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Carbon dot-integrated edible films: emerging synergies for advanced food packaging applications

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The escalating global demand for safe, sustainable, and environmentally friendly food packaging has stimulated the research of edible films as potential alternatives to conventional plastics. However, the inherent disadvantages associated with biopolymers, such as poor mechanical properties, their high moisture sensitivities and the absence of significant bioactive properties, hamper the large-scale use of such films. Recently, carbon dots (CDs), a new type of carbon-based nanomaterial with excellent photoluminescence properties and tunable surface wall chemistry and biocompatibility, have gained popularity as multifunctional nanofillers to strengthen edible films. Their incorporation into protein-, polysaccharide-, and lipid-based edible films has been shown to effectively enhance antimicrobial action, antifungal activity, and antioxidant activity and, at the same time, enable real-time detection of food quality and spoilage biomarkers. This review critically analyzes synthesis methodologies, functional activity, and the route of action through which CDs confer high performance levels on edible films. It particularly focuses on antimicrobial/antifungal protection, antioxidant-induced shelf-life extension, intelligent packaging applications, and multifunctional composite systems. In addition, toxicological and safety concerns of edible films based on CDs are addressed, with implications and future perspectives of their industrial adaptation as the key concerns. With sustainability filling the gap between nanotechnology and food packaging, edible films with CDs are a revolutionary and sustainable way of preserving food, which is longer lasting, safer, and more environmentally friendly.

1 Introduction

The modern food industry faces two major challenges: ensuring the safety and quality of food products while simultaneously minimizing environmental harm. Although conventional plastic packaging is effective in preserving food products, its widespread use for packaging has been shown to harm the environment and poses long-term environmental threats.[1] Consequently, there has been increased pressure regarding identifying environmentally friendly materials to develop eco-friendly packaging largely through the generation of biodegradable, sustainable, multifunctional packaging materials.[2] Polysaccharide-, protein-, and lipid-edible films have intrinsic biodegradability and non-toxicity and can even be tailored to deliver functional bioactive compounds. Nonetheless, even with these advantages, the practical use of the biopolymer films is hindered by inherent limitations such as poor strength, low moisture resistance, inferior barrier qualities, and inadequate antimicrobial/antioxidant action.[3] Such shortcomings impair them from being adopted at an industrial level, hence the need to employ new strategies that would aid them in improving in terms of structural and functional capabilities.[4] An innovative way to overcome these problems is nanotechnology, specifically the incorporation of CDs into edible films.[5] Graphene nanoparticles are quasi-spherical particles of carbon of order less than 10 nm,[6] characterized by a remarkable photoluminescence,[7] excellent water solubility, and inertness and biocompatibility.[8] These can be functionalized with several bioactive substances, metal ions, and polymers due to their tunable surface chemistry, and so they are potential nanofillers in food packaging.[9] In addition to their optical properties, CDs have intrinsic antimicrobial, antifungal, and antioxidant properties that can be utilized to improve the functional performance of edible films.[10,11] Inclusion of the CDs therefore not only strengthens the mechanical and barrier characteristics of the films but also adds active functionality and intelligent features to this film, such as in-time monitoring of food quality, food spoilage, and on-demand release of protective substances.[12]

CDs have been successfully incorporated into various edible film matrices, such as protein-based, polysaccharide-based, and lipid-based films.[13] By incorporating CDs, protein films have been found to increase mechanical strength and decrease water vapor permeability, and polysaccharide films have been

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improved with CDs to be more flexible and in turn have their barrier properties enhanced without losses to transparency.[14] The synergistic effect of CDs enables the production of composite films composed of proteins, polysaccharides, and lipids, with all three properties balanced in performance.[15] Additionally, the functionalization of CDs can be designed to bind specific pathogens, toxins, or oxidative substrates to offer multifunctional packaging material with responsive properties to external stimuli.[16,17] The integration of carbon dots into edible films significantly enhances their potential across diverse packaging functions serving as active packaging through antimicrobial and antioxidant defense, intelligent packaging *via* fluorescence-based freshness and pH sensing, and protective packaging by improving UV-blocking capacity, barrier performance, and mechanical integrity thereby creating a new generation of multifunctional, sustainable food packaging systems, as shown in Fig. 1. This strategic integration positions CD-integrated films at the top of intelligent and active food packaging technology.[18]

As shown in Fig. 2, a literature survey conducted on ScienceDirect using the keywords "carbon dots" and "food packaging" and "edible films" and "food packaging" reveals a remarkable increase in the number of publications from 2010 to 2025. This steady upward trend underscores the rapidly growing research interest in developing carbon dots-integrated edible films as next-generation materials for sustainable food packaging. The convergence of nanotechnology and biopolymer science has positioned this field at the forefront of innovations aimed at improving food safety, extending shelf life, and minimizing environmental impact. Data were retrieved in Nov 2025.

Despite these advancements, we still need to overcome certain obstacles to ensure widespread industry adoption. The production of CDs of uniform size, shape, and surface chemistry is highly technical and not cost-effective on a large scale. Food contact materials that incorporate nanomaterials must undergo significant toxicological testing, which includes long-term exposure tests and migration tests. Moreover, the mechanism of interaction between CDs and food matrices at the molecular level is also an open question of research. It is important to address these concerns to guarantee consumer safety and to scale laboratory innovations to commercially viable packaging solutions.[19–21]

This review attempts to provide an extensive report on CD-integrated edible films in terms of the methods of their synthesis and upgrades to their structure and functionalities, along with the applications in food packages that are yet to be discovered. So special attention is focused on antimicrobial and antifungal defense, prolonged shelf life based on antioxidant defense, intelligent responsive functionalities, and multiple functional composite systems. The review examines critically toxicological issues, scaling potential to the commercially industrial level, future research opportunities, and how CD-based edible films can bridge the gap between nanotechnology and green food packaging. By discussing these newly discovered synergies, the study will attempt to present a way forward in the rational design of edible films in the next generation that do not only act in the protection and preservation of food but also satisfy environmental and public health needs.

1.1 Novelty of this review article

Although the literature on carbon dots in food packaging has recently grown in magnitude, current literature reviews are filled with a strong incidence of CDs broadly incorporated as a subset of nanomaterials, intelligent packaging, or biopolymer

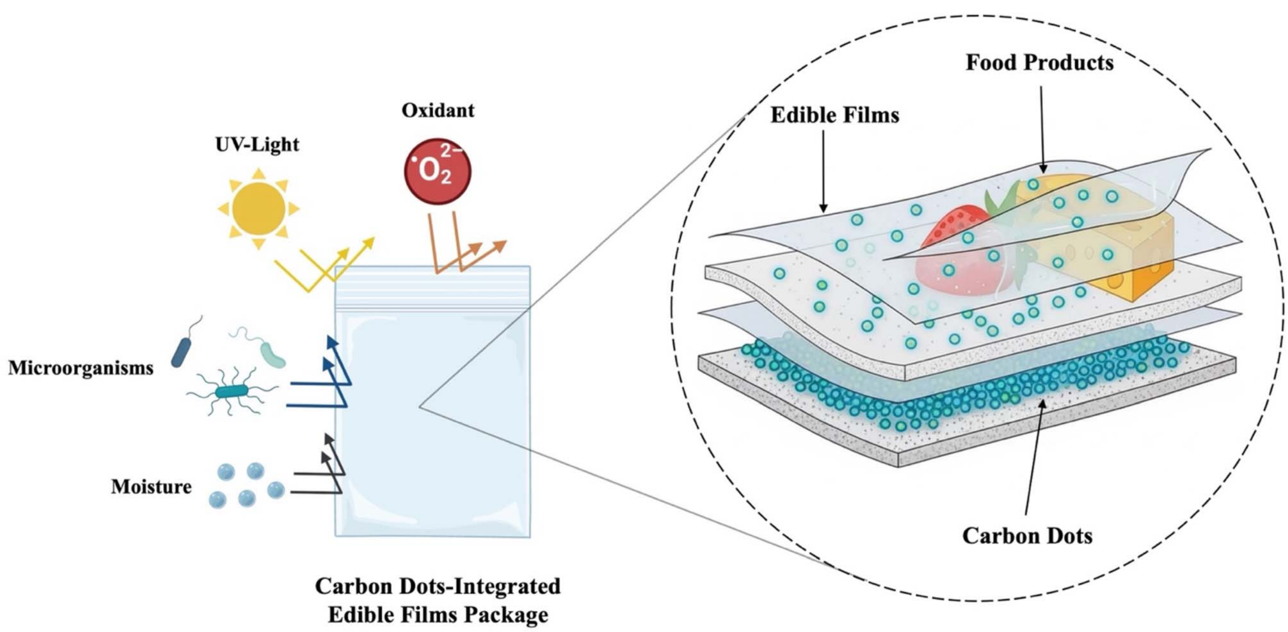

Fig. 1 Schematic illustration of the multi-barrier role of carbon dots-integrated edible film packaging in maintaining food freshness.

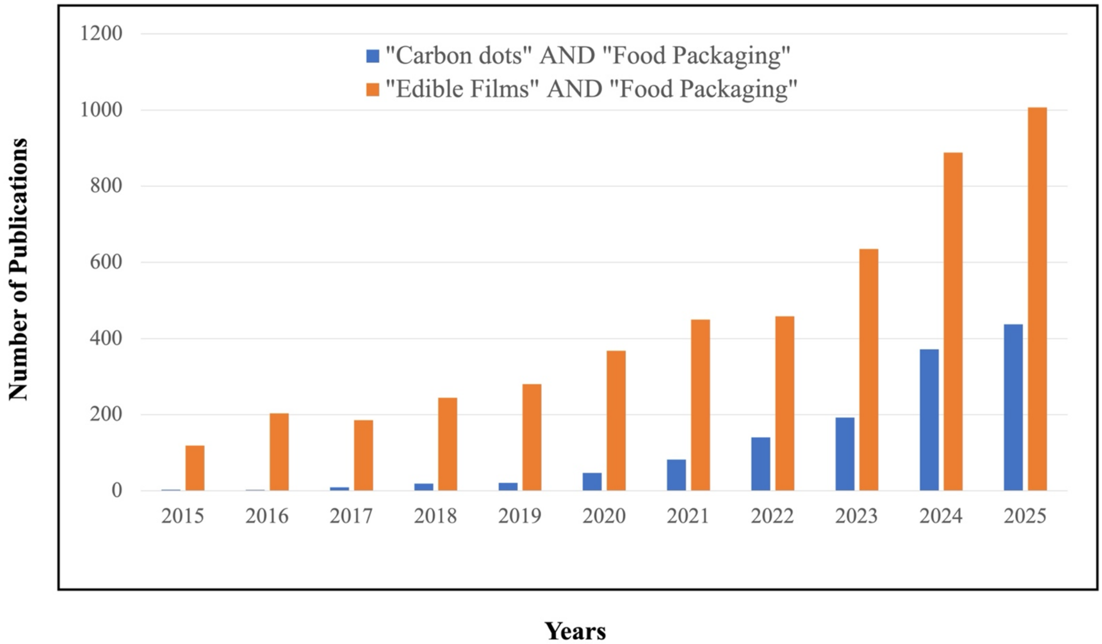

Fig. 2 Annual number of publications retrieved from ScienceDirect using the keywords "carbon dots" and "food packaging" and "edible films" and "food packaging" over the period 2010–2025. Data were retrieved in November 2025.

gel, with no coherent and critical evaluation of their practical application in edible films. The article represents the first review that specifically concerns the CD-embedded edible films and examines the technological basis, integration design, functional improvements, and new applications of edible films in active, intelligent, and protective packaging designs. The originality of the work consists of several contributions.

First, the review is the first to close the gap between the basics of edible film technology and the physicochemical processes that determine the behaviour of CD, thus offering a cohesive paradigm that has not been expressed in the previous literature. The review explains the relationship between these nanoscale functions and their interaction with protein, polysaccharide, and lipid edible matrices at a molecular and structural level by obtaining a systematic categorization of the roles of fluorescent CD markers, antioxidants, antimicrobials, UV blockers, and barrier enhancers.

Second, this review is novel in terms of the methodological emphasis on the strategies of CD integration, which is not a well-researched area in other surveys. The review differentiates between blending, coating, and immobilization systems with a critical assessment of the parameters that determine the dispersion stability, the polymers and CD interfacial compatibility, and the reproducibility of the performance. The absence of such a mechanistic understanding of integration pathways is a significant deficiency in current reviews on nanomaterial-enhanced packaging.

Third, this article has introduced a trifunctional classification: active, intelligent, and protective packaging, which is the first to have been introduced only in CD-based edible films. It provides an in-depth, practical study of the way CDs can optimally raise antimicrobial activity, freshness perception, and structural stability in actual food systems concurrently. This multidimensional approach brings about CDs not just as additives but as versatile enablers with the ability to convert conventional edible films into hybrid preservation-sensing-protection media.

Fourth, this review proposes a strict critical analysis of toxicological, safety, and regulatory issues, which are often overlooked in research that is eager to believe in the potential of CDs. The article successfully places safety considerations as a key determinant of industrial viability by synthesizing existing evidence on migration behaviour, digestibility, cytotoxicity, and the implications of biomass-derived variability and gives a comprehensive assessment of the topic based on functional properties alone.

Lastly, the review provides future outlooks specific to edible films, such as scalability, standardization, material–nanostructure interface and harmonization of safety framework. These insights present a concise research map and point to the innovation opportunities at the food technology-materials science–nanotechnology interface.

2 Fundamentals of edible films as packaging materials

Edible films are composed of layers made of biodegradable and food-grade biopolymers, which are very thin and made to be consumed as protective coatings or individual packaging material for food products of a diverse variety.[22] This type of film can be broadly divided into protein-based, polysaccharide-based, and lipid-based systems depending on the biopolymer source, each providing unique mechanical, structural, and barrier properties, as illustrated in Fig. 3. Edible films serve to prevent moisture, gases, and lipids as well as microbial contamination, help to prolong shelf life, and preserve product quality. These are usually created by solvent casting or extrusion, where the biopolymer structure is created as a whole matrix that can, to some extent, accommodate plasticizers or functional additives. Due to their renewable source, safety, and capacity to incorporate bioactive or sensing compounds, edible films are flexible matrices of advanced food-packaging uses, including the incorporation of carbon dots to enhance their antimicrobial, antioxidant, or detection properties,[23–25] as summarized in Table 1.

2.1 Protein-based films

The films made of proteins belong to the most studied types of edible packaging materials due to their high film-forming abilities, biodegradability, and good barrier properties. These films may be based on animal proteins, including gelatin, casein, and whey, as well as on plant ones, including zein, soy protein, and wheat gluten. They have excellent oxygen-barrier functionality due to their dense and ordered polypeptide networks, although they can be regularly vulnerable to moisture.[26,27] Protein structure, amino acid composition, and plasticizers or crosslinking agents have a significant impact on the mechanical properties of protein films, including tensile strength, elasticity, and flexibility.[28] Many of them also indicate that thermal treatments, enzyme modification, and nanomaterial incorporation may substantially enhance the stability, water resistance, and mechanical behavior of these films.[29,30] In addition to physical characteristics, protein-based matrices are also capable of being great vectors of bioactive agents, and they can be developed with antimicrobial and antioxidant capabilities to be used as active food-packaging materials.[31,32] The recent developments in animal- and plant-based proteins help demonstrate the increased promise of protein-based film as a viable, sustainable, and functional replacement of traditional plastic packaging.[33–35]

A number of studies have also shown how protein-based films can be used and how their functionality can be improved by carrying out some changes on them. Kaewprachu *et al.*[36] prepared fish-myofibrillar, fish-skin gelatin, and porcine plasma films and compared their transparency and mechanical properties, stating that fish-myofibrillar ones were the clearest and demonstrated greater applicability to food packaging. Purewal *et al.*[37] conducted a review of different sources of protein and modes of preparation, with the emphasis put on innovative methods to enhance the film's flexibility, barrier properties, and applicability in the form of an edible coating. Liu *et al.*[38] synthesized protein-based active films, which comprised antimicrobial agents, antioxidant agents, and UV-blocking agents, and proved to have superior food preservation properties. Zubair and Ullah[39] have stressed the importance of crosslinking and the formation of bionanocomposites in enhancing the water resistance and mechanical strength of protein films. Lastly, Zhang and Mittal[40] concentrated on soy protein-based films and demonstrated that the concentration of glycerol has a great impact on the water vapor permeability and flexibility, demonstrating how parameters of the formulation can be adjusted to attain desirable functional properties. All these studies point to the suitability of protein-based films as active and intelligent food packaging systems.

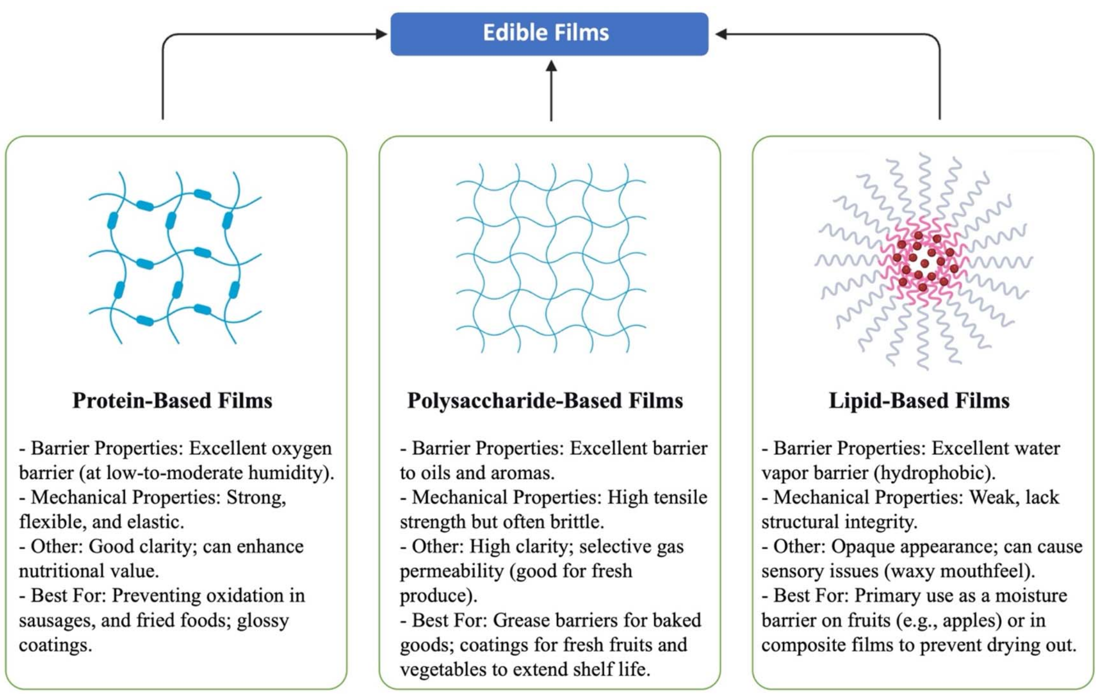

Fig. 3 Schematic of edible film components and their synergistic potential.

Table 1 Key studies on protein-, polysaccharide-, and lipid-based edible films and their food-packaging applications

Biopolymer category	Material/system studied	Key functional properties	Food-packaging applications	Ref.
Protein-based & polysaccharide-based	Cellulose, chitosan, whey/soy proteins	Oxygen barrier, biodegradability, film-forming ability	General food packaging; fruits, vegetables, meats	64
Protein-based	Gelatin, whey protein, casein films	Mechanical strength; transparency; oxygen barrier	Meat packaging; oxidation control	65
Protein-based	Gelatin + diacetyl	Antibacterial (*L. Monocytogenes*); improved water resistance	Cheese and dairy preservation	66
Protein-polysaccharide hybrid	Soluble soybean polysaccharide + soybean peptides	Increased tensile strength, flexibility, transparency	Biodegradable food packaging films	67
Protein- & polysaccharide-based	Various edible biopolymer films (production methods)	Industrial scalability; mechanical/barrier enhancement	Large-scale edible film production	68
Polysaccharide-based	Alginate films/coatings/nanofibers	High strength; oxygen barrier; enhanced by bioactives	Active & intelligent packaging; produce coatings	69
Polysaccharide-based	Alginate + cinnamon/lemongrass oil	Strong antimicrobial activity	Shelf-life extension of minimally processed foods	70
Polysaccharide-based	Alginate + green-tea polyphenols	Controlled antioxidant release; improved barrier	Functional films for nutrient delivery	71
Polysaccharide-based	Pectin films from by-products	Gas barrier; moderate strength; sustainable	Fruit/vegetable coatings; eco-friendly packaging	72
Polysaccharide-based (hybrid)	Pectin + CM-chitosan + roselle extracts	Antioxidant, antibacterial; flexible films	Functional/active packaging	73
Polysaccharide-based	Chitosan + CMC + anthocyanins/tea polyphenols	Antimicrobial; pH-responsive; strong mechanical properties	Beef preservation; intelligent packaging	74
Polysaccharide-based	Starch, alginate, CMC, pectin films	Biodegradable; balanced mechanical/barrier properties	Fresh food packaging	75
Polysaccharide-based composite	Biopolymers + microalgae biomass/extracts	Antioxidant, antimicrobial; added nutrients	Coatings for fruits, fish, snacks	76
Polysaccharide-based	Sweet potato starch films	Good mechanics; moisture resistance	Candy packaging	77
Polysaccharide-based	Native & modified starch films	Tunable strength; water barrier; biodegradable	Produce, bakery, dry food packaging	78
Protein- & polysaccharide-based	Scalable edible film formulations	Barrier improvement; industrial processing strategies	Industrial edible packaging	79
Protein- & polysaccharide-based	Biopolymer + essential oil antimicrobial films	Broad antimicrobial activity; active release	Meat, poultry, fresh-produce packaging	80

2.2 Polysaccharide-based films

Polysaccharide-based films are biodegradable, edible, and renewable, which makes them a more environmentally friendly choice than other types of plastic packaging.[41,42] Starch, chitosan, alginate, cellulose, and pectin are some common polysaccharides. They are hydrophilic and semi-permeable matrices that can control the movement of gases, moisture, and lipids.[43,44] The presence of thick polymer networks confers these films outstanding oxygen barrier properties, but their high sensitivity to water and low mechanical strength has limited their use in commerce.[45,46] Functional modifications, including chemical crosslinking, blending with other biopolymers, and the incorporation of active compounds, have been employed to enhance their stability, flexibility, and barrier properties.[47,48] Polysaccharide-based films also provide prospective opportunities as active and intelligent packaging to add antimicrobial agents, antioxidants, or pH-sensitive dyes, which provide enhanced food preservation and quality monitoring.[49,50]

Different studies that have been carried out recently have indicated practical uses of polysaccharide-based films. Li *et al.*[51] made composite films by mixing polysaccharides with functional additives that obtained better mechanical strength and barrier properties that were appropriate for food packaging. Deng *et al.*[52] made renewable polysaccharide-based composites, which had a higher biodegradability and could be controlled to have a water vapor permeability. Zhu[53] added polyphenol extracts to chitosan and starch films, producing multipurpose films that had antioxidating and antimicrobial properties and could be used as intelligent packaging. These examples illustrate the various applications of polysaccharide-based films as a useful biodegradable platform for developing an improved food packaging system.

2.3 Lipid-based films

Hydrophobic molecules, including fatty acids, waxes, and oils, are the main constituents of lipid-based edible films and confer them with excellent barriers to moisture and low water vapor transmission in packaged foods.[54,55] Such films, however, are brittle and mechanically weak in isolation, which restricts their use on their own.[56,57] To circumvent such drawbacks, composite films can be typically prepared by the conjugation of lipids with proteins or polysaccharides, which form bilayer, bi-emulsion, or multi-layers that mix the barrier properties of lipids with the mechanical properties and flexibility of hydrocolloids.[58] The films based on lipids are very sensitive to the nature, concentration, and structure of lipids and the nature of the penetrant molecules. As an example, the addition of a certain amount of waxes, including carnauba or beeswax, can be of significant help in lowering water vapor permeability, and the concentration of the waxes is usually between 35 and 40 percent.[59,60] Instead, composite films can be used with greater integration of bioactive or functional additives, such as carbon dots, essential oils, and antimicrobial agents, and have the advantage of active packaging.[61] Nanocarriers that involve lipids have also recently been developed to enhance controlled release of active compounds and resistance of the film matrix against environmental stressors, including liposomes and nanocochleates.[62] These nanostructured lipid systems are not only able to increase barriers and mechanical properties, but they also offer potential opportunities for nano-enabled sensing or antimicrobial functionality, which is also consistent with the increased focus on intelligent and functional food packaging. In addition, the literature on postharvest fruit preservation shows the effectiveness of lipid-based and lipid-based composite films in preserving freshness, moisture retention, and shelf life.[63]

3 Carbon dots: synthesis, functional properties, and classification for food packaging

3.1 Synthesis pathways and source materials

Carbon dots (CDs) are commonly produced by converting carbon-based precursors into nanostructures of carbonaceous materials by dehydration, polymerization, aromatization, and carbonization reactions. Throughout the literature, CD formation is always characterized by the transformation of small organic molecules, biomass constituents, or carbon-rich solids into fluorescent carbon nanoparticles by the external energy sources, including heat, pressure, or radiation,[81,82] as summarized in Table 2. The resulting CDs have tunable optical and surface properties that are highly dependent on the methodology of choice used in the synthetic approach, characteristics of the precursor, and reaction conditions. There are two general strategies of synthesis that are commonly known: bottom–up and top–down. Contrarily, bottom–up methods create CDs using molecular or polymeric starting materials by hydrothermal or solvothermal reactions, microwave irradiation, pyrolysis, or thermal decomposition.[83,84] These techniques enable both tight control of nucleation and growth and heteroatom incorporation, in which the type of dopant and optical characteristics are directly determined by precursor chemistry and reaction conditions.[85] Conversely, in top–down approaches, bulk carbon materials (graphite, soot, activated carbon, or carbon fibers) are broken up using chemical oxidation, electrochemical exfoliation, or laser ablation to form nanoscale regions with graphitic properties. Top–down approaches may result in the formation of very crystalline CDs but necessitate the use of severe oxidants and allow little control on the surface functions.[86]

Traditional CD synthesis applies many types of carbon-based feedstocks, such as small organic acids, aromatic compounds, polymeric matrices, and heteroatom-based molecular precursors.[81] The selection of precursors is very important since molecular structure, functional groups, and natural dopants can affect the nucleation, formation of carbon cores, and the specific density of surface defects of the produced CDs.[87] As an example, aromatic amino acids guide the creation of conjugated domains and nitrogen states on the surface, and sulfur- or phosphorus-containing ones bring in specific dopants to modify the emission wavelength and density.[85] The versatility of the bottom–up and top–down routes is demonstrated by numerous studies. Selvaraj *et al.*[88] can be used as an example, in which a one-pot microwave-assisted carbonization process was used to prepare CDs based on pumpkin seed waste, and the Fe^{3+}-responsive, fluorescent nanoparticles were produced with antibacterial activity. Similary, Ananda *et al.*[89] prepared eggshell membrane-based CDs through a quick process of microwave alkaline, allowing them to sensitize heavy metal. Abd Elhaleem *et al.*[90] described an ultra-fast room-temperature synthesis of 4-sulfonated 4-naphthoquinone CDs based on the use of 4-naphthoquinone-4-sulfonate sodium, which produced CDs suitable as biosensors in the pharmaceutical sector. In addition, hydrothermal CDs have demonstrated potential for enhancing oil recovery processes through improved fluid–rock interactions. These illustrations highlight the wide applicability of traditional routes and the flexibility of different feedstocks.

Green synthesis has become a significant trend due to the necessity to decrease the environmental impact, remove toxic reagents, and utilize renewable starting materials. Green methods are characterized by low-energy reactions, an aqueous solution, the minimum of catalyst consumption, and the absence of dangerous chemicals.[83,91] Additional goals of machine-learning research are to foretell optimum parameters that will decrease the duration of synthesis and minimize waste through the correlation of process parameters with CD structural results.[92] Mechanistic studies also demonstrate the polymer-derived carbonization pathways by showing that natural polymers (cellulose and hemicellulose) undergo degradation into carbonaceous clusters during green carbonization through recombination of reactive intermediates.[93] The precursors of green synthesis are biomass-based, such as rice husks, fruit peels, agricultural residues, amino acid-containing plant materials, and food-processing by-products. These feedstocks contain natural heteroatoms (N, S, P) that facilitate doping without any artificial additive, and the natural polymer structures direct the creation of carbon cores in hydrothermal or microwave processing. Also, they are biocompatible, inexpensive, and abundant, which makes them suitable for application in food, biomedical, and environmental applications. Several recent studies are good examples of green fabrication.[94,95]

3.2 Key functional properties relevant to packaging

The carbon dots (CDs) have become one of the most diverse nanomaterials in active food packaging because of their ability to offer a combination of optical, chemical, and physical characteristics, which may be specially designed to suit food quality, safety, and shelf life. The fluorescent property of the CDs is one

Table 2 Overview of common synthesis pathways for carbon dots, including key principles, advantages, and limitations

Synthesis pathway	Description/key principles	Advantages	Limitations	Ref.
Hydrothermal/solvothermal	Bottom–up carbonization of organic precursors (*e.g.*, citric acid, biomass, polymers) in sealed autoclaves under high temperature/pressure	Simple, low-cost, scalable; good control of surface functional groups; compatible with green precursors	Long reaction times; less precise control of size/distribution; batch-to-batch variability	96–99
Microwave-assisted synthesis	Rapid heating of carbon precursors under microwave irradiation to induce carbonization	Very fast (seconds–minutes); energy efficient; good for high-throughput synthesis	Risk of hot spots; sometimes poor uniformity; limited control of crystallinity	100 and 101
Pyrolysis/thermal decomposition	Direct heating of solid precursors (*e.g.*, carbohydrates, polymers, biomass) to high temperatures for carbonization	Straightforward; viable for large-scale production; high carbon yield	May produce polydisperse CDs; high temperatures required; fluorescence tuning difficult	102 and 103
Ultrasonic/sonochemical synthesis	Acoustic cavitation generates localized high-energy conditions to carbonize or fragment precursors	Mild conditions; relatively fast; suitable for aqueous systems	Scale-up is challenging; lower quantum yields compared to hydrothermal methods	104 and 105
Chemical oxidation/top–down cutting	Oxidative breaking of carbon sources (graphite, carbon fibers, soot) into nanoscale domains using strong acids	Produces graphene quantum dots (GQDs) with defined sp^2 domains; tunable size by chemical control	Uses harsh chemicals; requires long purification; lower biocompatibility without post-treatment	106–108
Laser ablation	High-energy laser pulses ablate carbon targets in liquid media to form CDs	Produces high-purity CDs; tunable *via* laser parameters; no chemical waste	Expensive; low throughput; requires specialized equipment	109
Electrochemical methods	Electro-oxidation of carbon electrodes or organic molecules yields CDs in solution	Mild conditions; good control of size and surface states; high reproducibility	Slower process; lower yields compared to thermal methods	110
Green/biomass-derived synthesis	Uses natural resources (plants, food waste, lignocellulosic biomass, amino acids) in hydrothermal, pyrolytic, or microwave processes	Sustainable, low-cost, low-toxicity; abundant resources; inherently doped (N, S, P)	Compositional variability from natural precursors; potentially lower reproducibility	111–113

of the most notable, and it allows observing the freshness of food in real time in non-invasive mode by the variation of visible photoluminescence. The fluorescence is contributed to by quantum confinement effects and surface defect states and can be controlled by heteroatom doping (*e.g.*, nitrogen, sulfur, or phosphorus) and surface functionalization.[114,115] More importantly, the intensity of fluorescence and the emission wavelength of CDs can be varied according to environmental conditions, that is, pH, temperature, or even the presence of metabolites that may indicate spoilage, and so intelligent packaging systems can be used as direct visual media to monitor food quality. A limitation, however, is that the stability of the fluorescence could be reduced with extended periods of UV radiation or with very humid conditions, and great care must be exercised in the choice of polymer matrices and stabilization processes to ensure the stability's reliability during storage.[116,117]

In addition to optical sensing, CDs have high antioxidant activity, which is important in retarding oxidative spoilage of lipids, proteins, and vitamins in packaged foods. This reaction is primarily attributed to the presence of electron-rich surface groups capable of neutralizing free radicals and reactive oxygen species.[116,118–120] CDs generated by biomass or plant polyphenols tend to have an increased radical scavenging activity because they contain inherent phenolic structures, illustrating the significance of precursor choice in enhancing antioxidant activity. One important point to note, however, is that the antioxidant efficacy can be influenced by the association between CDs and polymer matrices, with high binding with the polymer potentially reducing the free reactive surface sites. To achieve maximum protective efficiency in real-life packaging, it is essential to optimize both synthesis and incorporation strategies.[121]

Beyond preventing chemical spoilage, CDs also directly address microbial degradation, a major and time-sensitive challenge in food preservation. CDs inhibit bacteria and fungi through multiple mechanisms, including the generation of reactive oxygen species (ROS), photodynamic effects, and disruption of microbial cell membranes.[122] The particle size, surface charge, and heteroatom content are some of the factors that affect the antimicrobial efficacy.[123] Experimental research demonstrates that CDs produced using a wide array of resources (diethyl ferulate, husks of green walnut, tangerine peel, and mango peel) can display a broad-spectrum antibacterial effect in the case of polymeric matrixes (polyvinyl alcohol, chitosan, pullulan, gelatin, and alginate composites).[124,125]

This functionality is alongside other properties that have been introduced by CDs, such as UV-blocking ability, which protects food products against photooxidation caused by light. The π-conjugated carbon net and alloys allow the use of CDs to absorb and scatter ultraviolet light, reducing the loss of color, flavor, and nutrients. Although UV protection is typically an additional feature of fluorescence or antimicrobial actions, one should critically consider any possible trade-offs, including decreased transparency or changed film aesthetics, which can influence consumer acceptance.[126–128] Lastly, carbon dots (CDs) have the potential to enhance the barrier properties in food packaging by intrinsically restricting the gaseous and water diffusion. Surface functional groups and a tightly packed carbon core give rise to a tortuous route for molecules like water vapor and oxygen and make them less permeable and slow oxidative processes in packaged foods.[119,129] The characteristic preservation effect of CDs, which is independent of the polymer matrix, is to stabilize moisture- or oxygen-sensitive food ingredients and can be used together with other food preservation systems like antioxidant and antimicrobial activity. At the nanoscale, CDs are efficient in inhibiting the transport of molecules, which is considered an extra defense line and improves the total shelf life and quality of packaged products.[130] Table 3 summarizes the key functional properties of carbon dots (CDs) relevant to food packaging, highlighting both optical and chemical functionalities reported in individual studies. Review articles are presented with wording such as 'summarized', 'reviewed', or 'discussed', while original research studies are indicated by terms like 'demonstrated', 'showed', or 'revealed', providing an overview of the experimental evidence and mechanistic insights that support their applications in sustainable and active packaging systems.

In summary, CDs represent a special quintessential responsive fluorescence, antioxidant, antimicrobial, UV-blocker, and barrier properties, which, in turn, make them very appealing in developing intelligent, multi-purpose, and sustainable food packaging, as shown in Fig. 4. Importantly, although these properties have been confirmed in a range of

Table 3 Key functional properties of carbon dots in packaging: summary of individual studies

Study	Main functional property reported	Key findings relevant to food packaging
Sharma *et al.*[131]	Fluorescence, antioxidant properties	Summarized biowaste-derived CDs with tunable fluorescence and strong radical-scavenging ability, highlighting potential for sustainable intelligent packaging
Jiang *et al.*[132]	Multicolor fluorescence	Reviewed mechanisms of multi-emission CDs and their environmental responsiveness, supporting their use in freshness indicators
Qureshi *et al.*[133]	Optical sensing and imaging efficiency	Demonstrated high sensitivity and tunability of CDs, reinforcing their potential in optical monitoring systems in packaging
Ren *et al.*[134]	Sustainability, fluorescence, barrier improvements	Discussed CDs' optical properties and their role in enhancing material performance, including barrier improvements
Yang *et al.*[135]	NIR emission, ROS generation	Showed ROS-related mechanisms, providing insight into antimicrobial potential of CDs under light stimuli
Kuligowska *et al.*[136]	Sorption and sensing applications	Revealed CDs' ability to adsorb and detect environmental molecules, reflecting their potential for sensing spoilage gases
Nie *et al.*[137]	ROS modulation and antimicrobial action	Showed surface-state-engineered CDs can regulate ROS for microbial elimination—important for active packaging
Liu *et al.*[138]	Fluorescent sensing from food waste CDs	Demonstrated green-synthesized CDs for food safety detection, including spoilage monitoring and contaminant sensing
Atchudan *et al.*[139]	Antioxidant activity & optical sensing	Demonstrated biomass-derived CDs with strong antioxidant function and selective ion-sensing, implying dual protection in packaging
Huang *et al.*[140]	pH-responsive fluorescence & antimicrobial ability	Revealed citric-acid CDs with stable optical behavior and good antimicrobial properties relevant to food protection
Etefa *et al.*[141]	Comprehensive optical, chemical, and structural properties	Discussed synthesis–structure relationships determining fluorescence stability and antioxidant capacity in packaging films
Kayani *et al.*[142]	Photocatalytic detoxification	Summarized the potential of CDs and metal-oxide hybrids to degrade toxic dyes, supporting ROS-related antimicrobial activity
Sun *et al.*[143]	Photosensitized ROS generation (PDT)	Showed how CDs generate ROS efficiently, linking to antimicrobial potential in food packaging
Cai *et al.*[144]	Antioxidative biochemical activity	Demonstrated intrinsic antioxidant behavior of biofunctional CDs, relevant to delaying lipid/protein oxidation in foods
Jin *et al.*[145]	Conductive and barrier-related enhancements	Revealed how CDs improve matrix density and reduce molecular transport, strengthening barrier functionality in films

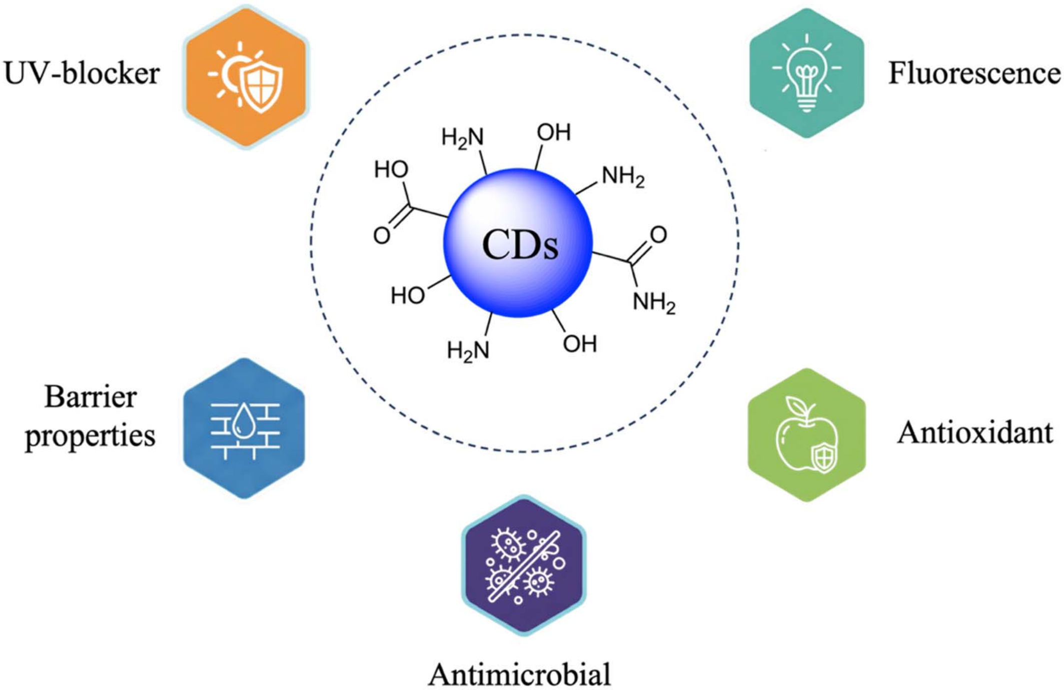

Fig. 4 Key intrinsic functional properties of carbon dots relevant to food packaging applications.

polymer systems, their usefulness is limited to careful design of CD synthesis, doping, surface chemistry, and film incorporation. The next generation of the study should invest in the relationship between CD properties and polymer matrices, the stability of the systems in the long term under the actual storage conditions, and the interplay between multifunctionality and cost-effectiveness to allow industrial-level applications.

3.3 Structural classes of carbon dots

CDs are a broad and structurally heterogeneous group of carbon-based nanomaterials, and their behaviour in edible films is also highly dependent on the subclass that a material belongs to. Carbon quantum dots (CQDs) are the most common of these types; these are typically smaller than 10 nm in diameter, have partially crystallized graphitic or graphitic-like cores and exhibit a photoluminescence that is excitation-dependent, due to discrete energy levels and quantum confinement effects (Fig. 5). All these features make CQDs highly applicable in intelligent packaging, where their steady fluorescence can be used to detect food spoilage signs, pH variations, and gaseous metabolites emitted through food degradation in real time. Their fairly high quantum yield also promotes their use in visual freshness sensors and optical barcoding.[146,147]

Carbon polymer dots (CPDs), on the other hand, consist of amorphous carbon domains within polymeric or oligomeric scaffolds, which confer increased density of functional surface groups (*e.g.*, hydroxyl, carboxyl, amino). This structural richness helps them spread out and interact with biopolymers like chitosan, gelatin, starch, or alginate. Therefore, CPDs have the potential to have a significant positive impact on the mechanical strength, antimicrobial activity, and free-radical scavenging of edible films. CPDs are highly beneficial for active packaging because of their high capacity to organise hydrogen bonding networks and electrostatic interactions that offer active antimicrobial and antioxidant activity over a prolonged period.[148,149] Another closely related but distinct subclass, carbon nanodots (CNDs), has amorphous spherical carbon structures of diameter between 2 and 20 nm and does not have the strong crystalline domains found in CQDs. In contrast to CQDs, surface defect states dominate the emission profile in CNDs, and therefore, the fluorescence is strongly excitation-dependent, resulting in broad, excitation-tunable emission spectra. A simple hydrothermal or pyrolytic conversion of food-grade biomass often leads to the straightforward synthesis of carbon nanodots, which commonly include naturally heteroatom-doped structures (*e.g.*, N-, S-, or O-enrichment). These inherent characteristics render CNDs very useful in edible-film applications, especially in cases where biocompatibility, antioxidant properties, and optical functionality are the highest priorities.[148,150]

In the meantime, graphene quantum dots (GQDs) are nanoscale-sized fragments of single- or few-layer sheets of graphene with planar sp^2-hybridized networks, sharp UV absorption, and outstanding photostability in comparison to amorphous CDs. Even though they are still in use in edible films, GQDs hold promising outlooks in protective packaging, as their capable ability to shield UV radiation and their stability against oxidation can avoid the process of photodegradation of food items and lengthen the overall shelf life. They also have a two-dimensional morphology, which enables them to provide enhanced gas-barrier properties in polymer matrices.[150,151]

Overall, these subclasses emphasise the fact that the CDs are not a homogenous material system but a broad spectrum of

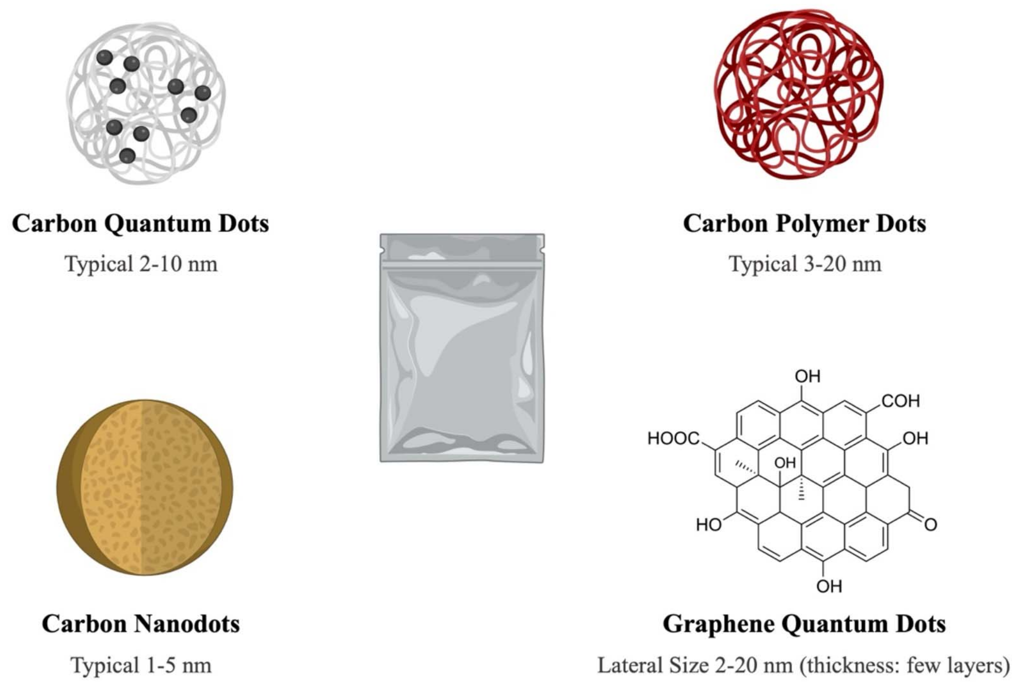

Fig. 5 Schematic classification of the main structural types of carbon dots with representative nanometer-scale sizes.

nanostructures with unique optical, chemical, and interfacial properties. These differences are key to the customisation of CD-biopolymer interactions and to the effective exploitation of the interactions in active, intelligent and protective uses in the packaging of food products.

3.4 Heteroatom-doped carbon dots (N-, S-, P-, and Co-doped CDs)

Heteroatom-doped carbon dots represent a purposefully designed subset where foreign elements, usually nitrogen (N), sulfur (S), phosphorus (P), boron (B), or a mixture of these elements, are intentionally incorporated into the carbon skeleton during manufacturing. This substitution or functional surface modification of the atom designates a significant change in the electronic structure, defect sites, and surface chemistry of CDs, as well as allowing substantial control of their optical and bioactive properties. This tunability is very beneficial in food packaging whereby increased fluorescence, better antioxidant, and better antimicrobial properties are directly related to better functionalities as far as active and intelligent properties are concerned. Another notable use of nitrogen-doped CDs (N-CDs) is the increase in electron density and addition of amine- and amide-containing groups, as well as quantum yield and interaction with hydrophilic biopolymers, such as gelatin, pectin, and chitosan.[152] Sulfur-doped CDs (S-CDs) often produce other mid-gap energy states, which strongly enhance visible-light-induced ROS generation, providing the capability to generate efficient antimicrobial activity applicable to high-moisture foods. P-CDs with an electron-withdrawing P–O functional group (phosphorus-doped CDs, P-CDs) can generally be found to be superior at free-radical neutralization and have potential in slowing down oxidative degradation of lipid-rich products.[153]

Co-doped or dual-doped (*e.g.*, N,S-CDs, N,P-CDs, B,N-CDs) have been an increasing focus of interest because of their synergistic properties, which can normally be superior to single-doped CDs. They have very stable fluorescence, wide pH responsiveness, and improved photochemical properties and can therefore be used as an ideal component of freshness indicators in real-time and colorimetric monitoring systems. Moreover, doping of the CDs enhances the surface chemistry of the CDs, raising the concentration of active groups (–OH, $-NH_2$, –SH, $-PO_4$), which supports interfacial adhesion and hydrogen bonding with edible film matrices.[154] These interactions are normally witnessed in enhanced mechanical characteristics, lower levels of permeability to water vapour and enhanced UV shielding, which enhances the structural and protective functionality of the films. Although these are the benefits, heteroatom modification brings about complications as far as biocompatibility and regulatory approval are concerned. Heteroatoms change charge distribution, catalytic behaviour, and possible patterns of migration; *i.e.*, doped CDs are unlikely to behave the same way as their undoped counterparts in food components, enzymes, or gastrointestinal tissues. Existing toxicology data is limited, and the effects of doped CDs in long-term storage, temperature, and simulated digestion are unknown. However, the significant functional improvements achieved through specific doping of heteroatom-modified CDs make them one of the best opportunities for use in the next generation of edible packaging systems, especially since intensive safety evaluations will accompany further technological advancements.[155,156]

4 Methods and strategies for integrating CDs into edible films

Various complementary strategies can be used to incorporate carbon dots (CDs) in edible films to optimize the quality of dispersion and functional performance. Physical mixing, or solution mixing, is the most commonly used method, in which CDs are placed in biopolymer solutions directly before casting or drying, and the nanoscale size and the hydrophilic surface groups of those CDs can ensure uniform dispersion throughout the polymer structure.[5] In other cases, surface coating and immobilization strategies place CDs on or close to the film surface by spreading, dipping, or layered deposition, which is especially favorable in increasing antimicrobial activity, fluorescence-based sensing, and UV protection at the film–food interface. The compatibility of the polymer with the CD surface chemistry, dispersion stability, and reaction with plasticizers or cross-linkers are some of the critical factors that determine the overall effectiveness of the CD integration. The processing conditions, such as pH, ionic strength, temperature, and drying rate, further dictate whether the CDs reinforce the mechanical strength or affect the moisture and gas barrier properties. These parameters can be optimized to ensure that CDs can achieve their full potential in terms of functional capabilities and maintain the structural and safety demands of edible packaging systems.[157]

4.1 Physical mixing techniques

One of the most popular methods of adding carbon dots to polymeric material used in food packaging consists of physical mixing, also known as blending. The technology of this method implies direct dispersion of pre-synthesized CDs in a polymer solution under regulated stirring, film casting, solvent evaporation, and other shaping methods. This process is simple and scalable and preserves the intrinsic chemical and optical properties of the CDs and the host polymer. Blending can make CDs in the polymer network more uniform, which is important for getting uniform optical properties, bioactive properties, and predictable mechanical performance.[158,159] Mechanistically, the addition of CDs can affect polymer chain interactions through blending, hydrogen bonding, electrostatic interactions, and van der Waals forces, depending on the surface functionality of the CDs and the chemical nature of the polymer matrix. As an example, nitrogen or oxygen surface functional groups on CDs may be hydrogen bonded with hydroxyl or carboxyl and amide functional groups on biopolymers to increase film strength, integrity, and mechanical and barrier properties. Moreover, the optical characteristics of the CDs, such as fluorescence, UV absorption, and photostability, can be directly transferred to the composite film, and it can be used in visual freshness indicators, UV-blocking layers, and active packaging with real-time monitoring capabilities. There are a number of studies that have demonstrated the efficiency of physical blending in the formation of functional packaging films.[160] Khoshkalampour *et al.*,[159] encapsulated green carbon quantum dots within cross-linked gelatin films and were able to achieve a bioactive film with a higher antioxidant effect and structural stability. Although outside the domain of edible films, Zhao *et al.*[158] showed how to prepare CD/PVA composite films, with even dispersion of CD enhancing UV-shielding and antibacterial properties, which is essential in preserving the quality of food in the light. Similarly, Hou *et al.*[161] demonstrated the case of the double cross-linked PVA carboxymethyl cellulose films with CDs, which revealed increased mechanical strength and regulated release of active ingredients to improve long-term preservation of foods.

The versatility of blending in various systems of polymers is further demonstrated by other studies. Mao *et al.*[160] created an alginate film with nitrogen-functionalized CDs and layered clay, which showed synergetic effects on mechanical reinforcement, water vapor permeability, and antimicrobial activity. Riahi *et al.*,[162] developed carboxymethyl cellulose films filled with chitosan-based CDs and proved the increased oxidative stability and bioactive functionality that can be used to create active packaging, as shown in Fig. 6. Zhao *et al.*[163] added CDs to soy protein isolate/PVA films in more recent studies. This made the films better at protecting foods that are sensitive to oxidation. These are just some of the applications of blending to a wide variety of biopolymer and synthetic polymer systems, ranging from gelatin and PVA to alginate and soy protein-based systems.

Overall, it is possible to conclude that physical mixing/blending is a powerful and scalable approach to the production of CD-based active and functional packaging films. This technique can be used to tune optical, mechanical, barrier, and bioactive properties of films systematically by regulating the concentration of CDs and dispersion quality as well as CD-polymer interactions. Therefore, blending is not only an effective fabrication technique but also allows the rational development of multifunctional sustainable food packaging materials that can prolong shelf life and increase food safety.

4.2 Surface coating and immobilization techniques

The techniques applied in surface coating and immobilization are very popular to improve the functional features of biopolymer-based packaging films by deposition or incorporation of bioactive compounds, nanoparticles, or other functional molecules on the surface of the substrate. Such techniques enhance mechanical performance, barricade attributes, and thermal steadiness while simultaneously incorporating dynamic features of antimicrobial, antioxidant, and antifungal activity, which are essential to the shelf life and quality of perishable foods. Nanomaterials, *e.g.*, carbon dots, can be immobilized to enable controlled release of functional compounds as well as strong interfacial interactions between the coating and underlying film, leading to increased stability and performance. Plant enzyme cross-linking of gelatin with Zn-carbon dots followed by coating the films with dots increases the structural integrity and provides responsive antioxidant properties. The development of carbon dots with added nitrogen-functional groups into a cellulose nanofiber-based coating enhances the film strength and provides active protection to food products by way of bioactive interactions. Surface

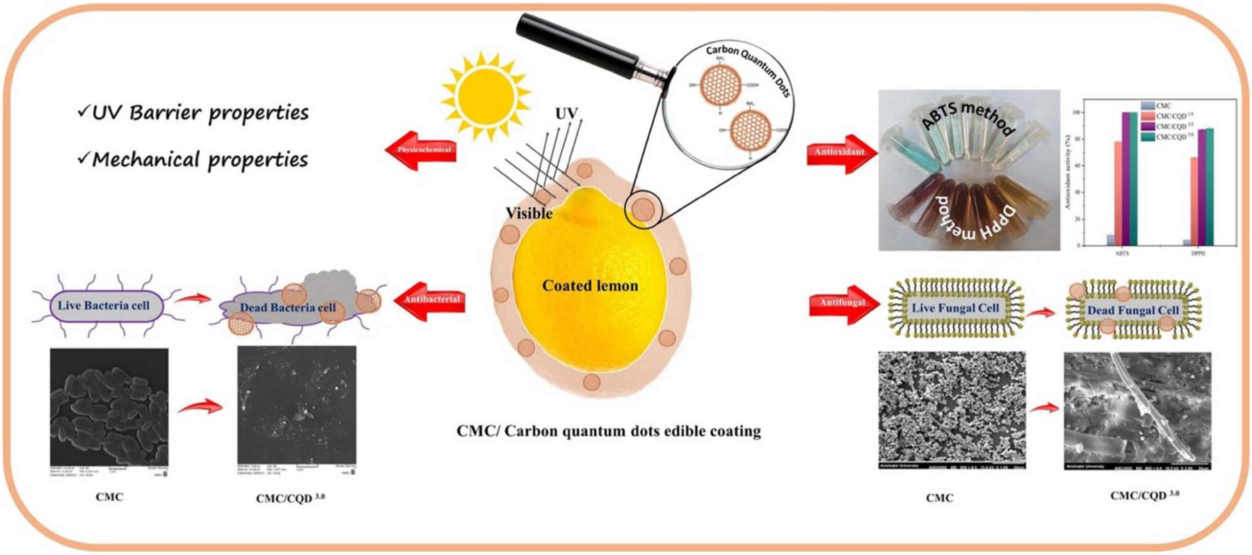

Fig. 6 Physical mixing approach for developing CMC/chitosan-CQD edible coating. Chitosan-derived carbon quantum dots are physically blended into the CMC matrix, creating a multifunctional coating with UV barrier, mechanical reinforcement, antimicrobial (antibacterial and antifungal), and antioxidant properties for active food packaging applications, this figure has been reproduced from ref. 162 with permission from Elsevier, copyright 2022.

coating and immobilization are thus strategic adjustments that convert traditional films into multifunctional materials that are protective as well as able to interact.[164,165]

There are a number of studies that have shown the practical use of the surface coating and immobilization methods for food preservation using carbon dot-based materials. Guo *et al.*[166] used multifunctional carbon dot-reinforced gelatin coating on strawberries, resulting in greater antimicrobial effect and increased film stability, as shown in Fig. 7a. Fresh egg preservation was done by the use of edible coatings composed of carbon dots and gelatin and cellulose nanofibers, which provided excellent mechanical strength and longer freshness, as reported by Tammina *et al.*,[167] as shown in Fig. 7b. Coatings made of carbon quantum dots were antifungal against avocado and could significantly extend shelf life and preserve quality.[168] Furthermore, carbon dots formed through egg-yolk pyrolysis and trapped in albumin-based bio-nanocomposite coatings demonstrate multifunctional properties, such as antimicrobial activity and enhanced barriers, which underscore their future role in numerous food packaging uses.[169] The examples demonstrate the influence and efficiency of coating and immobilization methods in promoting the functional attributes of packaging films for various food products.

4.3 Key factors influencing integration success

Achieving carbon dots (CDs) and other nanomaterials as a component of biopolymer-based packaging films is a reaction to a mix of material, structural, and processing parameters, which, together, define the performance, stability, and functionality of the composites formed. One of the most important is the compatibility of the polymer matrix and the nanomaterials. The dispersion of CDs in the hydrophilic polymer matrices, including alginate, cellulose, gelatin, or pullulan, should be homogeneous to guarantee the uniform distribution of the functional sites, increase mechanical strength, and extend the barrier properties. As an example, Mao *et al.*,[170] proved that enriched with carbon dots derived from plant polyphenols, as well as layered clay, the tensile properties of the alginate films and their active functionality improved because of good interfacial properties between the carbon dots and the polymer network. On the same note, Riahi *et al.*,[171] emphasized that cellulose nanofiber/pullulan films impregnated with Zn-doped carbon dots exhibited effective antimicrobial activity and extended the shelf life of chicken and tofu due to effective matrix–nanomaterial interaction that would not cause aggregation and would release the bioactive effectively. Conversely, when the nanomaterials and polymers do not disperse or interact well, phase separation, structural defects, and poor active performance can be the results. Another significant factor is the method of incorporating materials and forming the film. Solution casting, layer-by-layer assembly, or surface coating methods influence the distribution and stability of CDs in the film matrix. As an example, Du and Zheng,[172] have introduced silver nanoparticles/carbon dot nanocomposites into chitosan/polyvinyl alcohol films, obtaining long-term antimicrobial and antibiofilm effects due to the dispersion of nanocomposites in the casting process. The environmental factors in film preparation, such as pH, temperature, and drying rate, also determine the stability of nanomaterials and their interactions with the polymer. Handling of processing conditions assists in preserving the functionality of the CDs as well as inhibiting aggregation or degradation of the polymer matrix. The physicochemical characteristics of the carbon dots *per se* are also crucial. The particle size, surface charge, and surface functionalization define the level of the interaction with the polymer chains and, hence, the mechanical, barrier, and bioactive

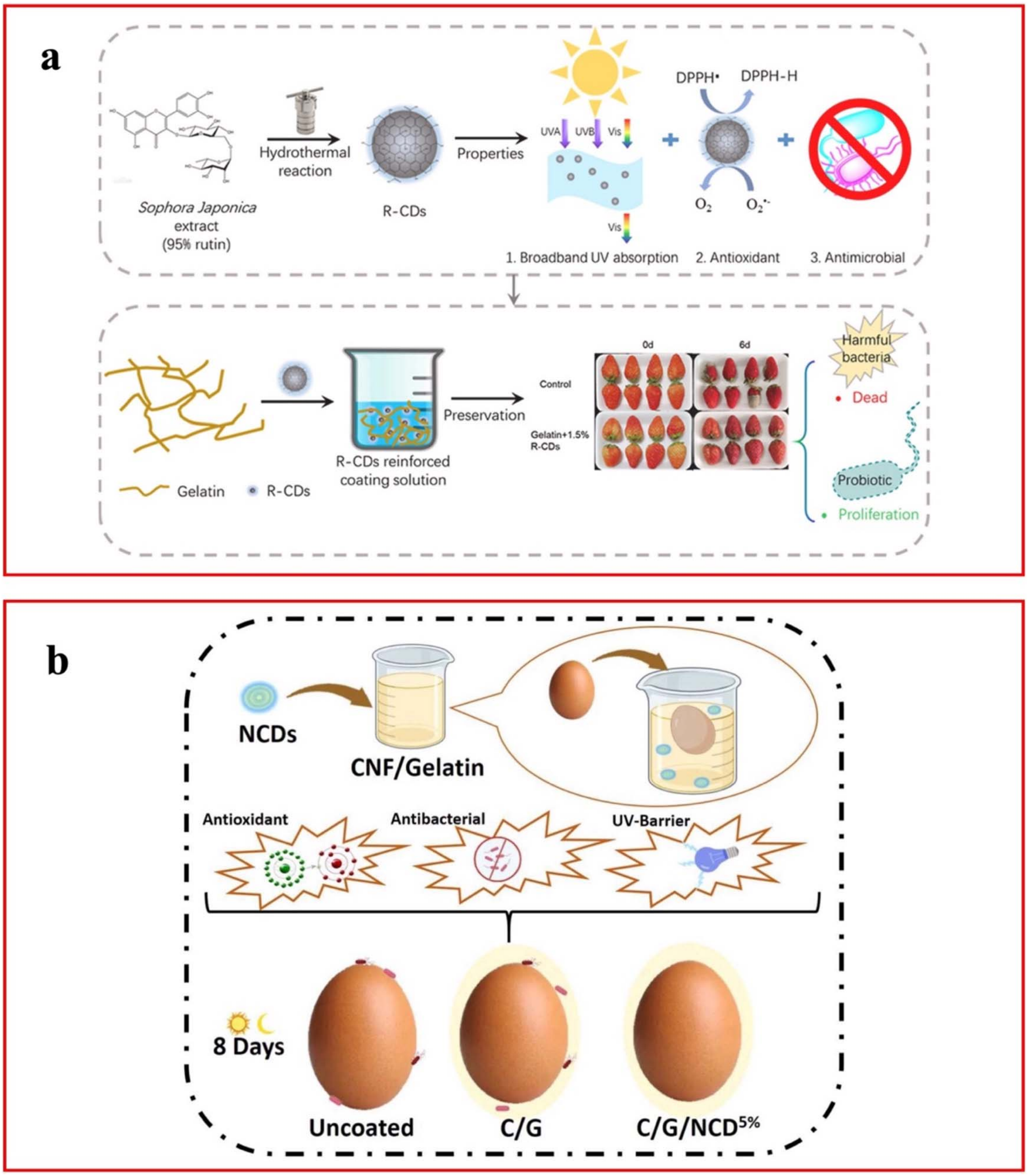

Fig. 7 Carbon dot-reinforced edible coatings for food preservation *via* surface immobilization technique. (a) R-CDs/gelatin coating on strawberries showing antimicrobial and probiotic-selective properties, this figure has been reproduced from ref. 166 with permission from Elsevier, copyright 2023. (b) NCDs/CNF/gelatin coating on eggs demonstrating multifunctional protection (antioxidant, antibacterial, UV-barrier) with enhanced preservation over 8 days, this figure has been reproduced from ref. 167 with permission from Elsevier, copyright 2025.

performance of the films. Antimicrobial activity and compatibility with the polymer can be increased by functionalization with elements like zinc or sulfur, as demonstrated in gelatin/polyvinyl alcohol films containing sulfur quantum dots and silica nanohybrids, which have been shown to have better fruit preservation performance.[173] Nanohybrids or co-additives, *e.g.*, silica, magnetite, or anthocyanins, can be used to provide further functionality, *e.g.*, provide UV-blocking properties or be used as colorimetric sensors, or for synergetic use as antimicrobials, *e.g.*, in carrageenan/gelatin films containing carbon dot-silica nanohybrids and red cabbage anthocyanins to make intelligent shrimp packages or in beef packaging using hydroxypropyl methylcellulose/mag.[174]

Lastly, the interactions of the matrix and nanomaterial and network structure are also essential to long-term performance. Strong interfacial bonding and entanglement between the polymer chains and the nanomaterials ensure mechanical stability, control over the release of functional agents, and resistance to environmental stresses such as humidity, temperature changes, and mechanical handling. Through the selective optimization of these parameters, matrix compatibility, nanomaterial properties, incorporation method, and environmental processing conditions, carbon dot-based composite films can be made to be multifunctional, with improved tensile strength, control over the release of biomaterials, improved barriers, and intelligent sensing functions, and be utilized in a wide variety of food packaging systems.[173–175]

5 Effects of CD integration on film properties

The novel methods of incorporating CDs into polymeric films have been demonstrated to significantly enhance their overall functionality, including physico-mechanical, barrier, functional, and optical performances that are critical in the creation of innovative active food packaging. Mechanically, CDs play a nanoscale role as reinforcing reinforcers, which interact with polymer chains by hydrogen bonding, van der Waals forces, and electrostatic forces, contributing to tensile strength, elongation at break, and flexibility. As an example, cornstarch/gelatin and 3D-printed films with cinnamon essential oil-derived CDs have been shown to be stronger and more versatile in mechanical properties, which is essential in packaging systems that need to be both strong and flexible.[176] This is also true of polyvinyl alcohol/cornstarch films that were added with CDs; they had more uniform mechanical behavior with enhanced longevity under stress, meaning that CDs have the capacity to counteract structural weak points that are inherent in biopolymer films.[177] Gelatin/alginate films reinforced with pomelo peel-derived CDs were found to be much more elastic and structurally stable, with a focus on the capability of natural CD materials to reinforce biodegradable films without affecting their operational integrity.[178] CD reinforcement in silk sericin-based films resulted in an improvement in tensile properties as well as the safety of packaging fragile fruits like litchi without causing ruptures in the film due to its adequate elasticity.[179]

A high incorporation level of CD is also important in improving barrier properties that are important in the regulation of moisture and oxygen. The small size and large surface area of CDs form tortuous pathways in the polymer matrix, which restricts the diffusion of water vapor and gases. Starch-derived graphene quantum dots included in starch/polyvinyl alcohol films were associated with a lower water vapor permeability and were efficient in preserving food products, which are sensitive to water.[180] Films created with polysaccharide and integrated with CDs made of cashew and jik leaves exhibited a better oxygen barrier effect, which slows down oxidation reactions and increases the shelf life of the products.[181] Moreover, a study on pectin and gelatin that used modified graphene quantum dots and carnauba wax demonstrated greater resistance to water and oxygen diffusion, as well as better retention of film integrity under varying storage conditions, indicating that CDs could enhance the performance and longevity of biodegradable films.[182] In addition to mechanical and barrier improvements, CDS confer significant functional qualities. The bioactive compounds of their natural sources are preserved in many CDs, and these compounds are antimicrobial and antioxidant, which are actively involved in the preservation of food against microbial infection and oxidative destruction. Indicatively, coffee husk CDs added to carboxymethyl cellulose films displayed high levels of antibacterial properties against the most common foodborne pathogens, and at the same time, CDs were found to be free radical scavengers, effectively lowering food spoilage.[183] The multifunctional characteristics of these properties enable the use of films made from CDs to create not only physical barriers but also active packaging systems that can extend shelf life and preserve food quality. Lastly, the CDs affect optical characteristics of films, enhancing the transparency and UV-blocking properties. CDs can be fluorescent and nanoparticles, which enables the films to be clear to the naked eye but at the same time captures or scatters harmful UV radiation, protecting light-sensitive food components. Corn starch/gelatin films containing banana peel-derived CDs, like, improved the clarity of the films as well as their UV-protectivity and provided both aesthetic and protective functionality.[176]

6 Applications of carbon dot-integrated edible films in food packaging

Carbon dot-integrated edible films represent an emerging technology that is considered a game changer in the modern food packaging industry, offering a versatile platform to address challenges in food preservation, monitoring, and protection, as illustrated in Fig. 8. Conventional food packaging has traditionally been passive, serving mainly as a physical barrier to prevent contamination and moisture loss. Conversely, the films made using CDs can incorporate active, intelligent, and protective features in the same biopolymer framework, which has never been seen before and provides a chance of improving the quality, safety, and shelf life of foods besides being environmentally friendly, as summarized in Table 4. Active packaging is one of the most explored areas of the use of these films, and in this area, the inherent antimicrobial and antioxidant characteristics of CDs are significant.[184] It has been shown that CDs, especially those based on natural or waste biomass, can be used to scavenge reactive oxygen species (ROS) and other free radicals, which effectively inhibit oxidative reactions to produce rancidity in perishable lipid foods, alter color, and cause loss of nutrients. This antioxidant effect is supplemented by the intrinsic antimicrobial actions, which can be augmented in the presence of light *via* photo-induced effects, making it possible to use it in a wide spectrum of inhibited spoilage microorganisms, including bacteria and fungi. The interaction of these properties enables the edible film to be more of an active preservative system that can interact directly with the food surface, reduce microbial load, and decant biochemical degradation. They are especially applicable to very perishable goods, such as fresh fruits, vegetables, seafood, and meat products, in which oxidative and microbial spoilage are the main factors that lead to loss of quality and wastage.[185]

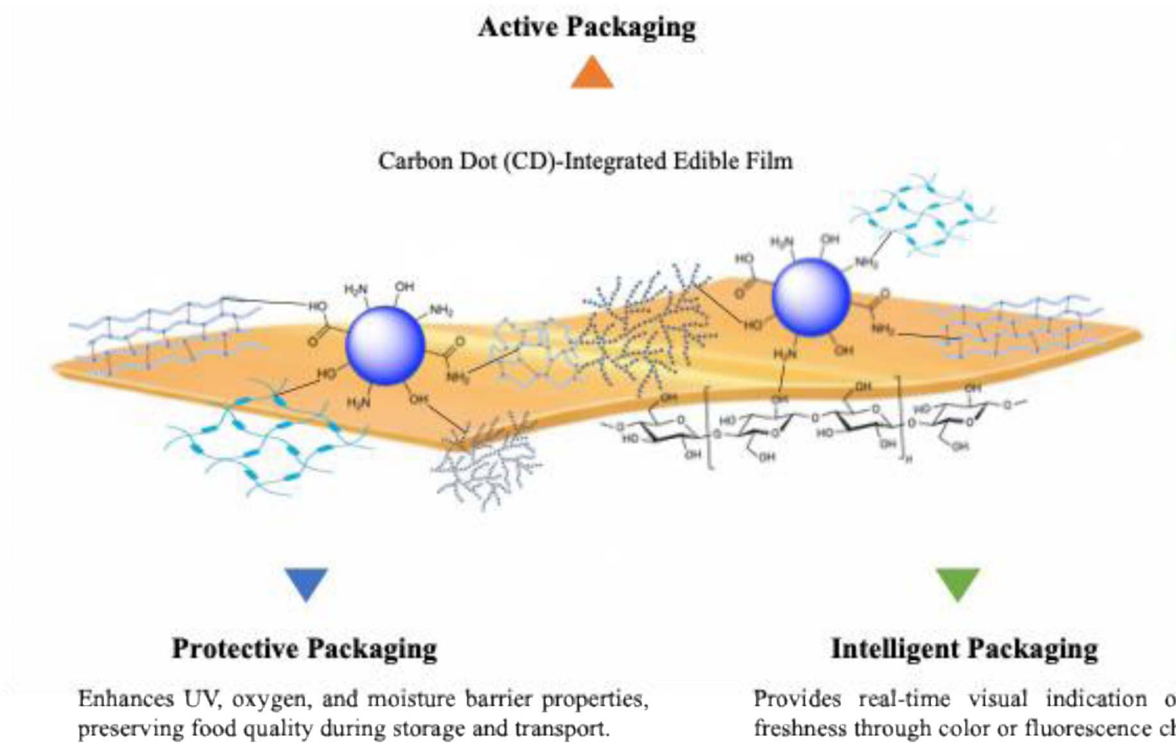

Fig. 8 Comprehensive overview of the multifunctional carbon dot (CD)-integrated edible film for next-generation food packaging.

In addition to the preservative feature, CD-integrated films can also be used for intelligent packaging by providing real-time monitoring of food quality. Optical and fluorescent characteristics of CDs allow the use of the CDs as visual cues of freshness, changes in pH, or accumulation of gases related to spoilage. As an illustration, when some food products degrade, the local alterations in pH may occur as a result of metabolic processes, which can produce volatile substances, ammonia, or organic acids, which form certain volatile compounds and spoilage gases.

This system uses CDs embedded in the film matrix to detect stimuli, as they are sensitive to changes in fluorescence or colorimetric variation, providing an immediate and non-invasive assessment of product quality. The method is especially beneficial in the cold-chain management system, retail display, and consumer application since it provides the chance to quickly evaluate the food safety without having to send samples to a laboratory. The CDs can be incorporated in edible or biodegradable films, which means that these intelligent sensors can be compatible with the same principles of sustainable packaging rather than adding extra non-degradable substances and toxic indicators.[186,187] The emergence of such sensing systems also portends opportunities for active-intelligent hybrid packaging, where a single film can at the same time do two jobs: preserve food quality and inform shifts in freshness, therefore heralding the completeness of the gap between preservation and monitoring. Besides their bioactive and sensing capabilities, CD-incorporated edible films have considerable protective properties, which enhance the packaging material's structural and barrier performances. UV light contributes significantly to food degradation, which speeds up the rate of photo-oxidation, pigment breakdown, and loss of nutrients, particularly in light-sensitive products like fruit juices, fresh produce, and dairy products. The introduction of CDs in polymer matrices increases UV-blocking properties that prevent the passage of harmful wavelengths without compromising optical transparency, which appeals to consumers. Furthermore, the CDs can react with the chains of the biopolymer to increase the mechanical properties of the film, including tensile strength and flexibility, and improve its barrier properties against oxygen and moisture, among other environmental factors. These safety measures are useful in preserving the integrity of the products during storage and distribution and alleviating the impact of changing temperatures, humidity, and light exposure that are common in retail and home settings. The functional bioactivity of CD-based edible films is achieved by integrating structural reinforcement and bioactive components, which interact through various degradation pathways to produce a more robust and effective packaging solution.[188–190]

This combination of active, intelligent, and protective features that are synergistically integrated in one CD-based film enables the film to offer an unequaled edge over traditional packaging. Unlike conventional films, which are basically passive protection, the CD-integrated systems actively postpone the spoilage and give real-time indicators of the food's condition, as well as protect the products against environmental pressures. This whole food method is especially useful with

Table 4 Applications of carbon dots-integrated edible films in food packaging

Study	Source of carbon dots (CDs)	Polymer matrix/film type	Main functionalities	Food application
Khan *et al.*[200]	Green tea residue CDs	Chitosan/gelatin	Antioxidant, antimicrobial, UV shielding, mechanical reinforcement	Pork preservation
Bao *et al.*[201]	Torreya grandis aril CDs	Fish scale gelatin + CNF + essential oil nanoemulsion	Antimicrobial, antioxidant, improved barrier properties	Tomato preservation
Bahramian *et al.*[202]	Turnip peel CDs	Methyl cellulose/Chitosan nanofibers	Antioxidant, antimicrobial, photostability, structural reinforcement	Perishable foods (general shelf-life extension)
Jiang *et al.*[203]	Crayfish shell nitrogen-doped CQDs	Konjac glucomannan/Sodium alginate	Antioxidant, antimicrobial, mechanical strengthening	Crayfish meat preservation
Murugan *et al.*[204]	Tangerine peel CDs	Chitosan/PVA	Antioxidant, antibacterial, improved thermal and mechanical properties	General active packaging
Ananthi *et al.*[205]	Cow milk CDs (Ag-functionalized)	Biodegradable polymer films	Strong antibacterial activity, mechanical enhancement	Active food packaging (general)
Khan *et al.*[206]	Kohlrabi peel Zn-CDs + anthocyanin	Carrageenan	Intelligent colorimetric pH sensing + antimicrobial effects	Shrimp freshness monitoring
Wagh *et al.*[207]	Blueberry (vaccinium corymbosum) CDs	Gelatin + anthocyanin	Intelligent pH indicator, antioxidant, mechanical reinforcement	Intelligent packaging (general)
Javdani *et al.*[208]	Onion peel CDs + anthocyanins	Chitosan/PVA	Freshness tracking, antibacterial, antioxidant	Red meat monitoring & shelf-life extension
Fu *et al.*[209]	Resveratrol-derived CDs	Gelatin/Chitosan	pH sensing, antioxidant, antimicrobial	Intelligent packaging (general)
Hu *et al.*[210]	CDs (unspecified biomass)	Chitosan	Dual-functional: antimicrobial + enhanced pH sensing	Fish freshness monitoring
Gao *et al.*[211]	Natural CDs from honeysuckle extract	Chitosan/attapulgite	Intelligent pH sensing + antioxidant	Fresh food packaging (general)
Koshy *et al.*[212]	Starch-based carbon nanodots	Starch + anthocyanin	pH sensitivity, spoilage detection	Pork spoilage monitoring
Tohamy[213]	Beetroot CDs	Cellulose sulfate	pH colorimetric sensor; metal ion (Cr^{6+}) and bacteria detection	Tomato safety assessment
Murugan *et al.*[214]	Guava leaf powder CDs	Fish gelatin/chitosan	Controlled release, antioxidant, antibacterial activities	Active packaging for fish products
Singh *et al.*[215]	Various CQDs (review paper)	Biopolymer matrices (various)	Antioxidant & antimicrobial enhancement	General overview (not specific)
Alamer *et al.*[216]	Hibiscus flower CDs	Gum Arabic/Chitosan/PVA	Postharvest quality preservation, antioxidant activity	Barhi date preservation
Fan *et al.*[217]	CDs with chitosan coating	CDs + chitosan	Antibacterial, quality maintenance under MAP	Fresh-cut cucumber
Khoshkalampour *et al.*[218]	CQDs	Casein/Modified tragacanth gum	Antioxidant, antimicrobial, improved barrier	Butter shelf-life extension
Sobhan *et al.*[219]	Activated carbon-based nanodots	Composite nanocomposite film	Antibacterial, intelligent packaging function	General intelligent packaging

perishable and high-value foods, where shelf life and safety are of significant concern. In the case of fresh seafood, a film coating on CD-based not only prevents bacterial growth and oxidative decomposition of lipids but also indicates freshness with a visual change in fluorescence and is also protective against discoloration caused by UV radiation on food during transport and display in stores. Other similar uses are in fresh-cut fruits and vegetables, dairy products, and meat, where oxidative and microbial spoilage are common and where UV, light, and moisture access may hasten further quality decline. CD-integrated films can be used to provide significant improvements in reducing food wastage, improving supply chain performance, and increasing consumer confidence in food safety by tackling several degradation processes in one packaging solution.[191,192]

Although these applications are promising, there are still several challenges that face the translation of the CD-based edible films that have been researched in the laboratory to the industrial practice. The size, functional groups on the surface, and fluorescence intensity of CDs are physicochemical properties that are very sensitive to the source and the conditions of synthesis, which might result in a possible variation in the performance across batches. The relationships among CDs, polymer matrices, migration behavior, and long-term stability, as well as their influence on sensory properties, require further study to ensure safety and efficacy. In addition, scalable fabrication technologies should be invented that allow large-scale fabrication without compromising bioactivity, barrier properties, and sensing. Regulatory approval and consumer acceptance are also issues, especially for edible films that touch food. However, current studies on biomass-derived CDs, biopolymer composites, and hybrid active-intelligent formulations indicate that these issues can be resolved, and the final step towards next-generation packaging solutions, which combine preservation, monitoring, and protection into one system that operates in an environmentally friendly manner, is possible.[193]

The recent research has been conducted to investigate the incorporation of carbon dots (CDs) into edible films as an attempt to boost active and intelligent packaging properties. CDs are commonly made by using natural or waste biomass, such as eggplant peel (Khan *et al.*[194]), enoki mushrooms (Roy *et al.*[195]), banana peel (Sul *et al.*[196]), Vachellia nilotica gum (Parveen *et al.*[197]), orange peel (Mohajjel Sadeghi *et al.*[198]), and other sustainable sources. Polymers like gelatin, chitosan, carrageenan, and pectin are biodegradable and biocompatible, and the optical, antioxidant, and antimicrobial properties of CDs are exclusive and unique, so these films are prepared by combining them to obtain multi-functional packaging materials.

Active packaging-wise, Kahn *et al.*,[194] Roy *et al.*,[195] and Sul *et al.*,[196] show that CDs have been able to remove free radicals and microbial growth, which reduce oxidative rancidity and spoilage in perishable foods like fruits and vegetables. This ascertains their possibility as bioactive agents in films that have the potential of directly prolonging shelf life. These investigations emphasize the use of CDs as functional additives, in addition to a means of valorization of agricultural waste, which is in line with sustainability objectives. Nevertheless, the vast majority of such research focuses on laboratory-scale testing, and little work has been done to analyze long-term storage functionality, food penetration, or regulatory safety, which limits their direct practice relevance (Fig. 9). In the case of intelligent packaging, Parveen *et al.*,[197] Kilic *et al.*,[199] and Mohajjel Sadeghi *et al.*,[198] incorporated CDs into films that could sense spoilage or change in freshness. The films of these films take advantage of the fluorescence or colorimetric characteristics of CDs to indicate changes in pH, the presence of gases, or other indicators of food spoilage. Interestingly, Kilic *et al.*,[199] linked the sensing potential to a phone app and showed progress on the way to the consumer level (Fig. 10). In the same manner, Mohajjel Sadeghi *et al.*,[198] used CDs as a composite with natural anthocyanins to produce dual-sensing pH-responsive films to detect meat freshness. These researches demonstrate how CDs could be used as an effective, non-invasive, real-time monitoring technology in food packaging. The long-term stability, reproducibility, and environmental sensitivity (*e.g.*, light, humidity, and temperature) of these sensors are, however, not investigated in detail, thus limiting confidence in their practical application.

Besides bioactivity and sensing, CDs also play protection packaging roles. They boost UV-blocking and mechanical strength as well as barrier attributes of biopolymer films that are vital in preserving food integrity in storage and transportation. As an example, Sul *et al.*,[196] demonstrated that the banana peel-derived CDs could enhance the UV-shielding property of chitosan/gelatin films, whereas Parveen *et al.*[197] proved that the gum-derived CDs could enhance the structural and barrier properties of the chitosan/gelatin nanocomposite films (Fig. 11).

These characteristics are needed to fight photo-oxidation, loss of moisture, and loss of gases, which are major factors that degrade food. However, the mechanistic description of the interaction of the CDs with the polymer matrices, especially when subjected to long-term storage or under different environmental conditions, is still incomplete. In all of these studies, there are a number of important limitations. First, biomass-derived CDs can have a high degree of variability in composition and quality depending on the precursor and synthesis conditions, causing batch-to-batch differences in the performance of the film. Second, most studies concentrate on proof-of-concept experiments that have no assessment in actual food system environments of commercial storage and distribution. Third, there has been the problem of scale to industry, with most CD synthesis and film fabrication protocols being optimized to produce on the laboratory scale. Lastly, regulatory and safety evaluations are not well matched, particularly in terms of migration, toxicity, and consumer acceptance of edible films containing CD.

7 Toxicological and safety considerations

Although carbon dot (CD)-integrated edible films have shown outstanding active, intelligent, and protective properties, their toxicological and safety profiles are also decisive factors in the attempt to apply them in food packaging. The CDs are commonly produced in natural or waste biomass, *e.g.*, peelings of fruits, mushrooms, and plant gum, and are incorporated within biodegradable polymer matrices, *e.g.*, gelatin, chitosan, carrageenan, or pectin. These materials are mostly believed to be biocompatible and non-toxic, but the complexity of the nanoscale of CDs must be carefully assessed. Depending on the precursor material and method of synthesis, the size, surface chemistry, and functionalization of CDs can range across a broad spectrum due to their influence on their reactivity, cellular reactions, and their potential migration into food.[204,205] As an example, surface functional groups like carboxyl, hydroxyl, or amino groups may affect bioactivity and cytotoxicity, especially when CDs are lost off the film during storage or when directly contacted with acidic or lipid-rich foods. The general *in vitro* biomass-derived CDs research has shown no or low cytotoxicity at the concentration of edible film, but a number of studies report compatibility between biomass-

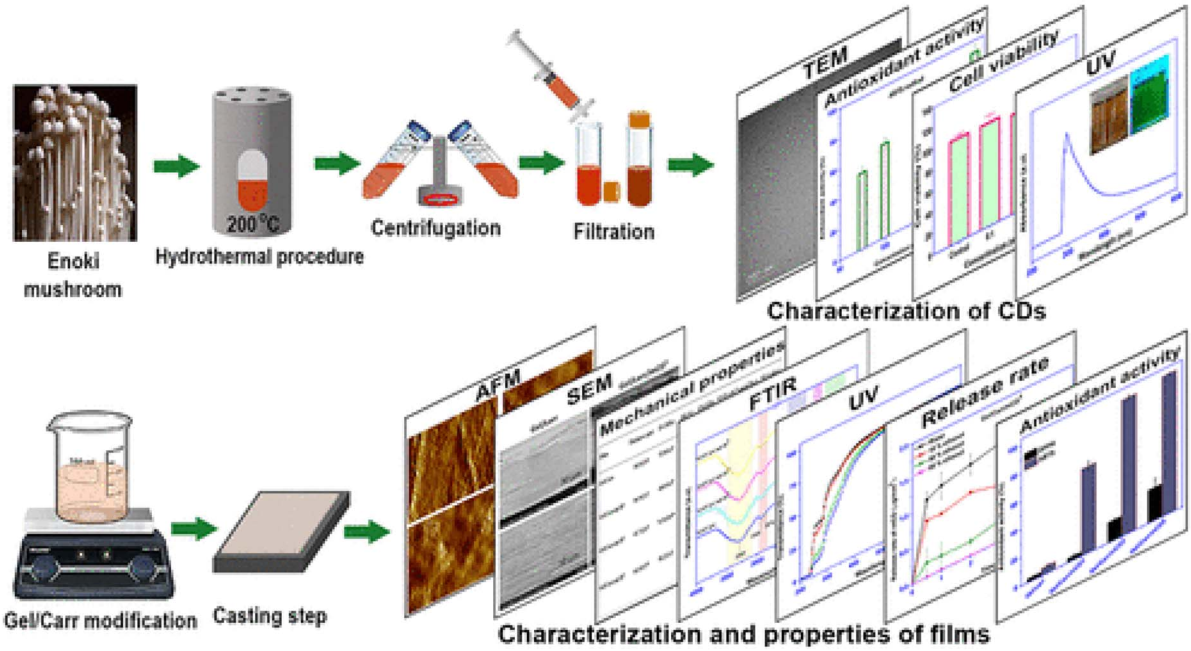

Fig. 9 Schematic illustration of the preparation process for functional gelatin/carrageenan (Gel/Carr) films incorporated with enoki mushroom-derived carbon dots (CDs), this figure has been reproduced from ref. 195 with permission from the American Chemical Society, copyright 2021.

derived CDs and human cell lines. Nevertheless, these studies have restricted scope, as many of them concentrate on the short exposure to a controlled laboratory environment. The systemic bioaccumulation and prolonged exposure of the CDs to ingestion are not well studied. Specifically, the risk of nanoparticle release of the polymer matrix into the food even in the presence of realistic storage conditions (different temperature, pH, or moisture) is another safety risk. The chemical modifications of CDs, such as processing in the form of film (*e.g.*, heating, crosslinking, or UV curing), might change the workability (*i.e.*, functional performance) and the safety profile of the films. Thus, detailed migration research to recreate the storage and handling conditions in reality is required.[211,215]

Toxicological studies are even lower *in vivo*. Limited literature has been done to study in detail the absorption, distribution, metabolism, and excretion (ADME) of CDs in animal models, and very little on chronic or repeated exposure. Since edible films are to be in direct contact with food, it is essential to learn how CDs interact in the gastrointestinal tract and whether they can be accumulated or cause oxidative stress, inflammatory reactions, or organ-specific toxicity. Besides that, the CDs can interact with other food components (lipids, proteins, acids, *etc.*) and can change their stability, bioavailability, and possible toxicity. The issue of regulation also makes the implementation of CD-based films a difficult pursuit. Most countries' regulations on food contact materials do not fully embrace nanomaterials, and the regulations provide little information on acceptable levels of migration, exposure assessment, and safety limits of nanoparticles. To pass through these changing standards, a rigorous safety assessment has to be conducted on the CDs, that is, with a comprehensive characterization of the particle size, surface chemistry, concentration, and release behavior. In addition, the consumer acceptance will require not just the established safety but also the displayed labeling and education about the utilization of nanomaterials in food packages.[209,210,216]

Another factor is environmental safety. Although most CDs are biodegradable when included in natural polymer matrices, their persistence in the environment upon disposal remains poorly studied. The effects that may be imposed on soil, water, or the microbial ecosystems ought to be considered so that the CD-based films are not only safe for consumers but also environmentally friendly. Overall, despite the promising functionality and sustainability of CD-integrated edible films, their toxicology and safety profile are the major challenges to be overcome in their conversion to industry. To deal with these issues, the multi-level strategy, including standard *in vitro* and *in vivo* toxicity testing, migration and stability tests under realistic conditions of food storage, regulatory compliance, and environmental impact assessment, is necessary. It is only through the systematic approach of addressing these aspects that CD-based edible films can transform from the laboratory level of innovation to safe, feasible, and acceptable packaging options for the consumer.[218,219]

8 Limitations and challenges

Despite the considerable progress achieved in the development of carbon-dot-integrated edible films for food packaging applications, several limitations and challenges remain that must be critically addressed to enable their safe and effective translation from laboratory research to industrial practice. A further

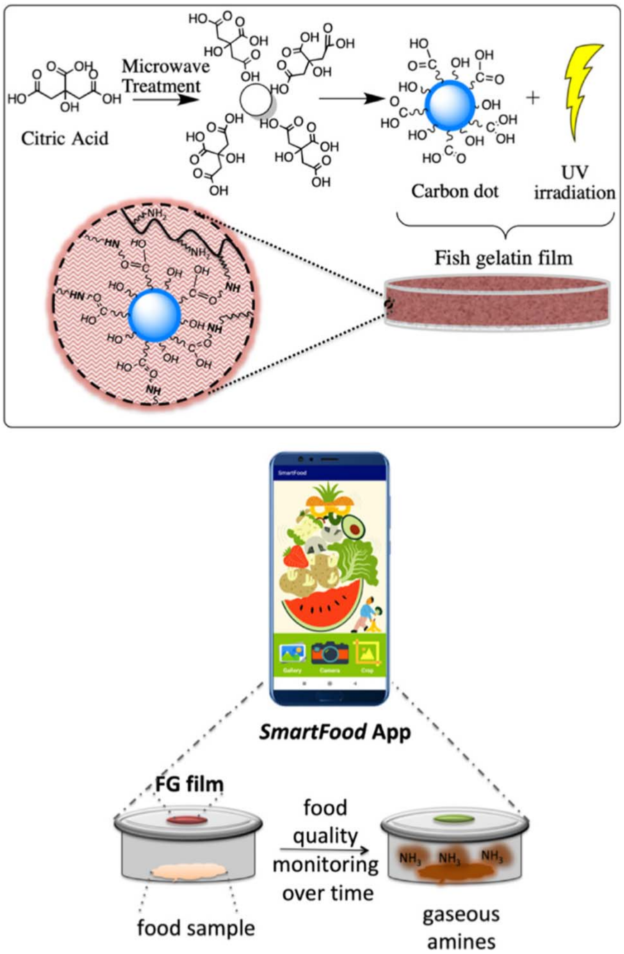

Fig. 10 Schematic illustration of carbon dot-integrated fish gelatin films for intelligent food packaging with smartphone-based freshness monitoring, this figure has been reproduced from ref. 199 with permission from Elsevier, copyright 2022.

limitation that is of significance is connected with the food processing and storage stability of carbon dots. Both edible films can undergo processing, transportation, and storage, which are exposed to thermal treatment, ultraviolet radiation, oxygen, and changes in humidity. In these circumstances, carbon dots can be aggregated, oxidized on their surface, or bleached under light and this process can affect their functionality, such as optical properties, antioxidant activity and antimicrobial properties.[220,221] Moreover, maturation of the biopolymer matrix can also change carbon dot dispersion and interfacial interactions, which also influence film performance. It has not been studied enough regarding the stability of long term stability assessments in realistic packaging conditions. Reproducibility and scalability of carbon dot manufacture is also another issue to the practical implementation.[222] Although there has been a lot of laboratory-scale synthesis routes described, there are many problems with these methods including batch-to-batch variability, low yield, and a lack of control over particle size and surface chemistry at larger scales. The production of materials that are both supplied on a regular basis and at the same time perform their functional tasks is still a great challenge to the industrial production.[223] Economically, the expense incurred in the mass synthesis and incorporation of carbon dots into edible films is a major issue of concern. Even though carbon dots could be prepared using relatively cheap or waste materials, subsequent processing procedures, including purification, surface functionalization, and homogeneous dispersion in polymer matrices, can significantly raise the costs of production. There must be a delicate adjustment between the use of functionality and cost-effectiveness hence justifying investment in commercial use in food packaging.[224]

9 Future perspectives and conclusion

CDs integration in edible polymeric films is a paradigm shift in the sphere of food packaging that combines active, intelligent, and protective properties on the same and biodegradable platform. The literature reviewed reveals that CDs, which are based on renewable biomass or agro-industrial waste, are able to confer antioxidant, antimicrobial, UV-blocking, and real-time sensing properties to biopolymer matrices, and at the same time extend shelf life, maintain sensorial and nutritional quality, and offer a non-invasive food freshness-monitoring instrument. Such innovations highlight the potential of the CD-based films to revolutionize the situation with the food security, waste minimization, and sustainable packaging issues. Nonetheless, even with these attractive qualities, there are still major loopholes that still need to be filled to upgrade this technology out of the laboratory and into the business world.

On the materials side, a major challenge is having precise control of the synthesis and functionalization of CDs. The physicochemical characteristics of the CDs, such as size distribution, surface functional groups, quantum yield, and fluorescence stability, directly determine their incorporation into the polymer matrices and hence the final film performance. Differences in biomass precursors and synthetic procedures may cause the variability between batches, impacting antioxidant activity, antimicrobial activity, and optical responses. To establish uniformity in the functional performance of industrially produced films, future investigations need to aim at standardized, scalable, and reproducible protocols to synthesize CDs, whether by the use of a green approach or continuous-flow techniques. The mechanistic relationships between polymer matrices and CDs also deserve more research. Although recent research has indicated an improvement in mechanical, barrier, and optical properties, little is known about the mechanism of interaction between CD and polymer at a molecular level. Multifunctionality needs to be optimized by systematic exploration of the dynamics of dispersion, compatibility, aggregation, and migration under variable environmental conditions without compromising the stability of the film, safety, or biodegradability. Combined with this, synergistic functionalities with antioxidant and pH-responsive functionalities, or dual UV-blocking and antimicrobial activity, of hybrid CD-polymer composites are a potentially fruitful direction of next-generation intelligent-active packaging systems.

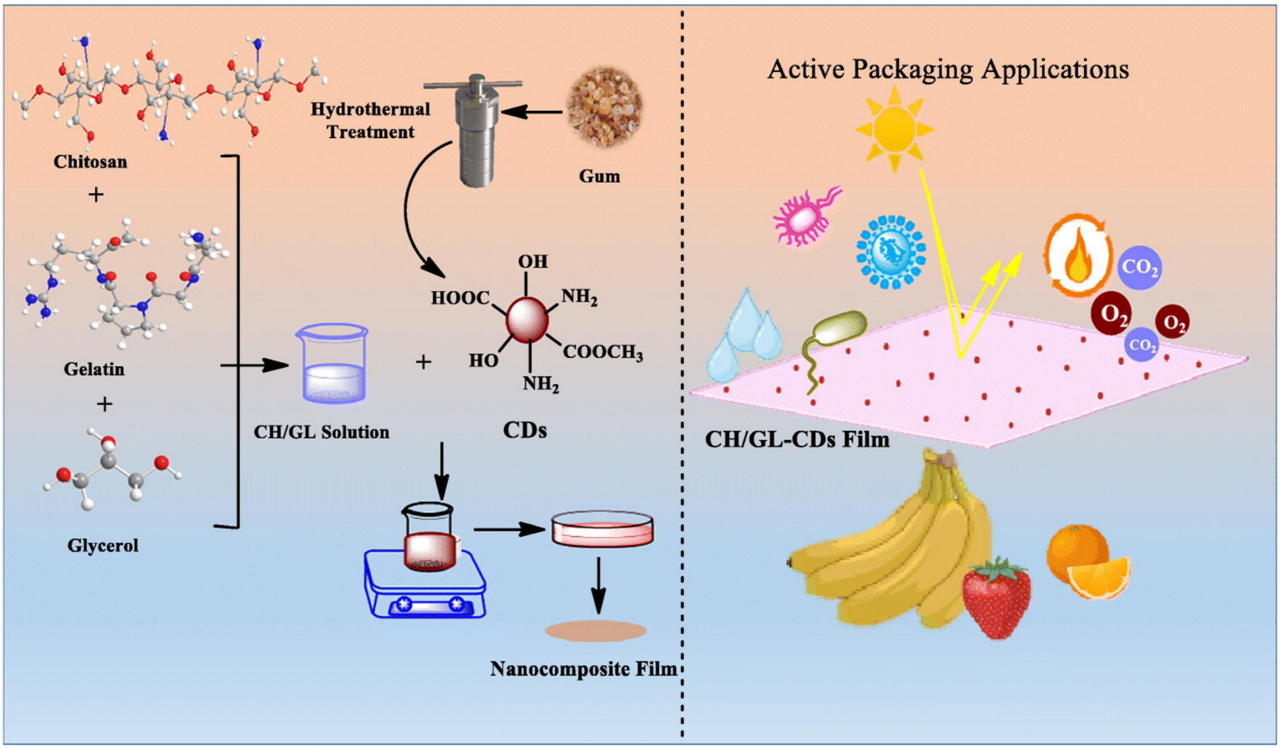

Fig. 11 Synthesis and application of carbon dot-integrated chitosan/gelatin nanocomposite films for intelligent food packaging, this figure has been reproduced from ref. 197 with permission from Elsevier, copyright 2025.

Another important frontier would be safety and regulation. Although CDs are considered to be biocompatible, not all of the aspects of the long-term toxicological profile, migration, and possible interactions with food components are fully profiled. To satisfy regulatory requirements for food-contact materials, rigorous *in vitro* and *in vivo* testing and chronic exposure testing and standardization of safety testing systems are required. In addition, it will be important to harmonize the regulations concerning the incorporation of nanomaterials in edible films in different jurisdictions internationally to enable their commercialization and acceptance by consumers. Application-wise, CD-based films present unprecedented possibilities of active-intelligent-protective hybrid packaging, though the current studies have remained mostly restricted to the laboratory-level validation. To close this gap, we need scalable methods for fabricating CDs through roll-to-roll casting, electrospinning, or 3D printing that allow global integration of CDs without affecting bioactivity, optical sensing, or barrier functionality. Additionally, testing under supply chain conditions—such as variable temperature, humidity, and light exposure—is necessary in real-world scenarios to evaluate the durability, responsiveness, and efficacy of the packaging for food.

Ethical approval

This article does not include any research involving human or animal subjects.

Consent to participate

We grant permission for our work to be included in the manuscript.

Author contributions

Awat S. Mohammed: conceptualization, literature review, writing – original draft, writing – review & editing, visualization, project administration. Sewara J. Mohammed: writing – review & editing.

Conflicts of interest

We declare no competing interests.

Data availability

No datasets were generated or analysed during the current study.

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