and bacterial decay, lower physiological weight loss, and slower overall quality deterioration, resulting in clear extensions of marketable life [74]. For instance, carboxymethyl cellulose coatings loaded with nitrogen-functionalized CQDs have been reported to triple the shelf life of lemons and completely suppress visible mould for 21 days [15]. In longan, formulations combining Zn-doped CQDs with chlorogenic acid effectively mitigated browning and quality loss, while Zn-CQDs/PVA films helped preserve mango firmness, vitamin C, and organic acids, and reduced both disease severity and weight loss during storage [89]. Similarly, CQD-based antifungal agents prepared from lemon and onion wastes significantly prolonged strawberry shelf life and strongly inhibited Botrytis and other spoilage fungi [91].

8.2. Vegetables: Quality Maintenance and Stress Mitigation

In vegetables, edible and nanocomposite coatings containing CQDs, applied to commodities such as spinach, cucumber, and assorted fresh-cut products, have been shown to suppress microbial proliferation, restrain oxidative changes, slow chlorophyll breakdown, and reduce mass loss, thereby extending storage duration [92]. As an example, a sericin-CQD coating used on fresh-cut spinach substantially improved antibacterial and antioxidant properties, lowered weight loss and malondialdehyde accumulation by over 40%, and consequently extended shelf life [93].

8.3. Ornamental Flowers and Smart / Sensing Functions

Beyond direct preservation, CQD-containing biopolymer films can function as smart indicators whose fluorescence or colour responds to pH variations, spoilage volatiles, or contaminant levels, providing real-time information on freshness for fruits and other perishables [10]. Smart films fabricated using CQDs derived from blueberry pomace have been applied to monitor quality and extend the storage of meat and seafood, illustrating concepts readily adaptable to high-value horticultural and ornamental products [49]. Recent reviews also highlight the potential of CQDs for ethylene detection and regulation, as well as broader intelligent packaging roles throughout fruit and vegetable supply chains, although detailed, commodity-specific investigations for cut flowers remain relatively limited [41].

9. Research Gaps and Future Directions

Despite rapid progress, several critical challenges must be addressed to enable the translation of horticultural waste-derived CQDs into reliable food-contact technologies. A major limitation is the lack of standardized synthesis and characterization protocols. Differences in how CQDs are prepared lead to large variations in particle size, surface chemistry, and overall yield, which makes it difficult to directly compare results across studies. Developing standardized protocols and reporting norms for structural, optical, thermal, mechanical, and barrier properties would greatly enhance reproducibility, allow more meaningful cross-study comparison, and support scale-up [52].

A major unresolved issue is the limited knowledge of migration behaviour and long-term safety. Only a few systematic studies have examined how CQDs move from coatings and films into actual food systems under realistic storage conditions. Their stability, interactions within complex food matrices, metabolic fate, and possible cumulative effects are still poorly understood. This uncertainty is compounded by the lack of dedicated regulatory provisions for CQDs in food-contact materials, even though many reports suggest low toxicity and good biocompatibility. To enable safe commercial use, there is a clear need for thorough toxicological assessment, harmonized migration testing, and alignment with existing regulatory frameworks (e.g., EFSA, FDA) [9], [49], [52], [94].

From an environmental perspective, using biomass and horticultural residues as precursors is attractive, but very few studies have rigorously quantified the broader impacts of CQD production and use. Life cycle assessment (LCA) is needed to examine energy demand, emissions, and end-of-life behaviour, and to verify that CQD-based solutions genuinely outperform conventional materials [7]. At the same time, issues of scale and cost remain significant: many current synthesis routes still struggle with low or inconsistent yields, limited reproducibility, and insufficient process control when translated to industrial production.

There are also promising future directions. Integrating artificial intelligence and data-driven optimization could help fine-tune CQD synthesis and improve packaging performance. Machine learning tools, for example, can be used to relate precursor composition and processing parameters to key nanomaterial properties and functional outputs, such as optical response, barrier behaviour, or shelf-life extension [95]. At present, however, most CQD-based systems are confined to laboratory or small pilot trials. Robust, field-scale testing under real storage, distribution, and retail conditions is still lacking. Closing these gaps will be essential to move CQD-enabled edible coatings and smart packaging from promising concepts to safe, standardized, and commercially viable technologies that can reduce postharvest losses and enhance the sustainability of food supply chains [49], [61].

10. Conclusion

Carbon quantum dots produced from horticultural residues are emerging as versatile nanomaterials for both active and intelligent postharvest preservation. When embedded in edible coatings or packaging films, they can improve UV shielding, mechanical strength, barrier properties, and antioxidant and antimicrobial performance, which in turn helps to prolong shelf life and maintain the quality of fresh produce. Moreover, using horticultural by-products as carbon sources fits well within circular-economy goals by converting low-value waste into functional, high-value components for sustainable packaging. Nevertheless, challenges remain regarding large-scale, cost-effective production, long-term safety, and regulatory acceptance, which must be addressed before these systems can be widely implemented in commercial food supply chains.

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