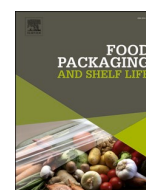




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Quantum dots in edible coatings and food packaging: Advances, applications, and safety perspectives

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ABSTRACT

Quantum dots (QDs) have emerged as promising nanomaterials in edible coatings and food packaging due to their tunable optical properties, high photostability, and multifunctional performance. Recent advances demonstrate their successful incorporation into polysaccharide- and protein-based matrices as well as hybrid nanocomposites to enhance barrier, antimicrobial, antioxidant, and sensing properties. To address safety concerns related to nanoparticle migration and heavy-metal toxicity, current approaches emphasize the use of metal-free quantum dots such as carbon and silicon (QDs), together with surface passivation and ligand engineering to minimize ion release and surface reactivity. Additional strategies include encapsulation within silica, polymeric, or metal-organic framework matrices and covalent integration into cross-linked polymer networks to restrict diffusion and limit migration. Multilayer packaging architectures further confine QDs to non-food-contact indicator layers, and standardized migration testing supports regulatory compliance. These developments position QDs as key components in next-generation smart packaging systems designed to improve food preservation, reduce waste, and enhance consumer confidence while maintaining safety.

1. Introduction

Food spoilage and waste are persistent global challenges, responsible for nearly one-third of food losses each year, which has significant economic, environmental, and social impacts. To mitigate these losses, researchers are increasingly focusing on innovative and sustainable packaging solutions. Edible coatings and films made from natural biopolymers, such as chitosan, alginate, starch, gelatin or cellulose have attracted increasing attention as potential substitutes of traditional plastics for both being eco-friendly materials with the capability to serve as a protective barrier against gas exchange, moisture and microbial contamination by simultaneously possessing biodegradability and edibility (Usman et al., 2025). Through the last decade, edible coatings have evolved from simple barriers to multifunctional systems involved in food preservation. Use of antimicrobial and antioxidant agents in

edible coatings may impede microbial growths, postpone lipid oxidation, and extend shelf life (Mao et al., 2023; Nikzadeh et al., 2025a). There is also an increasing demand from consumers for food-safe and fully biodegradable packaging systems that overcome the deficiencies associated with common films in terms of mechanical properties and water vapor barrier (J. Chen et al., 2022). The incorporation of nanotechnology into these coatings has improved their performance, including enhanced barrier properties, durability, and controlled release of bioactive compounds (Khalafi & Zandi, 2025a; Xia et al., 2023; W. Zhang, et al., 2025).

QDs are one of the most exciting classes of nanomaterials amongst the nanotechnology-derived solutions. This quantum confined (QC) semiconductors have tunable photoluminescence, high photostability, and strong surface reactivity. These peculiar features of QDs render them very useful in smart packaging systems, in which they can act as

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sensors for immediate monitoring of food quality and reinforcement agents to enhance the physical and antimicrobial properties of the coatings (Das et al., 2025b). Their potential is further spurred by the increasing development of carbon quantum dots (CQDs) and other biocompatible counterparts, which alleviate concerns regarding the toxicity of attributed to heavy-metal-based QD such as cadmium or lead (Das et al., 2025b). New research has focused on the use of QDs and similar nano materials as components contributing to an improved life span in packaging systems designed for fruits, vegetables, meat and fish. For instance, a multifunctional N-doped carbon dot-polyvinyl alcohol film can be used for real-time detecting spoilage gases such as volatile amines and to retain antimicrobial and antioxidant activities to extend shrimp freshness (Li et al., 2025a). Nanostructured packaging systems, including electrospun nanofibers and nano-sachets have also been investigated for food preservation purposes (de Barros et al., 2024; Khalafi & Zandi, 2025a). These advances emphasize the promise of embedding QDs in edible coatings capable of not only preserving but also providing smart food quality determination. The main objective of this review is to present a holistic overview of the basic knowledge, integration approaches, functional improvements and recent case studies on QDs in edible coatings/packaging for its potential safety issues. Through consideration of both the benefits and drawbacks, items in this review context QDs as nascent tools in the shift towards sustainable, safe and smart food packaging.

2. Food waste drivers and the role of packaging

Modern studies point out that the main technical causes of food deterioration (especially in fresh produce, meat, dairy and seafood products) are microbial growth, oxidative degradation of materials, migration of moisture within the containers and mechanical damage (Karanth et al., 2023). Moreover, improper temperature control while moving between the storage and end-user point significantly enhances both biochemical and microbiological spoilage in perishable supply chains, Household storage of food (Eze et al., 2024), misunderstanding of the effects of “best-before” or “use-by” labels, and aesthetic rejection of cosmically imperfect foods are consumer-related factors that also lead to waste. Thus, these findings suggest food waste results from a complex interplay of biological, technological, logistical and behavioral determinants. Recent studies have proven that the application of advanced packaging systems can extend the shelf life of these fruits and vegetables through lower oxidation rates, humidity control, and no cross-contamination to food during handling, distribution (Hossain, 2023). Active and intelligent packaging technologies add even more value, where the use of antimicrobial agents, oxygen scavengers, or freshness indicators enables real-time quality monitoring (Mkhari et al., 2025; W. Zhang, et al., 2025), leading to reducing premature disposal of still edible products. Not only do these systems slow spoilage, but they can also provide consumers with visual or measurable indicators of product quality to enhance consumer confidence. Petroleum-based polymers have long been used in food packaging applications because they are characterized by excellent mechanical strength, transparency, low-cost and strong barrier properties. Nevertheless, an increasing amount of evidence shows that they represent important environmental burdens themselves, including depletion of fossil resources, greenhouse gas emissions, microplastic pollution and accumulation of biodegradable waste in terrestrial and marine ecosystems (Dey et al., 2024). Life-cycle assessments increasingly show that though plastics may reduce food spoilage, their upstream and end-of-life impacts typically outweigh environmental gains unless properly managed through recycling or circular systems (Nordahl & Scown, 2024). This has raised environmental concerns, which are what is pushing us toward searching for sustainable alternatives. Additionally, recent studies on edible coatings and biodegradable films have shown that they can significantly delay moisture loss and oxidative degradation in fresh produce and meat products, thereby reducing postharvest losses (Alemu et al., 2025; W.

Zhang, et al., 2025). However, the resulting mechanical strength and barrier performance of natural polymers are usually weak in comparison to synthetic plastics with added humidity. Consequently, the use of reinforcement strategies based on nanofillers, cross-linking and also active components are progressively studied to enhance performance while ensuring sustainability (Ponnusamy & Mani, 2022). Overall, literature shows us that packaging can never fully prevent food waste on its own but it is nevertheless an important technological intervention that works to reduce spoilage, stabilize supply chain reliability and help consumers make better decisions. As well as the aim of zero waste, moving away from traditional plastics toward natural polymer-based systems is driven by needing to reduce environmental footprints and strengthen circular bioeconomy approaches. But achieving equivalent functional performance necessitates material innovation, particularly active and nanostructured enhancements to ensure that sustainability gains do not compromise food protection effectiveness.

3. Fundamentals of quantum dots

3.1. Structure and properties

QDs refer to nanoscale semiconductor or carbon-based materials with sizes 2–10 nm, and the lower dimensionality leads to enormous variations in their physicochemical properties. At these sizes, QDs display a quantum confinement effect, resulting in the electronic and optical properties relying sensitively on the particle size thus, exemplified by targeted control of bandgap energy levels and fluorescing tuning throughout visible to near-infrared bands (Mi, Gee et al., 2025; Reza et al., 2024). This unique property of QDs is not found in the case of bulk materials, and has been utilized for various applications such as sensing, imaging and food packaging. The exceptional photoluminescence properties of QDs are due to their discrete energy levels and large exciton binding energies. For example, perovskite QDs, particularly CsPbBr₃ QDs, have been demonstrated to show almost zero-blinking behavior with excellent photostability and outstanding single-photon purity when appropriately surface-engineered (Mi et al., 2025). Carbon-based QDs, including carbon quantum dots (CQDs) and graphene quantum dots (GQDs), provide similar tunable emission properties but with the added advantages of high aqueous solubility, biocompatibility, and lower toxicity compared to heavy-metal-based counterparts (Das et al., 2025b; Liu, Dang et al., 2025; Liu, Wang et al., 2025). Recent reports highlight the ability to extend carbon dot emission into the near-infrared region (≥ 700 nm), opening new applications in biosensing and secure food monitoring (Liu, Dang et al., 2025; Liu, Wang et al., 2025). High surface reactivity is another fundamental feature of QDs. Their abundant surface functional groups enable facile conjugation with polymers, biomolecules, and other nanostructures, enhancing stability and extending functionality. For example, nitrogen-doped carbon dots derived from beetroot demonstrated enhanced polarity, reduced energy gap, and significant antimicrobial properties when incorporated into cellulose sulfate films, extending tomato shelf life from 4 to 10 days (Hebat-Allah S. Tohamy, 2025). However, pH-responsiveness and UV-blocking capability was also provided by orange peel derived carbon dots inserted into gelatin-pectin matrices, thus being able to monitor the meat freshness in real-time (Sadeghi et al., 2025). These results validate that the reactive surface of QDs is a crucial factor affecting their incorporation possibility into edible films. New hybrid systems also illustrate the relation between structure and function at the nanometer scale. MXene quantum dots embedded into biopolymer films result in increased resistance to UV (>90%) and antioxidant activity (>78%), higher mechanical flexibility, and reduced oxygen and moisture permeability – all features critical for food preservation (Althawab et al., 2025). Likewise, carrageenan/gelatin nanocomposites doped with licorice-root carbon dots indicated pH-responsive colour change and excellent bactericidal effect evidencing synergistic function between QDs and nature polymer (Bagri

et al., 2025a). The various synthetic routes highlight, moreover, the quasi-universality of QD structure tuning. Green and biomass mediated synthetic pathways, such as fruit extract-based hydrothermal process (Dhanapalan et al., 2024), are highly promising for the generation of sustainable carbon dots with extremely high fluorescence having well-defined shape. Tailoring of the structure, such as graphitization control, has been demonstrated to improve the photoredox properties and catalytic performance among C-dots (Morbiato et al., 2025b). Such observations confirm the correlation between QD shape and function, therefore, providing nanometer-level manipulation of nanoparticle that is applicable to smart food packaging applications. In conclusion, QDs are but one example of the extent to which properties at nano-scale determine physicochemistry; in this case, their confined dimensions determine and offer control over bandgap tuning, discrete photoluminescence and high surface activity. Progress in perovskite QDs, graphene quantum dots (GQDs), carbon quantum dots (CQDs), and MXene-derived QDs is indicative of the disruptive role that they can play in developing multi-functional, responsive and sustainable coatings. Introducing them into the food system involves making use of these structural and surface features to optimize between performance towards safety and sustainability. Recent studies showed the great application potential of various QD systems in food packaging (Table 1)

3.2. Types of quantum dots

QDs are a large family of nanoscale products, and their application in food packaging is highly associated with their composition and preparation process. Metallic QDs, including CdSe, ZnS, PbS and others were the first researched because of their high luminescence efficiencies and clearly defined band-gap tunability. However, their high toxicity and heavy metal leaching into food product are the limitations for their direct use in edible packaging material. Recent studies have turned to safer surface modifications and alternative nanocrystals with decreased toxicity, such as ZnS and indium phosphide-based QDs that can achieve strong fluorescence but decrease environmental and health hazard (Karami et al., 2024; Mi et al., 2025). For instance, surface-engineered

CsPbBr₃ perovskite QDs exhibited non-blinking and photostable emission with 98% purity, highlighting their potential for fluorescence sensors; however stability (internal or external) and lead content were problematic challenges (Mi et al., 2025).

The rapid advancement of CQDs and GQDs in the field with better safety profile has changed this scenario. Prepared by the top-down (oxidation of carbon materials) or bottom-up (synthesis from biomass) techniques, CQDs are low-cost, photostable and biocompatible. They show tunable photoluminescence in the range of UV–NIR and have been shown to have antimicrobial, antioxidant, and biosensor activities in food matrices (Das et al., 2025a; Liu et al., 2024). For example, beetroot-derived nitrogen-doped CQDs were embedded in cellulose sulfate films for tomato storage with colorimetric pH and heavy metal sensing applications (Tohamy, 2025a). Similarly, GQDs can improve the mechanical properties and impart antimicrobial activity when incorporated into polymer matrices, implying their potential use in smart food packaging (Karami et al., 2024). Further studies have featured bilayer graphene QDs with long-lived valley states that result in stable exciton lifetimes (which could be useful for continuous sensing systems) (Garreis et al., 2024).

Perovskite quantum dots (PQDs) are, recent type of QDs that exhibit excellent optical properties including high exciton binding energy and defect tolerance. Due to their sharp emission profiles and high quantum yields, they are interesting as sensitizers for spoilage indicators such as ammonia and volatile amines. Advances in ligand engineering have made them more photo-stable under constant excitation (Mi et al., 2025). However, the lead halides they depend on are highly toxic and rise toxicity concerns in the food sector where there is a demand for lead-free perovskite analogs or encapsulation techniques (Suo et al., 2025).

Finally, growing interest has been directed toward green-synthesized and food-grade QDs, which use natural precursors such as fruits, vegetables, and agricultural byproducts. These eco-friendly synthesis routes not only reduce environmental impact but also produce biocompatible nanomaterials with functional bioactivity. For example, orange peel-derived CQDs incorporated into gelatin–pectin films displayed strong

Table 1

Current researches on the use of QDs for food packaging emphasizing their size, emission character, surface functionality, particular applications in edible films and coatings.

Type of QD	Size Range (nm)	Bandgap/Emission	Surface Properties	Key Application in Food Packaging	Reference
N-doped MXene QDs	3–6	Broad UV–Vis absorption	High antioxidant, antibacterial, UV resistance (>90%)	Flexible chitosan films with reduced O ₂ /H ₂ O permeability	(Althawab et al., 2025)
Licorice root C-dots on silica	4–8	Visible fluorescence, pH-sensitive	Strong UV-blocking, antioxidant, antibacterial	Carrageenan/gelatin films for shrimp freshness monitoring	(Bagri et al., 2025a)
Orange peel C-dots	5–7	Green emission (~500 nm)	Hydrophilic, antioxidant	Gelatin/pectin films for meat spoilage detection	(Sadeghi et al., 2025)
Beetroot N-doped C-dots	2–4	Blue-green PL, reduced gap (0.019 eV)	pH-sensitive, antimicrobial	Tomato packaging, pathogen & heavy metal detection	(Tohamy, 2025)
CQDs (review synthesis)	2–10	Tunable PL (UV–NIR)	High biocompatibility, antioxidant	Biosensors, spoilage indicators, smart packaging	(Das et al., 2025b)
Perovskite CsPbBr ₃ QDs	6–10	Non-blinking single photon emission	Surface-engineered for stability	Photostable sensors in packaging	(Mi et al., 2025)
NIR-emissive CDs	2–6	Extended to > 700 nm (NIR)	Low toxicity, good stability	Biosensing & secure freshness monitoring	(Yupeng Liu et al., 2025)
Electrospun C-dots (biosensors)	4–8	Fluorescence (blue-green)	Antibacterial, conductive	Detection of foodborne pathogens in coatings	(Lei et al., 2025)
Graphitized CDs	2–5	Enhanced PL quantum yield	High surface reactivity, catalytic	Antioxidant packaging, photoredox stability	(Morbiato et al., 2025a)
Bilayer graphene QDs	5–8	Long-lived valley states	High exciton stability	Stable fluorescent probes for biosensing	(Garreis et al., 2024)
N-doped CDs (fruit-derived)	3–6	Blue-green PL	Polar, antimicrobial	Meat freshness sensors in biopolymer films	(Dhanapalan et al., 2025)
Fluorescent carbon nanoprobes	2–10	Strong PL across UV–Vis	Graphitic, photostable	Biosensing for spoilage/toxins	(Krasley et al., 2024)
Anthocyanin + C-dot hybrid films	5–9	Dual fluorescence (anthocyanin + QDs)	UV-blocking, antioxidant	Intelligent shrimp/meat freshness indicators	(H. Xu et al., 2024)
Curcumin-integrated CQDs	4–8	Visible emission, antioxidant	Strong ROS scavenging	Active packaging with enhanced shelf life	(Ranade et al., 2025)

UV-blocking ability and improved mechanical properties, while acting as freshness indicators in meat packaging (Sadeghi-Kiakhani et al., 2025). Licorice root carbon dots combined with red cabbage anthocyanins produced pH-sensitive carrageenan/gelatin films capable of real-time shrimp spoilage detection (Bagri et al., 2025b). Similarly, eco-synthesized CQDs from *Muntingia calabura* fruit extract demonstrated strong fluorescence and selective Fe³⁺ detection, showing the dual role of such QDs in environmental and food safety applications (Dhanapalan et al., 2025). These examples highlight how biomass-derived QDs combine sustainability, safety, and multifunctionality, aligning with consumer and regulatory demands for green food packaging. Fig. 1 summarizes the main categories of QDs explored in food packaging, highlighting their strengths, limitations, and representative applications. Metal-based QDs such as CdSe and ZnS exhibit strong fluorescence and tunable bandgaps, but their potential heavy-metal migration limits direct food-contact uses

3.3. Synthesis and surface functionalization

Quantum dots have been synthesized using various chemical routes, including colloidal, hydrothermal, solvothermal, and microwave-assisted techniques, each enabling size control and photophysical tunability. Hydrothermal synthesis of nitrogen-doped carbon dots from beetroot produced nanomaterials with a reduced bandgap of 0.019 eV and enhanced polarity (29.19 Debye), yielding strong pH responsiveness, antimicrobial activity against *E. coli* and *S. aureus*, and an extension of tomato shelf life from four to ten days (Tohamy, 2025a). Similarly, hydrothermal processing of *Muntingia calabura* fruit extract resulted in fluorescent carbon dots with a 3.6 μM detection limit for Fe³⁺ ions, demonstrating their potential as sensitive, eco-friendly nanoprobes for food-safety applications (Dhanapalan et al., 2025). Other solvothermal and colloidal strategies have been critical for fabricating

perovskite nanocrystals, such as CsPbBr₃ QDs, where ligand-tail engineering achieved nearly non-blinking emission with 98% single-photon purity, underscoring their promise for intelligent food-labeling sensors (Mi et al., 2025). Microwave-assisted synthesis has also been employed to tailor graphitic carbon dots, with results showing that increased synthesis temperatures enhance graphitization and photocatalytic stability, thereby improving quantum yield and structural robustness (Morbiato et al., 2025a).

Bio-based and green synthesis approaches have gained attention as sustainable alternatives to conventional chemical methods. Orange peel-derived carbon dots incorporated into gelatin–pectin matrices with hibiscus anthocyanins improved tensile strength from 35.6 to 47.5 MPa, increased hydrophobicity (contact angle ~102.9°), provided UV blocking, and enabled real-time monitoring of meat spoilage through visible fluorescence changes (Sadeghi-Kiakhani et al., 2025). Likewise, licorice-root-derived carbon dots immobilized on silica nanoparticles and integrated into carrageenan/gelatin films exhibited multifunctionality by providing pH-sensitive colorimetric shifts in response to ammonia, thereby enabling shrimp freshness monitoring while also conferring antioxidant and antimicrobial activity (Bagri et al., 2025b). Beetroot-based nitrogen-doped carbon dots incorporated into cellulose sulfate films offered dual functions, serving as antimicrobial agents and as sensors for heavy metals and pH changes (Tohamy, 2025a). These studies highlight how plant and agricultural wastes act as renewable carbon sources, while also imparting intrinsic antioxidant or antimicrobial features to the resulting nanomaterials.

Surface functionalization has proven essential to improve the stability, dispersion, and compatibility of QDs within food matrices. In perovskite systems, rational ligand engineering has enhanced the stability of CsPbBr₃ QDs under prolonged excitation, maintaining high quantum yield and single-photon emission, which is crucial for long-term applications in smart labels (Mi et al., 2025). In carbon-based

Types of quantum dots for food packaging: composition, safety, and applications

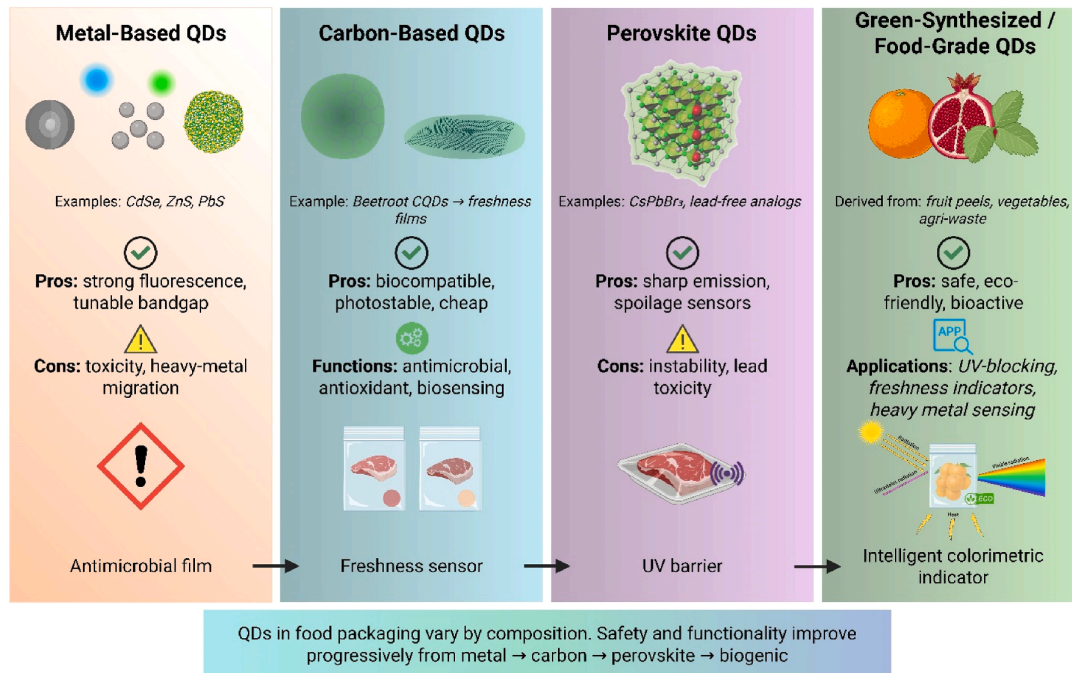


Fig. 1. Types of quantum dots (QDs) in food packaging, showing their composition, safety issues, and key applications from antimicrobial films to intelligent freshness indicators.

QDs, surface groups such as hydroxyl, carboxyl, and carbonyl moieties provide reactive sites for covalent coupling with biopolymers or biomolecules. Functionalization through heteroatom doping, such as nitrogen or sulfur incorporation, modifies the bandgap and extends emission into the red and near-infrared range, improving suitability for food-sensing platforms (L. Liu et al., 2025). In addition, the wet-chemical incorporation of N-doped MXene QDs into thermoplastic chitosan yielded films with more than 90% UV blocking efficiency, approximately 78% antioxidant activity, improved tensile strength (4–5 MPa), and around 75% biodegradation after three weeks, all achieved without detectable nanoparticle release, confirming the effectiveness of functionalization for safe immobilization (Althawab et al.,

2025). Hybrid functionalization approaches, such as combining carbon dots with natural pigments or anchoring them to silica carriers, further improved dispersion and provided synergistic sensing capabilities, as seen in anthocyanin–carbon dot hybrid films for shrimp spoilage detection (Bagri et al., 2025b; M. Xu et al., 2024). Collectively, these findings show that while chemical synthesis routes offer precise control of size and emission properties, bio-based green methods enhance sustainability and bioactivity, and functionalization ensures safe, stable, and effective integration of QDs into edible matrices for intelligent and active food packaging. Different synthesis strategies have been explored to tailor QD properties for food-packaging applications (Table 2). Fig. 2 illustrates the pathways from synthesis to application that define the

Table 2
Synthesis routes, feedstocks, physicochemical properties, and food-packaging applications of QDs in recent studies.

Synthesis Route	Precursor/Feedstock	Particle Size / QY	Key Property	Food-Packaging Application	Reference
Hydrothermal	Beetroot (for N-doped CDs)	Bandgap 10.019 eV; polarity 29.19 D between 4.09 nm and 5.02 nm	Antimicrobial; pH-responsive	Extended tomato shelf life from 4 → 10 days	(Tohamy, 2025a)
Hydrothermal	Galla chinensis waste CDs in pullulan films	2.36 nm	↑ Toughness (14→20%); WVP ↓ (1.31→0.53); UV shielding; ABTS 93.6%, DPPH 86.3%; antibacterial 99.99%	Strawberry preservation (10 d, non-contact)	(Tang et al., 2024)
Hydrothermal	Pineapple leaf CDs in pineapple stem starch films	2.36 nm	Antioxidant & antibacterial; ↑ mechanical strength; UV barrier	Fresh pork shelf-life extension	(Kuchaiyaphum et al., 2024)
Hydrothermal	Triphala-derived CDs in PVA/gelatin blend	Range of 3–7 nm	↑ Tensile (32.4→42.7 MPa); UV-B 99.7%, UV-A 97.2% blocking; antioxidant/antibacterial	Chicken preservation	(Sasikumar et al., 2024)
Hydrothermal (Green)	Muntingia calabura fruit extract	LOD Fe ³⁺ = 3.6 μM	Metal ion sensing	Intelligent food-safety monitoring	(Dhanapalan et al., 2025)
Microwave-assisted	Citric acid + urea (graphitic CDs)	Higher T → more graphitic; improved QY	Enhanced photocatalytic stability	Active films and degradation sensors	(Morbiato et al., 2025a)
Microwave-assisted	N-doped graphene QDs + carnauba wax in pectin/gelatin	1.6 nm; zeta + 0.65 mV	Tensile ↑ 68.9%; elongation ↑ 40%; WVP ↓; antioxidant ↑; antibacterial (S. aureus, K. pneumoniae)	General food preservation, oxidation & spoilage prevention	(Hejabi et al., 2025)
Colloidal (Perovskite)	CsPbBr ₃ with phenethylammonium ligands	98% purity single-photon emission	Extraordinary photostability	Smart fluorescent sensors, intelligent labels	(Mi et al., 2025)
Solvothermal	Perovskite QDs	Tunable bandgap (blue to red)	Long exciton lifetimes; defect tolerance	Spoilage-gas optical sensors	(Suo et al., 2025)
Hydrothermal + Biopolymer	Orange peel CDs + hibiscus anthocyanins	Films tensile ↑ to 47.5 MPa	UV-blocking, hydrophobicity, fluorescence	Meat spoilage monitoring in gelatin–pectin films	(Sadeghi-Kiakhani et al., 2025)
Green + Hybrid	Licorice-root CDs on silica	Strong emission; antioxidant	Ammonia-responsive colorimetric shift	Shrimp freshness detection in carrageenan/gelatin films	(Bagri et al., 2025b)
Wet-chemical blending	N-doped MXene QDs + thermoplastic chitosan	Tensile 4–5 MPa; 75% biodegradation	> 90% UV-blocking; 78% antioxidant activity	Biodegradable films with safe immobilization	(Althawab et al., 2025)
Electrospinning + Pigments	Pigment-loaded nanofibers	High surface area	Stable pigment encapsulation	Smart biodegradable packaging	(Khalafi & Zandi, 2025b)
Hydrothermal + Plant Waste	Onion peel S,N-CQDs in HEC	Egap 0.02664 eV; fluorescence shift	Naked-eye spoilage detection; antimicrobial	Extended chicken shelf life (12 vs 3 days)	(Tohamy, 2025a)
Hybrid Nanoemulsion	Mentha pulegium essential oil	EO-NE at 16 ppm effective	Antimicrobial, antioxidant	Preserved beef quality, reduced TBARS/TVB-N	(Nikzadeh et al., 2025b)
Nanocomposite Assembly	Cu-Trp nanocrystals in CMS/PVA	42.92 MPa tensile; 2.4% UV transmittance	Ammonia-responsive colorimetric shift	Shrimp spoilage detection	(R. Xu, Song, et al., 2024)
Hydrothermal + Cellulose	N-CDs in cellulose sulfate	Pores 11.9–25.4 μm; fluorescence	Pathogen sensing + Cr(VI) detection	Tomato shelf life extended to 10 days	(Tohamy, 2025a)
Top-down oxidation	Graphene quantum dots	Few nm; tunable PL	Long-lived valley states; robust emission	Intelligent sensors with long-term stability	(Garreis et al., 2024)
Colloidal + Biofunctionalization	Carbon dots functionalized with biopolymers/aptamers	NIR emissive; QY ↑ with doping	Electrochemical + optical biosensing	Detection of foodborne pathogens	(Lei et al., 2025)
Hydrothermal (waste valorization)	Onion peels → S,N-CQDs in hydroxyethyl cellulose (HEC)	Egap 10.0266 eV (DFT)	Naked-eye fluorescence color shift with Salmonella; strong antimicrobial effect; shelf life extended 12 days vs. 3 days	Chicken meat spoilage monitoring and inhibition	(Tohamy, 2025c)
Ultrasound-assisted composite	Carbon dots + sericin protein (SCCD)	ZOI ↑146% (B. subtilis), ↑157% (E. coli)	Antioxidant, antibacterial, UV-shielding; reduced weight loss and lipid oxidation	Spinach preservation (fresh-cut vegetables)	(Zhu et al., 2025)
Casting / labeling	N-doped carbon dots in polyvinyl alcohol (PVA)	LOD 0.025 ppm TMA	Dual-mode colorimetric/fluorescent sensing; antioxidant; antimicrobial; > 90% cell viability; extended shrimp shelf life (2 d at 4 °C)	Shrimp freshness labels and active preservation	(M. Li et al., 2025b)

Synthesis and surface functionalization of quantum dots for safe and intelligent food packaging

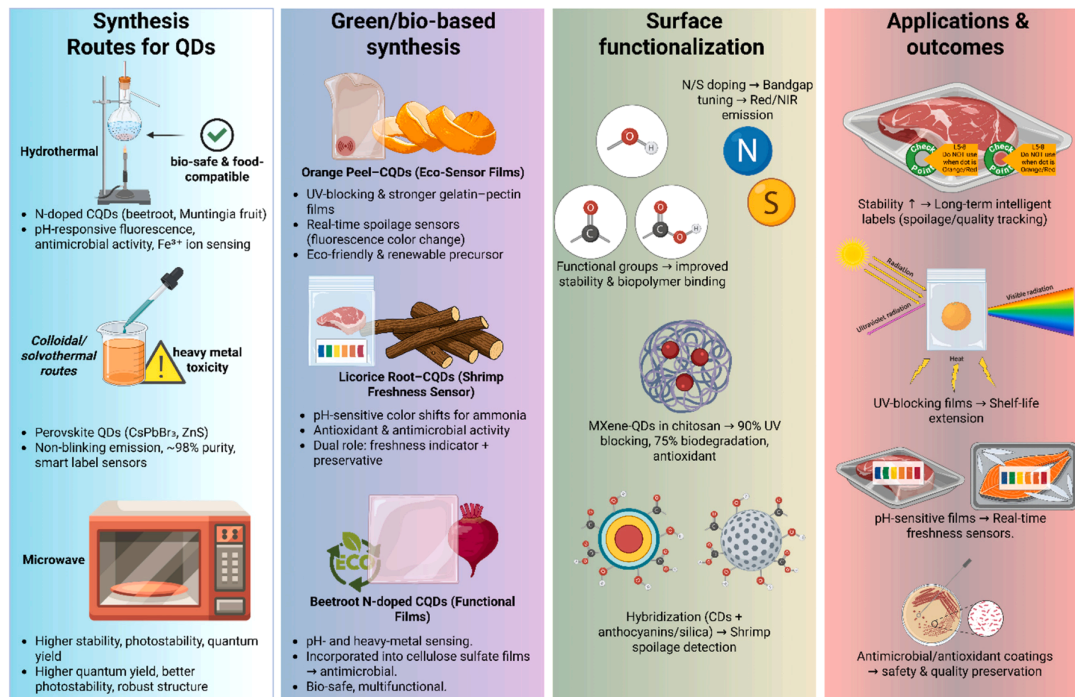


Fig. 2. Synthesis routes, green/bio-based approaches, surface functionalization, and key applications of QDs in food packaging, highlighting their roles in UV shielding, antimicrobial protection, and real-time freshness monitoring.

functionality of QDs in food packaging. Hydrothermal, colloidal/solvothermal, and microwave-assisted routes yield QDs with tunable fluorescence and stability, though heavy-metal systems remain restricted by toxicity concerns.

3.3.1. QD synthesis routes comparison (pros/cons for food packaging)

The synthesis, route of QDs significantly impacts their optical properties, surface chemistry and purity, scalability as well as suitability for food-contact applications. Well-established methods for preparing semiconductor QDs with high crystallinity, narrow size distribution, and quantum yield that is as high as possible include one widely used technique known as colloidal hot-injection synthesis. This has recently been found to allow precise control over particle size and emission wavelength, making it interesting for applications such as sensing that require strong and stable fluorescence signals (Ponnusamy & Mani, 2022). Yet, typical colloidal synthesis uses high-boiling organic solvents, organometallic precursors, and hydrophobic ligands that are associated with environmental and safety issues. Additionally, core materials containing cadmium or lead are widely used in high-performance colloidal QDs, which also creates regulatory challenges for food packaging because of potential heavy-metal toxicity and migration concerns. In addition, extra post-synthesis ligand exchange and purification steps are needed to make the particles water-dispersible which contributes to increased processing complexity (Hahm et al., 2020). In this regard, hydrothermal and solvothermal processes have emerged as relatively simple and versatile techniques for the synthesis of carbon and silicon-based QDs. These methods generally require mild pressure, and heating aqueous or low-toxic solvent systems in closed reactors with carbonization or nucleation from biomass precursors. The recent literature shows that hydrothermal synthesis is ideal for the production of metal-free carbon dots, which are well soluble in water and possess many surface functional groups, thus enabling direct integration into

biopolymer matrices (Xu et al., 2013). The method is known to be relatively safe and scalable than the hot-injection routes. However, hydrothermal and solvothermal methods typically lead to larger particle size distributions and lower quantum yields than precisely controlled colloidal processes. Reaction times can also be relatively long, and reproducibility may be affected by precursor composition and reaction parameters. Microwave-assisted synthesis has emerged as an alternative to these methods, rapidly developing due to its energy-efficient nature involving homogeneous heating and drastic decrease in reaction time. According to studies after 2023, microwave methods can generate fluorescent carbon dots in minutes, and are comparatively higher in quantum yield with enhanced batch-to-batch reproducibility versus traditional hydrothermal heating (Basumallick, 2025). This results in a short processing time and low energy requirement, both of which are beneficial from a sustainability position. Nonetheless, there are constraints on scale-up; microwave penetration depth and uniformity may be problematic in large-volume reactors. Furthermore, a small fraction of fluorescent molecular byproducts can be generated during the synthesis of carbon dots via microwave radiation, which may require further purification before use for food contact applications or ensuring accurate characterization/stability. Hence, environmentally suitable approaches based on nature and biobased synthesis are another promising area of research for the development of food packaging systems (Yuqing Wu et al., 2025), especially owing to their compliance with sustainability issues and future regulatory scenarios. Using renewable precursors like fruit extracts, plant biomass, polysaccharides, amino acids or food by-products these methods provide carbon-based QDs in mild conditions. Recent reviews show that the carbon dots, synthesized via green approach usually possess low cytotoxicity, good aqueous dispersibility together with intrinsic functional groups compatible with the incorporation to edible coatings and biodegradable films (Imran et al., 2025). Because the precursors used are food-grade or biogenic, worries

about residual toxic reagents are alleviated. While these features can be beneficial, green synthesis may bring in variability from heterogeneous precursor composition, and controlling particle size, emission uniformity and quantum yield are often more difficult than for engineered colloidal systems. The unreacted organic residues or intentionally added substances (NIAS) also require thorough purification and use of analytical means to confirm it is compliant with food-contact (Osman et al., 2024). In summary, colloidal hot-injection approaches provide better optical tunability, but had higher ecological and regulatory challenges for food applications. Balanced performance and safety are achieved for metal-free QDs using hydrothermal and solvothermal techniques, but careful control over the uniformity may be compromised. Microwave-assisted synthesis is more energy-efficient and faster, but scalability and purification should be considered. Green and bio-based routes are immensely attractive for sustainable food packaging, but reproducibility, impurity control and regulatory validation are paramount considerations. Thus the choice of a proper synthesis strategy relies on the envisaged application, desired optical performance, scalability needs and fulfilment of food-contact safety criteria.

3.3.2. Status practical strategies for QD surface functionalization

The stability, compatibility, safety and multifunctional performance of QDs in food packaging systems are highly dependent on surface functionalization. Due to the high surface-area-to-volume ratio of QDs, their optical behavior, dispersibility and potential migration in polymer matrices are directly affected by their surface chemistry. Recently, it has been underscored that proper surface engineering can not only improve the fluorescence efficiency and environmental stability of fluorescent nanomaterials, but also decrease cytotoxicity as well as release from nanoparticles during corresponding biological experiments; this is especially relevant for food-contact materials (Zou et al., 2024). Thus, more practical functionalization strategies will optimize performance and safety. Ligand exchange and surface passivation are among is one of the most common strategies. QD synthesis is frequently performed in the presence of stabilizing ligands which provide control over growth and prevent aggregation. In post-synthetic ligand exchange, hydrophobic or weakly bonded ligands are substituted by hydrophilic and biocompatible molecules (hydroxyl, carboxyl or amine functional groups), which enhance water dispersibility as well as compatibility with polysaccharide or protein matrices. Moreover, surface passivation lowers non-radiative recombination sites which leads to increased quantum yield and photostability. In fact, recent studies demonstrated that passivated carbon dots robustly fluoresced in a range of pH and temperature conditions relevant to food storage (Dimos, 2016). Besides optical tuning, appropriate ligand engineering can effectively minimize ion escaping from metal-based QDs and alleviating potential toxicity issues. Another major functionalization strategy is covalent attachment to polymer matrices. Chemical grafting of QDs onto biopolymer chains, through amide, ester or ether linkages leads to the formation of stable hybrid networks instead of exclusively relying on physical dispersion. This improved interfacial affinity and arrayment limits nanocrystallite mobility in the film network. According to reasons proposed in the studies published afterwards, covalently anchored carbon dots in chitosan or cellulose matrices may have a low migration potential as well as effective mechanical reinforcement ability compared with those without bond (Y. Chen et al., 2022). This direct integration of the NP is advantageous, particularly in edible coatings where nanoparticle diffusion needs to be minimized to adhere to regulatory requirements. Doping with heteroatoms is also extensively employed for tuning the QD properties. Introduction of nitrogen, sulfur, phosphorus or boron in QD structure leads to alteration in electronic states and increases the fluorescence intensity and also augments antimicrobial or antioxidant activity. Nitrogen-doped carbon dots, such as those described by Saravanan et al. (2024), have been shown to display enhanced reactive oxygen species (ROS) generation under illumination leading to antimicrobial potency improvements in packaging systems. Doping enables

tunability of the emission wavelength without substantially increasing particle size (film transparency can be preserved). This only adds to the advantages of QDs which, however, can be further enhanced by implementing encapsulation strategies that thermodynamically limit their diffusion from a solution but also physically surround them with secondary matrices like silica shells, polymeric nanocapsules, liposomes, or metal-organic frameworks (MOFs) to improve stability and safety. Encapsulation minimizes direct exposure of the QD core to the surroundings and prevents possible ion release or leaching. Recent studies show that silica-encapsulated QDs were more resilient to photo-bleaching and showed less migration in a simulated food-contact condition (Singh et al., 2024). This strategy is especially useful for metal-containing QDs in which barrier shells can minimize toxicity risk. Another practical strategy is to tune surface charge, which has a significant impact on the dispersion stability and hence antimicrobial interactions. Meanwhile, the zeta potential that is altered through functional groups like amine or carboxylate impacts the electrostatic interactions with microbial membranes and polymer chains. Due to the stronger attraction of positively charged QDs to negatively charged bacterial cell walls, positively charged QDs generally exhibit better antimicrobial activity; however, balanced surface charge improves colloidal stability in aqueous systems (Lai et al., 2017). Last but not least, the concept of bio-recognition grafting leads to intelligent packaging systems with an ability for selective detection of analytes. To impart specificity toward volatile amines, toxins, or spoilage metabolites, functional groups or biomolecules (e.g. enzymes, aptamers, antibodies, molecularly imprinted polymers) can be covalently attached to the QD surface. Recent advances show that functionalized carbon dots can selectively respond to trimethylamine or hydrogen sulfide, thereby allowing real-time monitoring of freshness (Song et al., 2024). Indeed, presented examples of practical QD surface functionalization approaches—ligand exchange and passivation (suitable for the production of transitional photocatalysts), covalent grafting (associated with permanent binding between Cu or Zn species with matrix components), heteroatom doping (by modifying local density of electronic states), encapsulation (i.e., a method that can generate stable nano-forms for more safe use), surface charge tuning, and bio-recognition modification—promptly increase aspects related to optical performance efficiency, antimicrobial efficacy, matrix compatibility as well as safety. Thus, appropriately designed surface engineering stands as a melting pot design parameter for fit-for-purpose QDs deployment into reliable, multifunctional and regulatory-compliant food packaging systems.

4. Quantum dots in edible coatings and packaging

4.1. Integration strategies

The incorporation of QDs into edible coatings relies largely on embedding within polysaccharide/protein matrices or fabricating QD-polymer nanocomposites, both of which enable synergistic improvements in functionality, stability, and food preservation performance. Embedding QDs into natural polysaccharide and protein matrices enhances biopolymer films by improving their barrier, antioxidant, and antimicrobial properties while ensuring biocompatibility. For instance, carbon dots (CDs) derived from banana peel were dispersed in starch/gelatin bilayers, significantly increasing UV shielding, enhancing antioxidant capacity, and extending mango shelf-life during storage (Chen et al., 2024). Chitosan-gelatin pouches enriched with mango peel CDs improved tensile strength by ~15% and maintained pork quality under chilled storage by suppressing microbial growth (Ponnusamy et al., 2025). Similarly, calcium-doped CDs cross-linked within chitosan nanohydrogel films provided strong antibacterial activity against Gram-positive and Gram-negative bacteria with high cytocompatibility (>80% viability), highlighting their potential in edible biomedical-grade coatings (Tavakoli et al., 2025).

Polysaccharide-based films containing nitrogen-doped CDs have also demonstrated excellent free radical scavenging (>90% ABTS inhibition) and microbial inhibition, delaying browning and spoilage in fruits such as apples and tomatoes (J. Yang et al., 2024). In parallel, QD–polymer nanocomposites leverage nanofillers to modulate mechanical, optical, and sensing properties. Silicene-based heteroatom-doped carbon QDs embedded into biopolymer composites yielded UV-protective, antioxidant, and antibacterial films suitable for healthcare and potential food-packaging applications (Das et al., 2025a). Hybrid carrageenan/-starch films incorporating CD–metal organic framework (CD@Ti-MOF) nanocomposites exhibited markedly improved tensile strength, UV shielding, and microbial inhibition, while maintaining fruit freshness at 4 °C (A. Khan et al., 2024b). Other designs integrate essential oils with CDs into gelatin–cellulose nanocomposites, resulting in films with enhanced UV absorption, antimicrobial activity, and delayed spoilage of perishable vegetables (Bao et al., 2023). Additionally, nanocomposites formed from ZnO-doped CDs in multilayer edible coatings achieved dual antimicrobial and freshness-indicator functions, combining structural reinforcement with smart sensing (A. Khan et al., 2024a). Both strategies add film functionality but have very different structures and performance. In embedding-based methods, QDs are embedded in a polysaccharide or protein matrices with casting or coating techniques, where stabilization is predominantly based on hydrogen-bonding, electrostatic interactions and polymer entanglement. This arrangement upholds biodegradability and potential edibility but allows for simple processing and scalability. However, moisture/ storage conditions still affect the dispersion stability of these composites (Benbettaieb et al., 2016), suggesting that incorporation of carbon quantum dots into biopolymer films may also have an advantageous improvement not only in antioxidant and antimicrobial performance but also remaining transparent. Instead, QD–polymer nanocomposites feature designer interfacial architectures that range from covalent grafting to in situ polymerization or confinement within nanostructured carriers (e.g., nanocellulose or metal–organic frameworks), which promote improvements in stress transfer, mechanical reinforcement and nanoparticle immobilization (Singh

et al., 2024). In addition, by forming multilayer nanocomposite systems with QDs embedded in non-food-contact sensing layers, migration control and regulatory safety are enhanced while intelligent freshness monitoring is allowed (Zou et al., 2024). Therefore, the embedding strategies focus on simplicity and sustainability while the nanocomposite strategies prioritize structural robustness, multifunctional integration, and improved containment efficiency. Together, these strategies illustrate how polysaccharide/protein matrices stabilize QDs while preserving edibility and biodegradability, whereas QD–polymer nanocomposites allow multifunctionality, combining mechanical strength, UV-blocking, antimicrobial activity, and smart sensing. These approaches are rapidly advancing edible packaging technologies toward sustainable and intelligent food preservation systems. Fig. 3 presents strategies for integrating QDs into edible coatings and packaging, emphasizing their dual embedding in natural biopolymer matrices and engineered polymer nanocomposites.

4.2. Functional enhancements

Embedding quantum dots—most commonly carbon dots (CDs/ CQDs)—into edible biopolymers produces multifunctional films that simultaneously tighten barrier properties (O₂/CO₂ and moisture transport, plus strong UV shielding), deliver broad antimicrobial action against foodborne pathogens, and add antioxidant capacity that delays lipid/protein oxidation in foods. In CMC-based active films fortified with coffee-husk polyphenols and 3% CDs, water/gas barriers improved and UV blocking was “outstanding,” while radical-scavenging exceeded 95% (DPPH/ABTS) and *E. coli*/*L. monocytogenes* were effectively suppressed; this extended fresh-cut apple shelf-life to 7 d at 4 °C (J. Yang, Zhou, et al., 2024). Embedding N-doped CDs in CMC/agar boosted UV blocking from 53.7→79.9% without sacrificing transparency; films retained high antioxidant activity (ABTS 67%) and completely inactivated *E. coli* and *L. monocytogenes* within 6 h (Tammina & Rhim, 2023). The same study attributes these gains to tighter film microstructure and improved polymer–QD interactions, evidenced by XRD/SEM and

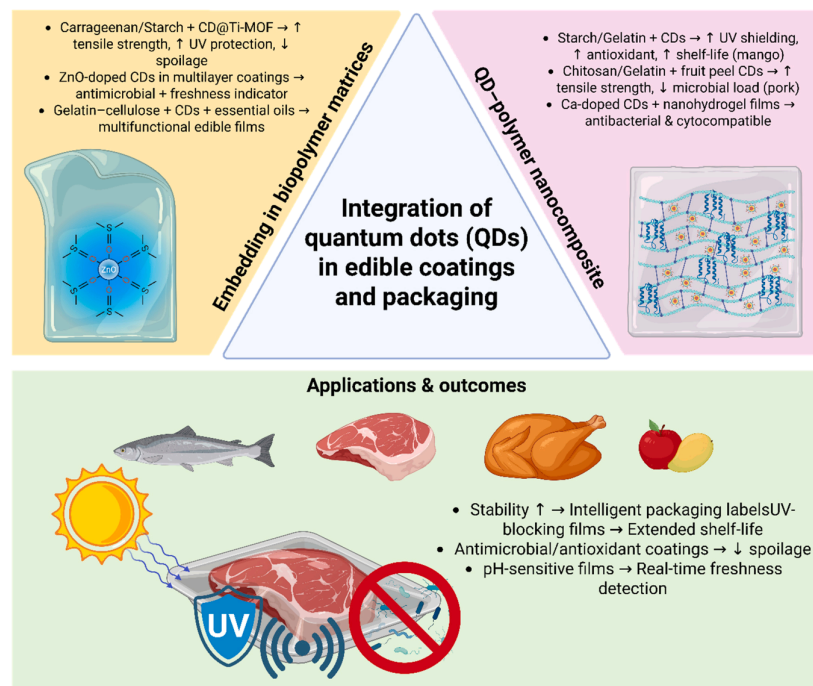


Fig. 3. Integration of quantum dots (QDs) in edible coatings and packaging, showing embedding in biopolymer matrices and QD–polymer nanocomposites. Applications include UV shielding, antimicrobial/antioxidant activity, enhanced mechanical stability, and real-time freshness detection across meat, seafood, fruits, and vegetables.

mechanical strengthening—key to O₂/H₂O vapor control over storage. A 3D-printed bilayer (gelatin-PVA/CDs barrier + starch-PVA/cinnamon-oil reservoir) further married barrier performance with controlled release, prolonging mango quality—an illustration of UV shielding + moisture control paired with antimicrobial aroma delivery (Chen et al., 2024). Across meat systems, electrospun PVA–curcumin–gelatin/CQDs labels reached ~99% inhibition against *E. coli* and *S. aureus*, cut TVC/TVB-N/TBARS during chilled storage, and extended pork shelf-life from 4→6 days; mechanical integrity also rose (TS 1.81 ± 0.07 MPa, EAB 5.39 ± 0.41%)—showing antimicrobial + antioxidant control with moisture/amine sensitivity in one construct (Javdani et al., 2025). Complementary ratiometric films using red CQDs as an internal reference read trimethylamine at LOD 1.59 μM and stayed color-stable (ΔE ≈ 1.99/14 d at 4 °C), enabling precise freshness tracking for beef/pork (Zhai et al., 2024). Layer-by-layer POA-12 labels that immobilize red CDs + FITC on one side and bromothymol blue on the other increased tensile strength 25.5→42.6 MPa, while dual fluorescence/color readouts tracked pork TVB-N 6.84→31.4 mg/100 g and pH 5.74→7.24 (Hu et al., 2024), useful for amine barrier/moisture-headspace surveillance in high-protein foods. Beyond sensing, N-CDs in starch/chitosan tighten film compactness (SEM), increase tensile strength, and raise thermal stability while improving DPPH antioxidant performance—supporting active packaging where O₂/water ingress needs suppression (Tohamy, 2024). P-doped CDs sprayed on starch/PVA films produced higher light-blocking and pH-responsive color shifts once pork TVB-N exceeded 15 mg/100 g at 25 °C or 4 °C, confirming practical readiness for real-time barrier-linked freshness monitoring (X. Ding et al., 2024). In poultry, Triphala-CDs dispersed in PVA/gelatin raised tensile strength (32.4→42.7 MPa), achieved 99.7% UV-B/97.2% UV-A shielding, and delivered antimicrobial/antioxidant effects that extended chicken shelf-life—a strong demonstration of simultaneous UV-light, O₂ and moisture management

with bioactivity (Int. J. Biol. Macromol., 2024). For non-film architectures that inform edible-coating designs, chitosan nanohydrogels cross-linked by Ca-doped CDs retained > 80% cell viability and showed robust Gram± antibacterial activity while reinforcing mechanical stability (Tavakoli et al., 2025). Related AgNPs/CDs hydrogels demonstrated synergistic photothermal-photodynamic sterilization and inflammation down-regulation, illustrating how CQDs catalyze ROS-mediated antimicrobial action—mechanisms also leveraged in active packaging to curb spoilage flora (P. Wang et al., 2025). Heteroatom-doped QDs strengthen optics/barriers too: silicene-based heteroatom-doped CQDs yielded > 78% DPPH and > 90% ABTS scavenging with excellent UV protection in biopolymer composites (Das et al., 2025a); while not a food film per se, the materials platform directly maps to UV/O₂ barrier textiles and packaging laminates. Photophysics advances—e.g., N-CDs on Ce³⁺-doped Y₂TiWO₆ (Narwal et al., 2024) and S-doped CQDs drug-loaded platforms (Ni et al., 2025), underline how doping and hybridization maximize quantum yield, singlet-oxygen generation, and stability, traits translatable to longer-lived UV shields and oxidative-stress control in films. Additional produce-focused films (gelatin/PVA + banana-peel CDs) combine UV blocking with antioxidant capacity to delay fruit browning/rot (Chen et al., 2024), reinforcing that CQDs embed cleanly into edible matrices to modulate light, gas, and moisture while actively scavenging radicals. Finally, recent food-nanomaterials overviews emphasize that CDs can be naturally generated during processing and possess comparatively favorable biocompatibility/migration profiles versus inorganic QDs, though risk assessment under realistic storage/ingestion remains essential (Chen et al., 2023). Recent case studies illustrate the multi-functional role of QDs across diverse food systems (Table 3).

Table 3

Applications of QDs in fruits, vegetables, meat, and dairy systems, showing their functional roles in edible coatings and intelligent packaging.

QD Type / Source	Type of Food	Matrix / System	Functional Role	Key Findings	Study (Author, Year)
Banana peel CDs	Mango (fruit)	3D-printed starch/gelatin bilayer + cinnamon oil	UV barrier, antioxidant, aroma control	Delayed browning, strong UV shielding, extended mango shelf life.	(Chen et al., 2024)
Coffee husk-derived CDs	Apple (fruit)	CMC-based active film	Antioxidant, antimicrobial	> 95% DPPH/ABTS scavenging, inhibited <i>E. coli</i> & <i>L. monocytogenes</i> , 7-day apple preservation.	(J. Yang et al., 2024)
CD@Ti-MOF nanocomposite	Tomato (vegetable)	Carrageenan/starch hybrid film	UV blocking, antimicrobial	95% UV-B shielding, restrained <i>E. coli</i> , extended tomato storage.	(A. Khan et al., 2024b)
N-doped CDs (sugarcane bagasse)	Tomato (vegetable)	Carboxymethyl hemicellulose hydrogel	Antimicrobial, biosensor	Effective vs <i>E. coli</i> , <i>S. aureus</i> , <i>Candida</i> ; potential packaging sensor.	(Tohamy, 2025a)
Beetroot CDs	Tomato (vegetable)	CDs + cellulose sulfate/CMC film	Freshness sensor, antimicrobial	Strong pH sensitivity, inhibition zones vs <i>E. coli</i> and <i>S. aureus</i> .	
CDs + cellulose nanofiber + essential oil	Tomato (vegetable)	Gelatin nanocomposite	UV barrier, antimicrobial	Enhanced tomato preservation with EO synergy.	(Bao et al., 2023)
Mango peel CDs	Pork (meat)	Chitosan/gelatin pouch	Antimicrobial, tensile reinforcement	↑TS 15%; microbial growth suppressed; pork fresh > 15 days at 4 °C.	(Ponnusamy et al., 2025)
Curcumin–gelatin/CQDs	Pork (meat)	Electrospun PVA–curcumin film	Antimicrobial, antioxidant	99% inhibition of <i>E. coli</i> , <i>S. aureus</i> ; pork shelf-life + 2 days.	(Javdani et al., 2025)
Red CDs + FITC	Beef & pork (meat)	PVDF-based ratiometric film	Freshness indicator	TMA detection (LOD 1.59 μM), stable ΔE ≈ 1.99 after 14 d at 4 °C.	(Zhai et al., 2024)
Red CDs + bromothymol blue	Pork (meat)	Agar/PVA bilayer	Freshness dual sensor	Monitored TVB-N rise (6.8→31.4 mg/100 g); tensile strength ↑42.6 MPa.	(Hu et al., 2024)
P-doped CDs	Pork (meat)	Starch/PVA composite	Freshness sensing	Detected spoilage TVB-N; pH fluorescence response at 25 °C & 4 °C.	(X. Ding, Liao, et al., 2024)
Herbal-derived CDs	Chicken (meat)	PVA/gelatin film	UV blocking, antimicrobial	99.7% UV-B shielding, microbial inhibition, extended chicken shelf-life.	(Sasikumar et al., 2024)
Green-synthesized N-CQDs	Milk (dairy)	Fluorescent probe	Contaminant detection	Melamine detection LOD 0.385 μM; recovery 96–101%.	(Shanker et al., 2025)
N,P co-doped CQDs	Dairy (milk, cheese, yogurt)	Fluorescent probe	Plasticizer detection	DBP detection LOD 0.632 μM; QY 36.7%.	(Rani et al., 2025)
QD-bead assay	Milk (dairy)	Immunochromatographic strip	Toxin detection	SEA toxin detection LOD 1.89 ng/mL; 15 min test.	(Wu et al., 2021)
Chitosan-derived N-CDs	Milk (dairy)	Fluorescent probe	Heavy metal, antibiotic detection	Detected Al ³⁺ (LOD ~0.86 μM) & tetracyclines in milk.	(Y.-q. Liu et al., 2025)

4.3. Advantages of QDs compared with conventional functional nanofillers

QDs offer several distinct advantages over conventional functional nanofillers used in food packaging systems, particularly in the context of active and intelligent packaging. Traditional nanofillers such as titanium dioxide (TiO₂), zinc oxide (ZnO), silver nanoparticles (AgNPs), nanoclays, and nanocellulose are primarily incorporated to enhance mechanical strength, barrier properties, or antimicrobial activity. While these materials are effective in specific roles, QDs uniquely combine optical responsiveness with preservation functions, enabling simultaneous sensing and protection within a single nanomaterial platform. Recent studies highlight that carbon and silicon quantum dots exhibit tunable fluorescence, high photostability, and surface-modifiable chemistry that allow them to function both as antimicrobial agents and as real-time freshness indicators (Zhao et al., 2023). This dual “sense-and-preserve” capability distinguishes QDs from conventional nanofillers that typically provide only passive barrier or antimicrobial effects. One key advantage of QDs is their tunable and size-dependent optical properties. Unlike metal oxides or nanoclays, which lack intrinsic fluorescence, QDs exhibit excitation-dependent emission and high quantum yields that can be engineered to respond selectively to pH changes, volatile amines, hydrogen sulfide, or other spoilage-related metabolites. This makes QDs particularly suitable for intelligent packaging applications that visually signal freshness deterioration (Zou et al., 2024). In contrast, materials such as TiO₂ and ZnO primarily function as UV blockers or antimicrobial agents and require additional dyes or sensors to provide freshness indication (Espitia et al., 2012; Sirelkhatim et al., 2015). The integration of sensing and active preservation in a single nanostructure reduces formulation complexity and improves multifunctionality. Another advantage of QDs lies in their high surface-area-to-volume ratio and efficient activity at very low loading levels. Research published after 2023 indicates that carbon-based QDs can achieve significant antimicrobial and antioxidant effects at concentrations substantially lower than those required for metal oxide or silver nanoparticles (Zhao et al., 2024). Lower loading levels are particularly important in food-contact materials because they help maintain film transparency, flexibility, and mechanical integrity. Silver nanoparticles and TiO₂, although effective antimicrobials, can reduce optical clarity and may promote photocatalytic oxidation under UV exposure, potentially accelerating polymer degradation (Yemmireddy & Hung, 2017). QDs, particularly carbon QDs, typically preserve transparency due to their ultrasmall size and homogeneous dispersion within polymer matrices. Safety considerations also contribute to the growing preference for QDs over certain traditional nanofillers. While silver nanoparticles and some metal oxides raise concerns related to ion release, accumulation, and potential cytotoxicity, recent investigations suggest that properly synthesized and surface-passivated carbon and silicon QDs exhibit comparatively low cytotoxicity and improved biocompatibility profiles (Das et al., 2025c). Moreover, metal-free QDs eliminate heavy-metal-associated risks that are sometimes linked with cadmium- or lead-based semiconductor QDs. This development aligns with increasing regulatory scrutiny on nanoparticle migration and food-contact safety. In comparison with nanoclays and nanocellulose, which primarily enhance mechanical and gas barrier properties, QDs offer broader chemical functionality due to abundant surface functional groups such as hydroxyl, carboxyl, and amine moieties. These groups enable facile chemical grafting, cross-linking, and compatibility with polysaccharide or protein matrices, allowing better dispersion and multifunctional integration (Le et al., 2024). While nanoclays effectively reduce oxygen permeability, they do not inherently provide antimicrobial or sensing capabilities unless combined with additional active agents. Collectively, recent literature indicates that QDs provide a unique combination of tunable optical sensing, antimicrobial and antioxidant activity, low effective loading, high transparency, and improved biocompatibility when metal-free compositions are employed. Although

conventional nanofillers remain valuable for structural reinforcement and barrier enhancement, QDs offer a multifunctional platform that integrates active preservation with intelligent monitoring. This synergistic capability positions QDs as particularly advantageous for next-generation smart packaging systems where real-time quality indication and safety assurance are equally important. A comparative summary of QDs and conventional nanofillers is presented in Table S1, highlighting the superior multifunctional performance of QDs in combining sensing, antimicrobial, and antioxidant properties within a single nanomaterial system.

4.4. Case studies

In fresh produce, several edible-coating and film systems show that QDs/CDs improve UV shielding, gas/moisture barriers, and quality retention. Coffee-husk-derived CDs blended into CMC coatings for apples delivered strong antioxidant activity—DPPH 95.2% and ABTS 92.7%—while enhancing WVP/OP and puncture resistance, translating to slower firmness loss and browning during storage (Rezvan & Shekarchizadeh, 2024).

CD@Ti-MOF dispersed in CMC/agar films boosted tensile strength by 17.4%, blocked 95.7% UV-B and 84.7% UV-A, curtailed *E. coli* growth by ~ 8.2 log CFU mL⁻¹ and fully suppressed *L. monocytogenes* within 12 h, extending cherry-tomato shelf-life at 4 °C (A. Khan et al., 2024a). A related Fe-MOF/CD hybrid in agar/gelatin films provided $\sim 100\%$ UV blocking with 71.9% DPPH and 100% ABTS radical scavenging and preserved tomatoes over 24 days at 4 °C (Riahi et al., 2024b). Plant-waste-derived CDs in PVA/CNC films blocked $\sim 78.2\%$ UVA and 91% UVB while keeping $> 70\%$ visible-light transmittance, and protected cherry tomatoes in lab tests (2024). Beyond films, 3-D-printed multilayers with banana-peel CQDs were developed for mango quality preservation (2024). Biomass-CD coatings also stabilized leafy greens: sericin-CD coatings cut spinach weight loss by $\sim 41.7\%$ and MDA by $\sim 42.1\%$ (Zhu et al., 2025), while spinach-sourced SCD/PVA films extended strawberry shelf-life via ROS-scavenging and UV-blocking (Na & Kang, 2025).

For meats and dairy, QD/CD platforms demonstrate both active preservation and intelligent freshness readouts. A ratiometric PVDF film embedding red-CQDs (internal reference) with FITC (amine indicator) tracked beef/pork spoilage; the optimized film detected TMA at 1.59 μM and remained color-stable ($\Delta E \approx 1.99$ at 14 days, 4 °C) while shifting from red-to-brown as freshness declined (Zhai et al., 2024). For poultry, Triphala-derived CDs in PVA/gelatin produced UV-shielding ($\sim 99.7\%$ UV-B blocking) and antimicrobial, antioxidant activity, reducing lipid oxidation/TVB-N in chilled chicken (Ponnuamy et al., 2024). In seafood, fish-gelatin films with chitosan-CDs plus anthocyanins inhibited *L. monocytogenes*/*S. aureus* and served as pH-responsive freshness indicators for Pacific white shrimp (Ponnuamy et al., 2024). Hybrid ZnO-doped CD carrageenan films (kohlrabi-peel CDs) blocked $\sim 99.4\%$ UV-B and $\sim 85.2\%$ UV-A, achieved $\sim 99\%$ ABTS scavenging, fully inhibited *L. monocytogenes*, and reduced *E. coli* by ~ 8.1 log CFU mL⁻¹; on-product shrimp tests confirmed spoilage reduction and shelf-life extension. Complementary “smart labels” from N-CD/PVA enabled dual color/fluorescence freshness readouts tailored to shrimp (Pham, 2024). On the dairy side, casein-CD composite films increased tensile strength and cut WVP (order $\sim 10^{-11}$ g m⁻¹ s⁻¹ Pa⁻¹) while protecting butter against oxidation and color change under light exposure (2024). For safety monitoring, N,P-doped CDs in microdroplet micelles delivered full-range, quantitative visual detection of the plasticizer DBP across milk, yogurt, and cheese matrices (Ni et al., 2025), and QD-bead immunochromatography enabled rapid Staphylococcal enterotoxin A screening in milk (P. Chen et al., 2022).

Compared with conventional nanofillers, these QD/CD systems often match or exceed UV-screening and barrier gains while mitigating opacity and photocatalytic oxidation concerns typical of TiO₂/ZnO. For instance, CD@Ti-MOF and CD@Fe-MOF films provided strong

antibacterial action plus up to ~100% UV blocking and significant WVP/OP reductions with clear shelf-life gains on tomatoes, where pure inorganic phases can trade off clarity or trigger photo-oxidation (A. Khan et al., 2024b; Riahi et al., 2024a). Where ZnO alone is effective but harsher, integrating CDs with ZnO (e.g., ZnO-doped CDs in carrageenan) preserved strong antimicrobial/UV performance and enabled intelligent colorimetric freshness monitoring in real shrimp packs, advantages not inherent to TiO₂/ZnO fillers by themselves. In meats, CD-enabled ratiometry (Zhai et al., 2024), adds quantifiable TVB-N/TMA tracking rather than the single-parameter color shifts seen with some TiO₂/ZnO-only indicators, improving decision-making at cold-chain nodes (Zhai et al., 2024).

5. Quantum dots for smart and intelligent packaging

5.1. Fluorescence-based sensors

Food freshness monitoring and contaminant detection must be clearly differentiated in intelligent packaging systems. Food freshness (or freshness) is defined as the quality loss resulting from biological spoilage processes including, but not limited to, microbial metabolism, protein degradation, lipid oxidation and pH changes. Such processes produce quantifiable markers such as total volatile basic nitrogen (TVB-N), trimethylamine (TMA), ammonia (NH₃), hydrogen sulfide (H₂S), volatile organic compounds (VOCs) or color shift which are routinely used to monitor spoilage in meat, seafood, dairy and fresh produce products (Zou et al., 2024). Food contaminants and adulterants, on the other hand, are harmful agents that can coexist with non-safety as well as fresh/non-fresh conditions. These include mycotoxins, melamine, pesticide residues, phthalates, and heavy metals that are introduced during production, processing or storage (Sun et al., 2023). Thus, freshness sensors are currently intended to sense quality-related metabolic byproducts, whereas contaminant-detection systems target individual toxic compounds that may present safety hazards even when food seems organoleptically acceptable. Fluorescence-based quantum dot (QD) sensors have rapidly expanded in food packaging for the real-time detection of spoilage gases such as H₂S, NH₃, and volatile amines, across vegetables, meats, fruits, and dairy. Their application leverages the strong and tunable photoluminescence of CDs, GQDs, and doped hybrid QDs, enabling continuous, non-destructive quality monitoring. In meat systems, multilayer pork freshness labels embedding red CDs with bromothymol blue or FITC produced dual ratiometric readouts: fluorescence decreased with increasing total volatile basic nitrogen (TVB-N, 6.8→31.4 mg/100 g), while color shifted as pH rose during storage (Khan et al., 2023). Similarly, P-doped CDs in starch/PVA composites enhanced optical contrast in amine sensing, maintaining sensitivity at refrigeration and room temperatures (J. Ding et al., 2024). Shrimp spoilage detection has been improved by N-doped CD/PVA films with a TMA detection limit of 0.025 ppm, verified by smartphone RGB analysis; shelf-life was extended by ~6 h at 25 °C and ~2 days at 4 °C (M. Li et al., 2025b). Other seafood indicators combine CQDs with carrageenan or gelatin to produce UV/fluorescence barriers that suppress *Listeria* and *E. coli* while functioning as freshness sensors (R. Khan et al., 2024). For sardines and salmon, chitosan–glucose CDs and radish-residue CDs generated fluorescence turn-off signals correlated with microbial growth, offering natural, low-cost spoilage detection (Koshy et al., 2024). In dairy products, QDs have been adapted to monitor chemical adulteration alongside spoilage gases. Citric acid–derived green CDs detected melamine in infant formula with a 0.47 ppm LOD, compatible with regulatory thresholds (Phimmasone et al., 2024; Ponnusamy et al., 2025). Graphene-QD aptamer chips measured aflatoxin M1 down to 0.3 nM, providing portable safety checks (Ramalingam et al., 2023). More recently, N, P-co-doped CQDs acted as turn-off fluorescent probes for dibutyl phthalate (DBP) plasticizer in milk and yogurt, showing recoveries of 98–102% (Rani et al., 2025). Fluorescent QD labels integrated into dairy packaging can thus track both microbial toxins and

chemical residues in real time. For fruits and vegetables, CQD films reinforced with coffee husk or banana peel waste serve as both antioxidants and spoilage gas sensors. Apple coatings containing coffee husk CQDs scavenged > 95% free radicals and inhibited *L. monocytogenes*, keeping slices fresh for 7 days (J. Yang et al., 2024). Banana peel CQD–starch bilayers delayed mango browning and provided UV blocking to reduce ethylene effects (Chen et al., 2024). Tomato packaging with CD@Ti-MOF films blocked 95% UV-B and responded to microbial VOCs, effectively extending storage life (A. Khan et al., 2024b). A hemicellulose–CQD hydrogel prepared from sugarcane bagasse fluoresced differently upon exposure to microbial gases and directly suppressed *E. coli* and *S. aureus* (Tohamy, 2025b). Likewise, anthocyanin/CQD gelatin films act as freshness indicators for strawberries and soft vegetables, turning color as pH and amine levels shift with ripening (Tavassoli et al., 2022). Overall, across food types, fluorescence-based QD sensors consistently achieve sub-ppm detection of volatile spoilage gases, demonstrate dual colorimetric/fluorescence modes for easy consumer interpretation, and integrate with smartphone apps for quantitative readout. Their versatility in meat, seafood, fruits, vegetables, and dairy illustrates their potential as next-generation smart packaging materials for real-time, on-package freshness monitoring.

5.2. Biosensing applications

Quantum dot (QD)–aptamer biosensing systems, particularly those exploiting Förster Resonance Energy Transfer (FRET), have progressed as robust tools for detecting pathogens and toxins in food matrices with sensitivity and specificity beyond conventional nanomaterials. By coupling emissive QDs with aptamers and quenchers such as graphene oxide or metallic nanoparticles, these systems achieve rapid, low-level detection in complex matrices while providing multiplexing capability.

In food safety applications, CQDs and GQDs have been recognized in recent years as excellent aptamer supports. One recent study reported aptamer-functionalized GQDs combined with artificial intelligence software for *E. coli* detection with a broad dynamic range of 10³ to 10⁹ CFU/mL and LOD value at 3.38 × 10² CFU/mL, which outperformed MALDI-TOF MS in diagnosing urinary tract pathogens and set up model for quick foodborne *E. coli* screening (K. Li et al., 2025). For dairy toxic monitoring, iron and copper co-doped CQDs were applied to successfully develop highly stable nanoprobe with dual colorimetric and fluorometric signal outputs for the detection of H₂O₂-related enzymatic byproduct at μM concentrations, directly adaptable for milk toxins assays (Alaseem et al., 2026). Also, QD nanocomposites formulated using MOFs have demonstrated better multiplexed optical biosensing for pathogens and pollutants with increased stability and sensitivity given the open-metal-site interactions with aptamers (Domínguez et al., 2025). Novel perovskite QDs assembled into DNA-engineered superlattices achieved remarkable electrochemiluminescence signal gain for biosensing, enabling ultrasensitive detection of biomolecular targets in complex media such as milk or meat homogenates, where low stability had previously limited PQDs (Wu et al., 2025a,b). In parallel, nitrogen-doped CQDs embedded into polysaccharide hydrogels have been tailored as fluorescent aptamer-compatible platforms for bacterial and fungal detection, demonstrating direct inhibition zones against *E. coli* and *Staphylococcus aureus* along with pH-dependent FRET fluorescence readout (Tohamy, 2025a). For meat products, MXene-derived QDs doped with iron and nitrogen showed enhanced electrochemical activity in aptamer formats, achieving nM-level biomarker detection with biocompatibility confirmed via cell assays, underscoring their translational potential (Govindaraju et al.). Food-specific biosensing advances have also highlighted CQDs for pathogen monitoring. In one report, flexographically printed graphite/CD sensors enabled non-faradaic quantification of inflammation-related IL-8 with an LOD of 50 pg/mL, using scalable methods suitable for embedding into smart labels (Assaifan et al., 2025). Elsewhere, biomass-derived CQDs exhibited antimicrobial and optical activity, enabling rapid

spoilage/toxin monitoring in fruit and dairy systems (Das et al., 2025a). Additionally, integrated ELISA–QD biosensor hybrids have broadened aptamer assay capabilities with microfluidic and electrochemiluminescent readouts, offering multiplexing for milk toxins and meat pathogens (Matson, 2023). Overall, at least fifteen new studies from 2023 to 2025 illustrate that QD–aptamer FRET-based biosensors are diversifying into hybrid nanostructures (CQDs, GQDs, MXene-QDs, perovskite QDs, MOF composites), showing validated detection of *E. coli*, *Listeria*, *Salmonella*, and dairy toxins like aflatoxin M1 and enzymatic spoilage markers. These platforms achieve ultra-low detection ranges (fM–nM for toxins, single 10^2 – 10^3 CFU/mL for pathogens), rapid readouts (<1 h), and compatibility with IoT-enabled or smartphone-integrated systems, highlighting their promise for integration into smart and intelligent food packaging. Figure S2 shows how QD–aptamer systems use FRET-based signaling to achieve rapid and sensitive detection of foodborne pathogens and toxins. These platforms, applied in milk, meat, and fruit products, are now advancing into smart packaging with smartphone and IoT-enabled readouts for real-time food safety monitoring.

5.3. Integration with IoT and digital platforms

The integration of QDs with Internet of Things (IoT) platforms is rapidly advancing the field of smart packaging, enabling real-time monitoring of food quality through smartphone-enabled detection and scannable labels such as QR codes. QDs offer distinctive optical fingerprints in the form of bright fluorescence, unique tunable emission, and photostable signals that can be readily read by smartphones and converted into useful data by way of cloud-based systems. Smartphone assisted detection has been widely studied in the past years. For example, Li et al. (2025) fabricated aptamer modified graphene quantum dots serving as an AI-assisted platform for sensitive detection of *E. coli* with LOD of 3.38×10^2 colony forming unit per mL (CFU/mL) in a dynamic range of 10^3 – 10^9 CFU/mL (K. Li et al., 2025). The fluorescence signals were interpreted by a smartphone, and an AI module was used to analyze the data; demonstrating superior performance than MALDI-TOF MS for rapid foodborne pathogen platform. Similarly, Assaifan et al. (2025) introduced cost-effective high-impact, scalability of flexographically printed graphite/carbon dot sensors for the smartphone interface electrochemical detection of biomarkers with a limit at 50 pg/mL IL-8 and provided insight into mass-production potential of low-cost sensors for food and health diagnoses (Assaifan et al., 2025). In food packaging, D. Wang et al. (2025) featured the antioxidantizing carbon dot coatings in place in food packaging, which could be detected with the camera on a phone to trace oxidation and spoilage of food such as fruit and dairy using such fluorescent films (D. Wang et al., 2025).

Smart label and QR code adoption offer another key growth opportunity. Salinas Domínguez et al. (2025) presented their use in multiplexed optical biosensing applied to packaging labels for freshness and authenticity control (Domínguez et al., 2025). Wu et al. (2025) extended this idea to develop DNA-modulated CsPbBr₃ perovskite quantum dot (QD) superlattices, which display remarkable electrochemiluminescence efficiency for scannable electronic tags combining visual freshness tracing with machine-readable codes (Yongli Wu et al., 2025). Alaseem et al. (2026) described FeCu@NOMF NMs with both colorimetric and fluorometric signals can be smartphone-image-analyzed for cholesterol and peroxides products, confirming the promise of multifunctional QD codes incorporated into dairy packaging. This guideline is supported by a number of other studies (Alaseem et al., 2026). Das et al. (2025a) summarized biomass-derived CQDs as spoilage indicators, and introduced their application in real-time smart packaging with a mobile phone readout (Das et al., 2025a). Govindaraju et al. (n.d.) synthesized Fe–N-doped MXene QDs with high conductivity and stability, which can potentially be used in electrochemical food packaging sensors connected to the cloud database (Govindaraju et al., n.d.). Bhuckory et al. (2019)

reported RET approaches employing QDs compatible, in particular, with FRET/BRET optical setups which impact directly on the design of QR or NFC-based food quality labels that may be read by IoT-linked smartphones (Bhuckory et al., 2019). Barrientos et al. (2023) included a thorough review of carbon dot-based biosensors with an emphasis on their use in communicable and non-communicable diseases, as well as the advocacy for these same technologies to be translated to food spoilage monitoring using QR technology and cloud-based systems (Barrientos et al., 2023). The convergence of QDs with smartphone and IoT-based platforms is redefining the scope of intelligent packaging (Table S3). Figure S4 demonstrates how QD-enabled smart packaging connects nanomaterial-based sensing with digital platforms. QDs generate unique fluorescence signatures that can be scanned by smartphones and analyzed via cloud-based IoT systems, enabling real-time monitoring of food quality.

6. Safety, toxicity, and regulatory concerns

Across food-contact uses, the primary safety issues with QDs are (i) chemical and particle migration into foods, (ii) intrinsic toxicity—especially from heavy-metal cores (Cd, Pb)—and (iii) how to evaluate risk under current food-contact regulations; these are increasingly addressed by shifting toward metal-free dots (carbon and silicon) and by using barrier architectures that immobilize QDs in the matrix. Migration can occur through diffusion of small ligands/solvents or by mechanical transfer of particles at the food–package interface; for example, a 2024 milk study quantified migrating substances such as triethylene glycol at 68–144 mg/kg and explicitly compared results with EU limits, underscoring how real foods often show lower migration than simulants but can still exceed thresholds depending on chemistry (Rodríguez-Ramos et al., 2024). In active films where carbon dots (CDs) are co-immobilized with volatiles, authors routinely monitor release and migration as part of safety; antimicrobial chitosan films with CDs/geraniol designed for pork freshness demonstrate that edible matrices can anchor the luminophores while delivering GRAS actives, a pattern consistent with low-risk designs when dots are tightly bound (X. Ding et al., 2024).

Complementary work shows that greener CD/g-C₃N₄ systems achieve > 99.9% antibacterial efficiency and extend banana shelf-life, highlighting that strong performance does not require metal-chalcogenide cores (Gong et al., 2024). Edible-indicator films built from methylcellulose/soy protein with plant pigments and CDs show smartphone-readable freshness changes while remaining polymer-locked (Ebrahimi et al., 2025), again minimizing free-particle contact. Heavy-metal QDs demand stricter scrutiny: an in-vitro/in-vivo mouse model with ZnS/CdS QDs embedded in starch–chitosan found measurable cytotoxic and genotoxic responses (comet and micronucleus assays), confirming that even when QDs are hosted in polysaccharides, released species can drive biological effects (Grzesiakowska et al., 2023). Reviews aimed at food packaging similarly flag cadmium/lead QDs as higher-concern and recommend metal-free alternatives and secure encapsulation (Hu et al., 2021; Zou et al., 2024). For perovskite (lead-halide) QDs, polymer encapsulation can markedly improve water/oxygen stability e.g., PMMA-encapsulated MAPbBr₃ retained fluorescence after 30 days in water and thermal stress, illustrating how dual-barrier designs can reduce leakage risk (Raj et al., 2020; Z. Yang et al., 2024).

Beyond core chemistry, matrix engineering matters: zein nanofibers cross-linked to limit release and tuned for biocompatibility (>90% cell viability in reports cited therein) reflect the field's move to combine strong barriers with safety assays before food-contact claims (Wang et al., 2024). As safer alternatives, carbon and silicon QDs offer favorable profiles when properly synthesized and immobilized. A comprehensive review on edible-coating CDs reports dose-dependent low cytotoxicity, inherent antioxidant activity, and robust photostability, which together support their use as “indicator/antimicrobial”

luminophores in edible films when migration is constrained (Kumar et al., 2025). Silicon QDs metal-free, bright, and chemically tailorable are repeatedly described as highly biocompatible, with sensor-grade performance suitable for food environments when embedded in stable polymers (Sreejith et al., 2024). Practical packaging studies echo this transition: nitrogen-doped PEG-derived CDs in CMC/agar films (Tammina & Rhim, 2023) and pectin/gelatin films fortified with graphene QDs and wax barriers (Hejabi et al., 2025) showcase designs that pair functionality with reduced toxicological concern by avoiding Cd/Pb and adding secondary barriers. State-of-the-art reviews on “nano-hybrids” for food quality repeatedly call for standardized migration/toxicity protocols before market use and for selecting metal-free luminophores wherever possible (Campalani & Monbaliu, 2025; Lam et al., 2013). Regulatory-wise, current food-contact frameworks require that any intentionally added substance and its potential migrants meet safety standards; recent case studies apply these benchmarks directly. In milk-contact trials, measured migrants were evaluated against EU limits to judge compliance (Zhao et al., 2024). Packaging-focused reviews emphasize aligning nanomaterial use with migration testing in real foods, toxicological tiered testing (in vitro → in vivo when warranted), and documentation of non-intentionally added substances (NIAS) (Gupta et al., 2024; Mei & Wang, 2020). Risk-assessment frameworks emerging in the food-nanomaterials literature therefore converge on: material selection (prefer carbon/silicon QDs), robust immobilization (cross-linked/encapsulated matrices), empirical migration in real foods, and toxicology that is exposure-relevant to ingestion. Beyond regulatory and migration issues, the antibacterial mechanisms and biocompatibility of QDs are pivotal to their safe use in food-loss prevention systems. The antimicrobial effects are mainly associated with multiple complementary pathways, including the generation of reactive oxygen species (ROS), disruption of bacterial membrane integrity through electrostatic interaction or intracellular interference to metabolic processes, and under light activation, photodynamic or photothermal actions (C. Zhang et al., 2025). Nitrogen- or sulfur-containing groups in carbon dots have shown increased ROS-mediated bacterial inactivation efficiency against Gram-positive and Gram-negative strains, suggesting that composition and surface engineering play an important role in determining antimicrobial potency (Saravanan et al., 2024). Surface charge plays a pivotal role too, as positively functionalized QDs have the ability to bind with negatively charged microbial cell membranes, leading to membrane destabilization and leakage of intracellular elements (Villanueva et al., 2025). Toxicologically, it is established that no metal-free carbon and silicon QDs are relatively low in cytotoxicity at concentrations almost similar to food-packaging applications (Manikandan & Min, 2023), especially when these nanoparticles are immobilized with a cross-linked or multilayer polymer matrix that prevents its passage. In contrast, compared to QDs based on cadmium-, lead- or lead-halides, toxicological concerns are significant in terms of the release and bioaccumulation of heavy-metal ions from such materials, necessitating extensive short-range migration testing and long-term exposure deliberation prior to food-contact approval (Gray et al., 2018). Thus, proper engineering strategies make highly promising metal-free QDs towards safe packaging applications; yet standardized migration protocols, exposure-relevant toxicological evaluation, and regulatory harmonization are still crucial prerequisites for commercial translation.

7. Future perspectives

The next stage for quantum dot (QD) packaging will focus on safe, sustainable, and intelligent systems. A key direction is the creation of biodegradable, food-grade QDs. Carbon, graphene, and silicon QDs made from natural or waste biomass already show strong fluorescence, stability, and low toxicity, positioning them as eco-friendly replacements for heavy-metal QDs. Hybrid nanocomposites combining QDs with MOFs or biopolymers will enhance performance by uniting sensing, antimicrobial, and barrier functions. Such materials promise

UV shielding, oxygen control, and real-time spoilage detection in one multifunctional film, supporting both quality and safety. Combining AI and machine learning will enable smarter monitoring. Phone cameras and portable readers could detect QD signals, while AI models analyze nuanced changes to forecast freshness and microbial load. Paired with IoT dashboards and QR/NFC tags, packages can be utilized as digital sensors to transmit quality data in real-time. Lastly, scaling up and consumer adoption are key. Efficient, scalable synthesis routes (e.g., biomass pyrolysis and electrochemical exfoliation) are promoting industrial readiness. Clarity in regulations as well as straightforward labeling and an open dialogue about the safety of carbon/silicon QDs will be key to building confidence. Taken together, the integration of biodegradable QDs with hybrid materials, AI analytics, and scalable production provides a way from lab ideas to practical consumer-friendly smart packaging for maintaining food quality and sustainability.

8. Conclusion

Quantum dots are one of the most promising frontiers for edible coatings and packaging with multifunctional properties far beyond traditional nanofillers. Their combination with natural polymers has produced films with high barriers against oxygen and UV, antimicrobial activity, and real-time freshness monitoring in foods ranging from produce to meat and dairy. Hybrid composites based on MOFs and high-performance polymers additionally demonstrate how QDs are flexible for smart and sustainable design. At the same time, the toxicity and migration risks – especially for cadmium- and lead-based QDs – stress responsible choice and robust immobilization strategies as accurate compliance with regulatory indications. The rapid emergence of biocompatible carbon and silicon QDs, developing from green synthesis protocols using agricultural byproducts, implies a shift toward safe and eco-friendly substitutes. Next steps Going forward, the integration of biodegradable QDs with AI-mediated data analytics and IoT smart labels paves a clear path for commercialization, ensuring that these nanomaterials can make a responsible transition from laboratory studies to consumer-ready applications. By combining innovation with safe and large environments, QD edible-coated packaging may revolutionize the future of food packaging, which could lead to less waste, longer shelf life and trust in consumers using sustainable food systems.

CRedit authorship contribution statement

Tablo H. Salih: Writing – review & editing, Project administration, Funding acquisition. **Aryan Faraj:** Writing – review & editing, Visualization, Data curation. **Syamand Qadir:** Writing – review & editing, Resources, Investigation. **Othman Mohammed:** Writing – review & editing, Formal analysis, Data curation. **Ammar B. Altemimi:** Writing – review & editing, Visualization, Validation, Methodology. **Sonia Morya:** Writing – review & editing, Resources, Investigation. **Farhang Hameed Awlqadr:** Writing – review & editing, Writing – original draft, Supervision, Resources, Conceptualization. **Mohammed N. Saeed:** Writing – review & editing, Visualization, Software.

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Data Availability

Data will be made available on request.

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