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Exploring Sustainable Carbon Dots as UV-Blocking Agents for Food Preservation

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ABSTRACT

Exposure of foods to ultraviolet (UV) radiation during processing, storage, and retail display can result in quality deterioration, reduced shelf life and nutritional value, and potential food safety issues. The use of UV-blocking food packaging is an effective strategy to minimize these harmful effects. Carbon dots (CDs) are a class of carbon-based nanomaterials that have emerged as promising candidates for enhancing the UV-blocking performance of biopolymer-based films and coatings. Their unique advantages of excellent UV absorption ability combined with their low toxicity, biocompatibility, and facile production from sustainable precursors make CDs superior alternatives to traditional UV-blocking agents. Incorporating CDs into biopolymers can significantly enhance UV protection without compromising the transparency of the packaging, thereby maintaining the visual appeal of the packaged product. In addition to UV protection, CDs confer multifunctionality to packaging systems by imparting antioxidant, antimicrobial, and pH-responsive properties, thereby meeting the demand for sustainable and intelligent packaging solutions. These advancements not only protect food from photodegradation but also address broader food safety issues through their active and responsive functions. This review provides an in-depth exploration of the role of CDs as UV-blocking agents in sustainable food packaging. It highlights their mechanisms of action, the advantages they offer over conventional materials, and their contribution to the development of multifunctional and eco-friendly packaging systems.

1 | Introduction

Ultraviolet (UV) radiation, a high-energy segment of the electromagnetic spectrum spanning wavelengths from 100 to 400 nm, poses a significant threat to food safety and quality during production, storage, supply, and retail (Vijayakumar et al. 2022). UV rays are classified into three regions: 100–280 nm (UVC), 280–315 nm (UVB), and 315–400 nm (UVA), which differ in their penetration levels and photochemical effects. The ozone layer absorbs most UVC radiation, but UVA and UVB can reach the Earth's surface and have adverse impacts on health, materials, and food systems (Wang et al. 2022). UV exposure triggers photochemical reactions that degrade food components such as proteins, lipids, vitamins, and pigments, resulting in decreased nutritional value, impaired sensory attributes, and shortened shelf life (Tan et al. 2021). To address these issues, UV-blocking packaging materials have emerged as a critical innovation to protect foods from photodegradation and extend shelf life (Fathima et al. 2018).

Traditional UV-shielding materials, including brown glass, aluminum foil, and certain plastics, effectively block UV radiation but often fail to meet modern consumer demands for transparency and environmental sustainability (Stanton et al. 2019). The environmental sustainability and ecological impacts of petroleum-based plastics necessitate the exploration of sustainable alternatives (Channa et al. 2022). In recent years, environmental concerns and consumer preferences have accelerated the shift toward sustainable and biodegradable packaging materials. Biopolymers, such as cellulose, chitosan, and gelatin, offer promising alternatives. Despite their advantages, these materials often lack significant intrinsic UV-blocking properties, necessitating the incorporation of additives to enhance their protective capabilities (Khan, Ezati, Kim, et al. 2023). The incorporation of UV-blocking agents, including inorganic nanoparticles (NPs) (e.g., TiO_2 and ZnO) and organic components (e.g., lignin and cellulose), into polymer matrices has shown promise (Sani et al. 2024). However, the demand for higher efficiency and concerns about material safety, migration risks, and regulatory compliance have highlighted the need for novel solutions.

Carbon dots (CDs) are a novel class of nanoscale carbon-based materials that have appeared as a revolutionary innovation in UV-protection packaging systems. CDs are distinguished by their small size (< 10 nm), distinct optical properties, biocompatibility, and environmental safety (Hong, Ha, et al. 2024). They exhibit strong UV absorption and photoluminescence (PL) due to their surface functional groups and quantum confinement effects (Khan, Ezati, Kim, et al. 2023). CDs can also serve as a sustainable and effective additive to packaging materials, providing strong UV protection without compromising transparency or mechanical strength. Additionally, their easy functionalization allows the development of multifunctional films that combine UV-protection properties with bactericidal and radical scavenging functions (Hu et al. 2019).

Recent investigations have shown that CDs have the potential to revolutionize the UV-blocking packaging field (Ezati, Priyadarshi, et al. 2022; Zhao et al. 2023). Furthermore, eco-friendly synthesis methods for CDs are further positioning them as a sustainable alternative to conventional UV absorbers, in-line with global efforts to lessen the environmental footprint of packaging substances. Therefore, a comprehensive and in-depth review is essential to support the ongoing research on the use of CDs for UV-blocking applications in food preservation. This topic has attracted considerable interest from many researchers. According to previous studies, Oladzadabbasabadi et al. (2023) reviewed the green synthesis strategies and starting materials of CDs, and Deepika et al. (2023) discussed the sources, functions, and challenges of CDs in food packaging. Zhao et al. (2023) systematically reviewed CDs for improving the mechanical and active properties of packaging materials, and Moradi et al. (2023) focused on CDs from animal wastes for active and intelligent films. In addition, Chelladurai et al. (2024) explored the use of CDs in terms of food safety. However, these reviews only partially addressed the UV-protection properties of CDs and did not systematically summarize their applications in the preservation of various food types. This review uniquely focuses on CDs for UV-blocking food packaging, emphasizing the incorporation into biopolymers, UV-protection mechanisms, and specific effects of CDs on various foods. This review also emphasizes the latest innovations and benefits of CDs as environmentally sustainable and functionally superior additives, which are expected to revolutionize the UV-protection strategy of food packaging systems. CDs are highlighted as superior to existing nanomaterials in terms of sustainability and functional performance. In this context, an in-depth review outlining the growth and potential of CDs in the still under-explored field of UV protection in food safety is urgently needed.

2 | Effect of UV Radiation on Food Deterioration

UV radiation, generally categorized as UV-A, UV-B, and UV-C, is located in the electromagnetic spectrum between visible light and x-rays (Figure 1a). It makes up around 6% of total solar energy and plays an important role in our daily lives (Bai et al. 2020). The ozone layer absorbs nearly all high-energy UV-C radiation, and only a small trace reaches the surface of Earth (Urban et al. 2016). However, over the past few decades, ozone layer depletion has increased the UV radiation reaching the biosphere. In addition to immediately cleaving DNA strands, UV-C light can encourage the creation of covalent connections between adjacent pyrimidines. Endogenous photosensitizers like porphyrins can be induced by UV-A radiation, producing reactive oxygen species (ROS) that can harm cells by causing protein carboxylation, lipid peroxidation, and other cellular damage. UV-B radiation causes both indirect and direct damage (Li et al. 2020). Hence, excessive UV exposure has been shown to enhance the skin aging risk, endocrine and neurological disorders, and cancer (Bai et al. 2020). Additionally, UV rays cause auto-oxidation and deterioration in biodegradable polymer films, weakening chemical connections and deteriorating their physical characteristics (Li et al. 2020; Perez-Puyana et al. 2022).

Furthermore, UV has a significant impact on food quality deterioration (Figure 1b). These mechanisms include photooxidation, ROS generation, stress response activation, and irreversible DNA impairment. Due to its strong oxidizing properties, UV radiation induces various spoilage reactions in foods, including antioxidant degradation, protein degradation, lipid oxidation, off-flavor formation, and pigment loss (Roy and Rhim 2021; Yang et al. 2020). Due to the fact that high-energy UV can initiate photooxidation reactions in the presence of photosensitizers. Specifically, many covalent bonds (bond energy range 250–650 kJ/mol) in organic substances can be cleaved by energy transfer from UV, generating singlet oxygen ($^1O_2$) and free radicals (e.g., $H^•$, $O_2^{-•}$, $^•OH$, $ROO^•$, and $CH_3^•$). These highly reactive species can damage photosensitive compounds in food items, accelerating their decay. In addition, some photosensitive organic molecules can be directly energized by UV rays to singlet or even triplet states. These excited molecules exhibit kinetic instability and can undergo heterolysis, homolysis, or photoionization. For example, hydroxyl radicals can nonselectively oxidize alkyl groups and aromatic rings via the photo-Claisen reaction (Zhang and Jiang 2023).

The main mechanisms of UV radiation effects on the freshness status of foods are as follows (Figure 1b):

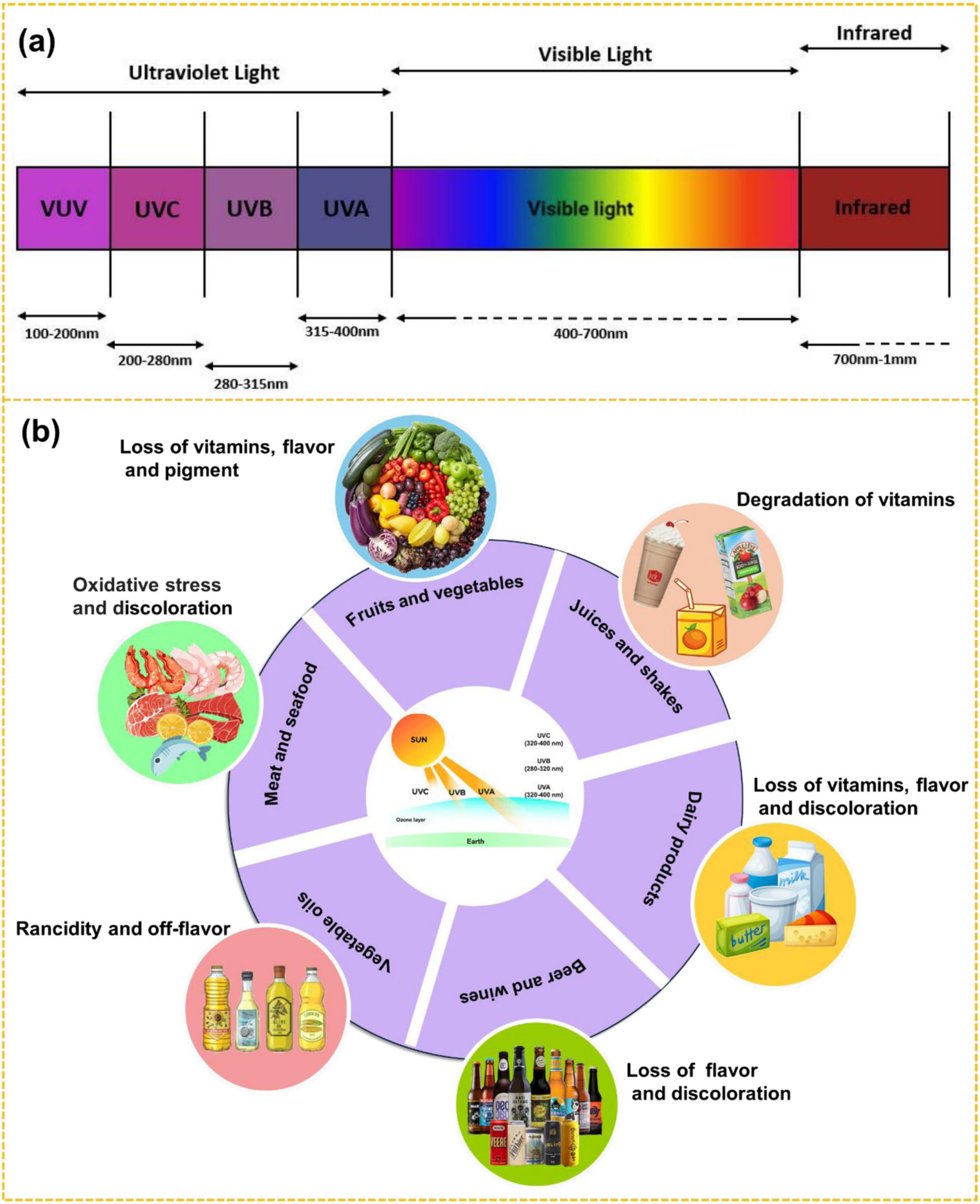

FIGURE 1 | (a) The position, wavelength, and frequency of UV radiation within the electromagnetic spectrum; (b) the impact of UV light on various packaged foods depends on the type of foods. *Source*: (a) Reprinted from Palma et al. (2022).

i. UV exposure can alter the metabolic profile of fruit and vegetable cells, including disruption of enzyme protein structure, damage to plastoquinone, membrane potential loss, and induction of PCD (programmed cell death) (Urban et al. 2016; Zhang and Jiang 2019).

ii. UV light accelerates the spoilage of meat and seafood by triggering photooxidation, leading to discoloration, texture degradation, and nutrient loss (Sani et al. 2024).

iii. UV exposure accelerates the spoilage of bakery products by triggering lipid oxidation, leading to texture deterioration, off-flavors, rancidity, and color changes. This reduces quality, shortens shelf life, and affects consumer acceptance (Tripathi et al. 2024).

iv. Meanwhile, it can also be used as a food preservation technology to inactivate foodborne pathogens without significantly changing the physicochemical and sensory properties of food, depending on the amount of UV dosage and exposure time (Monteiro et al. 2024).
All the processes described above can lessen the attractiveness of food products to consumers. Hence, it is essential to improve the UV-blocking properties of packaging films and coatings.

3 | UV-Blocking Nanomaterials

The selection of appropriate packaging material can help minimize the negative effects of light interaction with food. Currently, there has been considerable attention on the advancement of UV-protective food packaging films as a promising solution in both academia and industry (Roy et al. 2023). Various substances, including biopolymers, phytochemicals, organic nanomaterials, inorganic nanomaterials, and hybrid systems, can be employed as UV-blocking candidates in packaging systems owing to their aptitude to absorb and/or scatter UV light.

Some biopolymers, such as gelatin, chitosan, cellulose, and lignin, naturally absorb UV light due to their functional groups, such as carbonyl, amino, hydroxyl, and aromatic functionalities (Sani et al. 2024). For example, the aromatic amino acids in gelatin enhance UV absorption, and chitosan provides excellent UV-blocking properties through its hydroxyl and amino groups (Gore and Prajapat 2022). Films made from biopolymers such as gellan gum and hydroxyethyl cellulose have shown significant UVA (90%) and UVB (100%) blocking effects (Rukmanikrishnan et al. 2020). Phytochemicals, including quercetin, anthocyanins, carotenoids, curcumin, and essential oils, absorb UV rays due to their functional moieties, such as phenolic, catechol, and aromatic rings (Sani et al. 2024). These natural additives advance the UV-protection characteristics of biopolymer-based films, such as quercetin-enhanced gelatin/chitosan films (Yadav et al. 2020). Essential oils, such as thyme, clove, and cinnamon, have also been impregnated into packaging films to enhance UV protection (Liu et al. 2021). Organic nanomaterials, such as nanoencapsulated lycopene, β-carotene, and melanin NPs, improve UV protection by absorbing and scattering UV light (Sani et al. 2024). For example, NPs of melanin in cellulose films (Roy et al. 2020) and β-carotene in methylcellulose films (Lino et al. 2022) have significantly enhanced UV-blocking efficiency. Inorganic nanomaterials, including metal oxides such as ZnO, TiO_2, and CeO_2, provide excellent UV protection due to their high refractive index and absorption properties (Gore and Prajapat 2022). In particular, ZnO NPs are cost-effective and effective in both UVA and UVB ranges (Sani et al. 2024). Films incorporating these materials, such as TiO_2 NPs in CMC/guanidinylated chitosan films, can block up to 98% of UV rays (Salama and Abdel Aziz 2020). Hybrid systems combining inorganic NPs with UV-blocking agents such as phytochemicals or biopolymers provide enhanced UV protection. For example, films containing TiO_2 NPs and anthocyanins (A. Sani et al. 2022) or silver NPs and quercetin (Braga et al. 2019) have shown superior UV absorption and scattering properties. Together, these agents contribute to the development of effective, sustainable, and UV-resistant food packaging solutions.

4 | CDs: An Effective UV-Barrier Functional Filler

Recently, CDs have emerged as promising UV-blocking agents for food packaging purposes (Tripathi et al. 2024). Owing to their simple synthesis and cost-effectiveness, CDs have become attractive alternatives to conventional UV absorbers commonly used in commercial products (Hu et al. 2019). Although the precise mechanism of the UV-blocking ability of CDs is not yet fully elucidated, some studies suggest that it originates from electron transitions occurring in both the core and shell structures of CDs (Moradi et al. 2023).

4.1 | Overview of CDs

CDs, a notable candidate of the carbon family, are nanoscale carbon particles with remarkable properties that have gained extensive attention in the area of material chemistry (Baker et al. 2010). CDs are often described by their unique core–shell structure, but the clear boundary between the polymer shell and the carbon core is not clearly defined (Shi et al. 2017). The core of CDs is mainly comprised of sp^2 and sp^3 hybridized carbon atoms, which can vary from amorphous to graphitic crystalline forms depending on the synthesis method and precursors used. The occurrence of sp^2 domains in the graphitic core and the characteristic lattice spacing of approximately 0.2 nm contribute to the optical and electronic properties. The surrounding shell is enriched with functional moieties such as amine, carboxyl, and hydroxyl groups or polymer chains, which enhance the solubility, stability, functionality, and surface modification potential of CDs (Yadav et al. 2023). These zero-dimension (0-D) carbon-dominant nanomaterials exhibit several unique properties, making them highly versatile for numerous purposes.

4.1.1 | Core of CDs

The carbon core of CDs is primarily derived from pure carbon or organic sources, with potential doping of nitrogen, oxygen, and other elements depending on the reaction conditions. The core of CDs is usually composed of sp^2-hybridized carbon atoms, forming a conjugated π-system in which the electrons are delocalized throughout the structure. This delocalization plays a crucial role in the electronic transitions observed in CDs. The energy gap between the ground state (HOMO) and the excited state (LUMO) depends on the number of conjugated aromatic rings in the core. As the number of conjugated rings increases, the energy gap between these orbitals decreases, resulting in redshifted absorption and emission spectra. Conversely, smaller CDs or CDs with fewer aromatic rings exhibit larger HOMO–LUMO gaps, resulting in blue-shifted fluorescence (Liu 2020; Zhang et al. 2016, 2023).

CDs have a variety of morphologies, typically showing a dot-like structure, but careful precursor selection and reaction conditions can produce various shapes, such as ribbons, rods, and triangles (Fawaz et al. 2023). Two primary morphologies are generally observed. One is a disk-shaped structure, which resembles a 2D graphene sheet with one to three layers and surface functional groups (Jorns and Pappas 2021). The second, more common morphology features a quasi-spherical polyaromatic network with an amorphous or crystalline carbon structure and tunable surface groups (Wang and Hu 2014). The morphology of CDs also influences their optical properties, with larger CDs exhibiting redshifted emission wavelengths consistent with quantum confinement (Yadav et al. 2023). High-resolution transmission electron microscopy (HR-TEM) and atomic force microscopy (AFM) help elucidate the three-dimensional structure of CDs and distinguish them from graphene quantum dots (GQDs) (Fuyuno et al. 2014; Shinde and Pillai 2012).

4.1.2 | Surface Functional Groups of CDs

The functional groups present on the CD surface are highly dependent on the precursors used during synthesis. Commonly observed functional groups include –OH, –CHO, –COOH, –SH, and $-NH_2$. Nitrogen-containing functional groups often impart a positive charge to CDs, whereas oxygen-based functional groups typically introduce a negative charge. This charge polarity imbalance allows for diverse passivation functional groups. For example, carboxyl groups enhance the water solubility of CDs, and additional surface passivation or functionalization with other functional groups can tailor the properties for specific applications (Yang et al. 2019).

The type and quantity of functional groups of CDs play a pivotal role in defining the electronic and geometrical structure, directly affecting parameters such as charge distribution, energy gap, and energy levels of the HOMO and LUMO in both the ground and excited states. The tunability of CDs through surface modifications such as passivation or oxidation provides various strategies to tailor the optical properties to target applications. For example, electron-donating groups such as hydroxyl and amine can lower the energy of the LUMO, narrowing the HOMO–LUMO gap (Figure 2a) (Abdelsalam et al. 2018). The surface of CDs introduces n–π^* transitions that originate from surface oxygen-containing functional groups such as hydroxyl, carboxyl, and epoxy groups. These groups contain non-bonding electron pairs (lone pairs) that can interact with the π-system of the core. When electrons in these non-bonding orbitals are excited to π^*-orbitals, n–π^* transitions occur. These surface-related transitions generally occur at lower energies than the core-related π–π^* transitions and significantly affect the optical behavior of CDs. The influence of oxygen-containing functional groups varies with the spatial location. The functional groups on the planar surface of graphene quantum dots (GQDs) have a greater influence on the optical properties than those on the edges. Investigations of CDs with surface- and edge-bound oxygen-containing groups revealed contrasting trends in the LUMO–HOMO gap. The presence of oxygen-based functional groups on the surface leads to an uneven electron density distribution, which further reduces electron localization and alters emission characteristics (Feng et al. 2017).

It is reported that amine-functionalized CDs exhibited a PL redshift of approximately 30 nm compared to unfunctionalized CDs. Density functional theory (DFT) calculations revealed that this redshift was associated with a reduction in the LUMO–HOMO energy gap due to charge redistribution induced by the amino functional groups. Similarly, Kundelev et al. (2019) investigated the PL and absorption properties of $-NH_2$-functionalized CDs using time-dependent DFT (TDDFT) calculations. Their results revealed that increasing the degree of functionalization with amino groups enhanced charge transfer from the amino groups to the CD core, which resulted in a significant redshift in the emission spectra. These studies highlight the important role of functional groups in modulating the optical properties of CDs.

4.2 | Mechanism of UV Light Absorption of CDs

CDs exhibit strong optical absorption in the UV region, and their absorption spectra extend to the visible and near-infrared regions (NIRs) (Baker et al. 2010; Li et al. 2018). Figure 2b depicts the relationship between the electronic transitions and the absorption spectra in the core and shell of CDs, where the shell is composed of functional groups surrounding the core. The short-wavelength region below 300 nm (Band I in Figure 2b) corresponds to the $\pi \rightarrow \pi^*$ transition of aromatic sp^2 carbon (aromatic C=C bonds). The spectral region between 300 and 400 nm (Band II) is attributed to the unique $n \rightarrow \pi^*$ transition of the C=O bond in the carbon core.

The electron lone pair transition in the surface states is responsible for the absorption bands observed above 400 nm (Figure 2b, Bands III–V) (Chen et al. 2016; Zhu et al. 2018). These broad surface-state absorption bands overlap with the $n \rightarrow \pi^*$ transitions, which are generally not separate or independent characteristics. This overlap enables emission tuning, producing a continuous color gradient as the excitation wavelength changes (Wang and Hu 2014). Additionally, the low-energy absorption band around 300 nm arises from a combination of $n \rightarrow \pi^*$ and $\pi \rightarrow \pi^*$ transitions, which involve interlayer charge transfer processes with a predominant $\pi \rightarrow \pi^*$ component (Sudolská et al. 2015). Other factors, such as structural or energetic disorder, environmental effects, deprotonation, and excitonic coupling, have only a minor effect on the observed spectral features (Sudolská et al. 2015). Incorporation of graphitic nitrogen into the carbon sp^2 lattice induces a redshift in the UV–vis absorption spectrum, extending from approximately 420 nm (Figure 2b, Band III) to the NIR spectral region (Figure 2b, Band V). This is because graphitic nitrogen centers can significantly reduce the HOMO–LUMO gap and the energies of the corresponding optical transitions by injecting excess electrons into the unoccupied π^* orbitals (Holá et al. 2017; Sarkar et al. 2016). Furthermore, oxygen-containing functional groups such as hydroxyl, carboxyl, and epoxy groups on the surface of CDs also play a role in narrowing the energy levels, further contributing to the redshifted absorption (Bao et al. 2015; Sudolská et al. 2015).

Some studies also suggest that the absorption peaks of CDs shift to longer wavelengths (redshift) when the surface functional groups of CDs are changed or the size is modified (Dhenadhayalan et

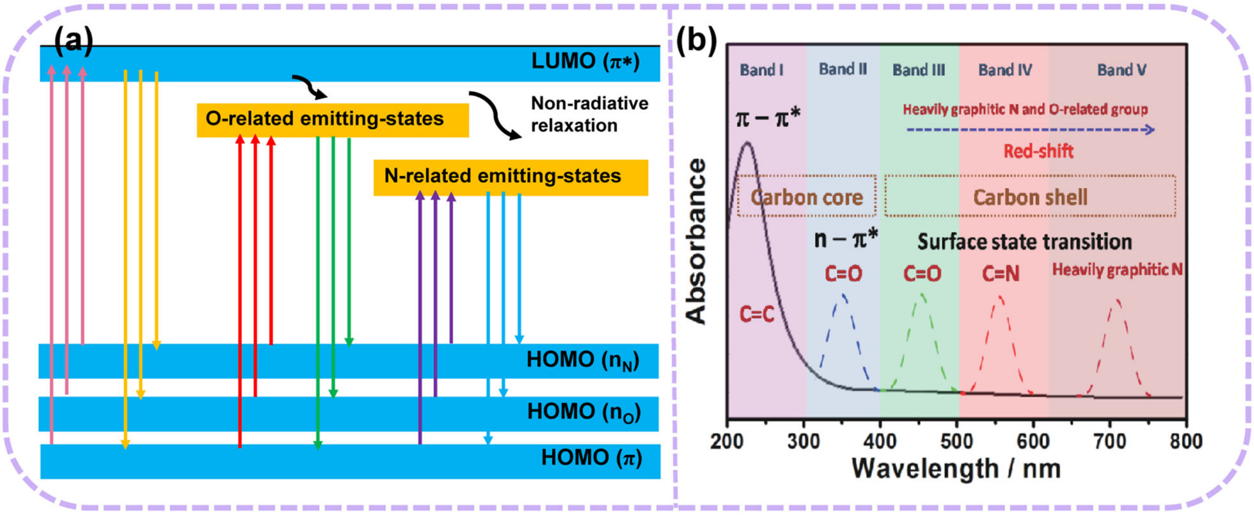

FIGURE 2 | (a) Influence of surface functional groups on the optical properties of CDs. (b) A graphical depiction of the light absorption mechanism in CDs in terms of the relationship between the absorption spectrum and the electron transitions in CDs. *Source*: (b) Reprinted from Liu (2020).

al. 2016). In addition, certain specialized CDs show an extended absorption in the range of 600–800 nm, which is attributed to the presence of aromatic ring structures (Holá et al. 2017). The oxygen and nitrogen content, structural defects, and overall morphology of CDs play an important role in determining the positions of these absorption peaks.

Therefore, factors such as synthesis methods, the choice of precursors, and surface modifications such as elemental doping have a great influence on the optical absorption properties of CDs (Dhenadhayalan et al. 2016). For instance, Li et al. (2011) dispersed 4.0 g of activated carbon in 70 mL of hydrogen peroxide and then sonicated at 25°C for 2 h to prepare a suspension. After filtration, spherical fluorescent CDs with a diameter of 5–10 nm were obtained. The UV–vis absorption spectra of these CDs showed characteristic peaks in the range of 250–300 nm, which is typical of aromatic π-electron systems. However, highly luminescent amorphous carbon NPs were synthesized by adding 0.5 g of anhydrous citric acid to the AEAPMS solution under vigorous stirring at 240°C (Wang et al. 2011). They maintained the mixture at that temperature for 1 min before cooling and purifying it naturally. The resulting NPs, with a diameter of about 0.9 nm and a quantum yield of 47%, showed a distinct absorption peak at 360 nm in the UV–vis absorption spectrum. Interestingly, a photoluminescent CD was prepared by carbonization of citric acid at 200°C, yielding nanosheet-like CDs with a width of approximately 15 nm and a thickness of 0.5–2.0 nm (Dong et al. 2012). Their UV absorption spectrum showed a peak at 362 nm with a narrow peak width, indicating that the size of the NPs was uniform. In another study, Tang et al. (2012) synthesized CDs with a diameter of 1.65 nm using microwave-assisted pyrolysis of glucose solution. The fluorescence quantum yield of these CDs was found to be 7–10%. The UV absorption spectrum of CDs in aqueous solution displayed two distinct peaks at 228 and 282 nm.

Therefore, CDs exhibit UV-blocking properties through mechanisms such as excited-state intramolecular proton transfer facilitated by interactions such as O…H…O and O…H…N, and a wide range of conjugated structures (Chung et al. 2020). CDs can then be incorporated into various biopolymer formulations to enhance the UV-absorbing capability of packaging films, which can absorb specific wavelengths and convert light energy.

5 | Evaluation of UV-Barrier Properties

The UV-protection characteristics are often represented by UV-protection factor (UPF) values for fabrics or sun protection factor (SPF) values for sunscreens (Zhang and Naebe 2021). SPF measures the percentage of UV radiation that reaches the skin when sunscreen is applied compared to unprotected skin. For example, SPF 30 means that the skin is exposed to 30 times less UV radiation, meaning that it blocks approximately 96.7% of UV radiation. The SPF value is calculated using the following equation:

$$\mathrm{SPF} = \frac{\sum_{290}^{400} E_\lambda S_\lambda}{\sum_{290}^{400} E_\lambda S_\lambda T} \tag{1}$$

where E_λ represents the erythema spectral effect defined by the International Commission on Illumination, T represents the spectral transmittance of the sample, and S_λ corresponds to the solar spectral irradiance (Zhang and Naebe 2021).

UV–vis spectroscopy is commonly used to measure the optical absorption spectrum of materials other than sunscreens. In the context of food packaging, UV–vis spectroscopy plays an important role in evaluating the UV-blocking capability of packaging films by analyzing their absorbance and transmittance characteristics (Duncan and Chang 2012). To evaluate the UV-blocking and transparency properties of packaging films, the light transmittance within the range of 200–800 nm is usually analyzed. The light transmittance spectrum of a film is often presented by measuring the percentage of light transmitted at 660 nm (Riahi, Khan, Shin, et al. 2024). The UV-blocking performance is evaluated by determining the average transmittance values for the UV-A (315–400 nm) and UV-B (280–315 nm) regions, which are calculated using the following equations, respectively (Wang et al. 2022):

$$\text{UVA blocking } (\%) = 100 - \frac{\int_{315}^{400} T(\lambda)\, d_\lambda}{\int_{315}^{400} d_\lambda} \tag{2}$$

$$\text{UVB blocking } (\%) = 100 - \frac{\int_{280}^{315} T(\lambda)\, d_\lambda}{\int_{280}^{315} d_\lambda} \tag{3}$$

where $T(\lambda)$ represents the average transmittance of the film at a specific wavelength λ, and d_λ represents the bandwidth of the film. Light absorbance depends on both the quantity and nature of the material; however, it is also influenced by the material's physical state, such as whether it is solid or liquid.

Jayakumar et al. (2024) investigated the UV-blocking properties of polyvinyl alcohol (PVA) films incorporated with carbon dots derived from lemon peel (LCQDs) using UV–vis spectroscopy. Their results showed that the pure PVA film blocked 20.7% of UV-B and 15.2% of UV-A radiation. In contrast, the PVA film with 3 wt% LCQDs blocked 99.92% of UV-B and 99.98% of UV-A radiation. Despite this significant UV-blocking effect, the visible light transparency of the film decreased from 89.1% to 78.2%, indicating that the UV-blocking effect was not achieved at the expense of transparency.

6 | Application of UV-Protection Properties of CDs in Food Packaging

CDs have been increasingly studied for use in food packaging because they can act as UV-blocking active agents to prevent food oxidation and induce antimicrobial/antioxidant effects to preserve food quality. The excellent UV-absorbing ability of CDs may be attributed to two key factors. First, CDs have a structure rich in conjugated π-electron systems, which allows delocalized electrons to efficiently absorb photons in the UV spectrum, resulting in strong UV-blocking properties. Second, the surface of CDs is decorated with functional groups, including hydroxyl, carbonyl, carboxyl, and amino groups. These groups not only interact with UV photons but also expand the surface area of CDs, further amplifying their UV-absorbing ability (Figure 3) (Nguyen et al. 2016).

Unlike conventional UV absorbers such as titanium dioxide, zinc oxide, benzotriazoles, and triazines, which dissipate the absorbed UV energy as heat, CDs re-emit most of this energy as visible light. This unique property ensures that CD-based UV-blocking materials do not cause significant temperature increases under UV radiation, which is very beneficial for food packaging materials designed to block UV radiation (Lien and Van Nguyen 2024).

Therefore, CDs can be seamlessly incorporated into various polymer matrices to create biocompatible packaging films and coatings with excellent UV protection. Common polymer processing techniques, such as solvent casting, electrospinning, coating, and layer-by-layer assembly, are widely used to fabricate CD-based packaging materials (Liu et al. 2021).

Solvent casting, one of the most commonly used methods, ensures consistent UV-blocking performance by uniformly dispersing CDs within the biopolymer film. On the other hand, electrospinning produces nanofiber-based packaging films with a high surface area-to-volume ratio, which further improves the light-scattering properties of CDs and enhances UV protection. Layer-by-layer assembly allows for the development of multilayer materials with tailored optical and mechanical properties by precisely controlling the arrangement of CDs within the film structure. However, the selection of UV-barrier packaging material is closely related to the type of food being packaged, as different foods have different sensitivities to UV radiation (Figure 1b). For instance, fatty foods like oils and nuts are particularly susceptible to oxidative rancidity when exposed to UV light, so UV-protective films are essential to maintain quality and nutritional value. Dairy products, such as milk and cheese, require packaging with high UV-protection efficiency to extend shelf life, as UV exposure can rapidly degrade vitamins and cause off-flavors. Fresh produce, including fruits and vegetables, benefits from UV-protection packaging that reduces the photodegradation of pigments such as anthocyanins and carotenoids, thereby retaining their color and nutritional properties. These examples highlight the need for UV-protection films tailored to the specific photodegradation pathways of different food types to ensure optimal protection and quality retention (Andersen and Skibsted 2010). This section explores potential applications of CD-based UV-protection films for different types of food. Table 1 summarizes recent studies that have applied CDs as UV-protection fillers to develop sustainable active food packaging designed to extend the shelf life of diverse foods.

6.1 | Meat Products

Light, especially UV light, has a significant impact on the spoilage and discoloration of meat products. UV exposure accelerates the photooxidation of major pigments, resulting in undesirable changes in color and quality. For example, the photooxidation of oxymyoglobin increases exponentially with light energy, resulting in brown discoloration, which poses significant challenges to meat retailers. This process also induces lipid oxidation, which further deteriorates the quality of meat (Bao et al. 2016). This phenomenon highlights the importance of using UV-protection packaging films to protect meat products during storage. Therefore, CD-based films and coatings are proposed as promising candidates for UV-protection packaging materials. For example, Khan, Priyadarshi, et al. (2023) synthesized highly efficient UV-absorbing CDs from garlic cloves (*Allium sativum*) to prepare carrageenan/sodium alginate (Car/Alg)-based functional films for UV-blocking food packaging. Car/Alg-$CD^{4\%}$ film showed excellent UV-blocking effects with 85.1% of UV-A and 99.0% of UV-B radiation. The film also showed strong antioxidant properties, with ABTS and DPPH radical scavenging activities of 98.6% ± 0.3% and 34.2% ± 0.3%, respectively. The use of functional films in raw meat packaging helped preserve the color of meat even after direct UV exposure for 30 h (Figure 4a).

TABLE 1 | Overview of recent carbon dots-based UV light protection packaging materials for food preservation.

Food type	CD source and polymer matrix	UV-blocking efficiency	Other functional properties	Food tested	Main findings	Ref.
Meat products	Garlic CD in carrageenan/alginate	85.1% (UV-A), 99.0% (UV-B)	Radical scavenging of DPPH: 34.2%, ABTS: 98.6%	Raw beef meat	Maintained color stability after 30 h UV exposure	Khan, Priyadarshi, et al. (2023)
	Coffee ground CDs + GSE in gelatin/polyvinyl alcohol	99.9% UV blocking at 280 nm	Strong antioxidant/antibacterial, maintained transparency (T_{660} = 86.5%)	Minced pork	Prevented discoloration and rancid odor under UV; retained redness (a^*) value	Min et al. (2023)
	N,P-doped green tea CDs in chitosan/starch	93.1% (UV-A), 99.7% (UV-B)	Radical scavenging of DPPH: 71.4%, ABTS: 97.9%, and strong antibacterial versus *Listeria monocytogenes*, *Escherichia coli*, and *Staphylococcus aureus*	Minced pork	Extended shelf life through antioxidant and antibacterial activity	Khan, Ezati, and Rhim (2023)
	Zn-CD from avocado peel in cellulose nanofibers/pullulan	100% UV blocking	Radical scavenging of DPPH: 68.0%, ABTS: 100.0%	Chicken	Reduced lipid oxidation; preserved quality for 9 days at 10°C	Riahi, Khan, Rhim, et al. (2024)
	Sulfur-doped *Pseudomonas aeruginosa*-derived CDs in polyvinyl alcohol	97.17% UV blocking	83.63% for DPPH and 94.98% for ABTS radical scavenging	Minced pork	Extended shelf life by 8 days at 4°	Hong, Riahi, et al. (2024)
	Spent coffee ground CDs in cellulose nanofibers	98.8% of UV-B and 87.4% of UV-A	98.2% ABTS and 78.8% DPPH radical scavenging	Minced pork	Shelf life extension of packaged foods and solving environmental problems by recycling resources	Sul et al. (2024)
Sea food	Fish scale-derived CDs in gelatin/chitosan	94.2% UV blocking	Radical scavenging of DPPH and ABTS, antibacterial versus *E. coli*, *S. aureus*	Fish slices	Reduced lipid oxidation and extended shelf life from 6 to 10 days	Fu et al. (2022)
	Radish residues derived CDs in starch/chitosan	100% UV protecting at a 1.5% concentration of CDs	93.8% for DPPH and 99.36% for ABTS radical scavenging, along with potent antimicrobial activity	Salmon	Inhibited microbial growth and preserved salmon quality by 4 days	D Wang et al. (2024)
	Kohlrabi-derived Zn-CD + anthocyanins in carrageenan	85.2% (UV-A), 99.4% (UV-B)	~58.6% for DPPH and ~99% for ABTS radical scavenging	Whole shrimps	Extended shelf life; preserved quality effectively	Khan et al. (2024a)
	Pistachio-derived CDs and anthocyanin in chitosan/soy protein isolation	100% UV protection in the range of 200–330 nm	~82.3% ± 0.1% for DPPH$^{\bullet}$ and 90.6% for ABTS scavenging	Fish	Reduced microbial growth and lipid oxidation and extended the shelf life up to 12 days	Hadavifar et al. (2025)
	Crayfish shell-based CDs in konjac glucomannan and sodium alginate	83.0% UV blocking at 300 nm	Inhibition rates of over 98% versus *Shewanella putrefaciens* and *S. aureus* along with 77.92% DPPH scavenging rate	Crayfish	Reduced TVB-N level and extended shelf life to 8 days	Jiang et al. (2025)

(Continues)

TABLE 1 | (Continued)

Food type	CD source and polymer matrix	UV-blocking efficiency	Other functional properties	Food tested	Main findings	Ref.
Fruits and vegetables	PEG- and urea-doped CDs derived from lemon salt in polyvinyl alcohol	92.22% (UV-C), 87.04% (UV-B), and 87.04% (UV-A)	Antimicrobial and antioxidant properties	Strawberry	Delayed spoilage by minimizing fungal growth	Alaş et al. (2022)
	Banana paste-derived CDs in polyvinyl alcohol	98.50% UV-blocking (200–400 nm)	Antimicrobial and antioxidant properties	Banana and jujube	Delayed spoilage and extended shelf life	Zhao et al. (2023)
	Tea residue-derived CDs in polyvinyl alcohol	100% blocking of UV-C and UV-B, and 60% of UV-A	Biocompatible and biodegradable in nature	Grapefruit	UV-blocking packaging material in food and pharmaceutical storage	Patil et al. (2020)
	Pomelo peel-derived CDs in gelatin and alginate	99.4% UV-shielding	100% for ABTS and 91.71% of DPPH radical scavenging	Strawberry	Shelf life extended by 7 days at room temperature	Li et al. (2023)
	Apple waste-derived CDs in polyvinyl alcohol/cellulose nanocrystals	91% of UV-B and 78.2% of UV-A	High transparency (70%) in the visible region (660 nm)	Cherry tomatoes	Delayed the spoilage up to 15 days	Lien and Van Nguyen (2024)
	Banana peel CDs + cinnamon essential oil in starch–polyvinyl alcohol	71.45% UV blocking	14.85% for DPPH and 77.68% for ABTS radical scavenging rate	Mango	Shelf life is extended by delaying rot and browning	Chen et al. (2024)
	Red pepper CDs in alginate/gelatin	92.5% UVA and 99.9% UVB	100% ABTS and 65.4% DPPH radical neutralization	Table grapes	Extending the storage life and preserving grape quality up to 24 days	Riahi et al. (2025)
Bakery products	Sulfur-nitrogen-doped CDs derived from citric acid and cysteine in polyvinyl alcohol	Over 95% UVA blocking	88% DPPH radical scavenging and 99.999% reduction of Gram-positive bacteria	Sweet bread	Lowered water activity and delayed mold growth on bread up to Day 6, enhancing bread shelf life	Thanawutthiphong et al. (2025)
	Tangerine peel-based carbon dots	Blocking 98.8% of UV-A and 100% of UV-B	62.7% and 91.6% DPPH and ABTS radical scavenging and reduced *L. monocytogenes* and *E. coli* by over 4 and 5 log CFU/mL	Bread	Retarded the invasion of foodborne pathogens on bread surface and extended the shelf life up to 12 days	Sul et al. (2025)
Dairy products	Coconut husk-lignin-derived carbon dots in carrageenan	72.7% UV blocking	84% visible light transparency, excellent antimicrobial, and antioxidant properties	Milk	Preservation and detection of milk quality	Sangeetha et al. (2024)
	Milk permeate-derived CDs in casein	99.09% of UV-C and 97.46% of UV-A	94% DPPH and 89.3% of ABTS radical scavenging	Butter	Coating the butter with the film reduced oxidation during storage for up to 60 days	Khoshkalampour et al. (2024)

Abbreviations: ABTS, 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); CDs, carbon dots; DPPH, 2,2-diphenyl-1-picrylhydrazyl; TBA, thiobarbituric acid; TBARS, thiobarbituric acid reactive substances; TVB-N, total volatile basic nitrogen; TVC, total viable count.

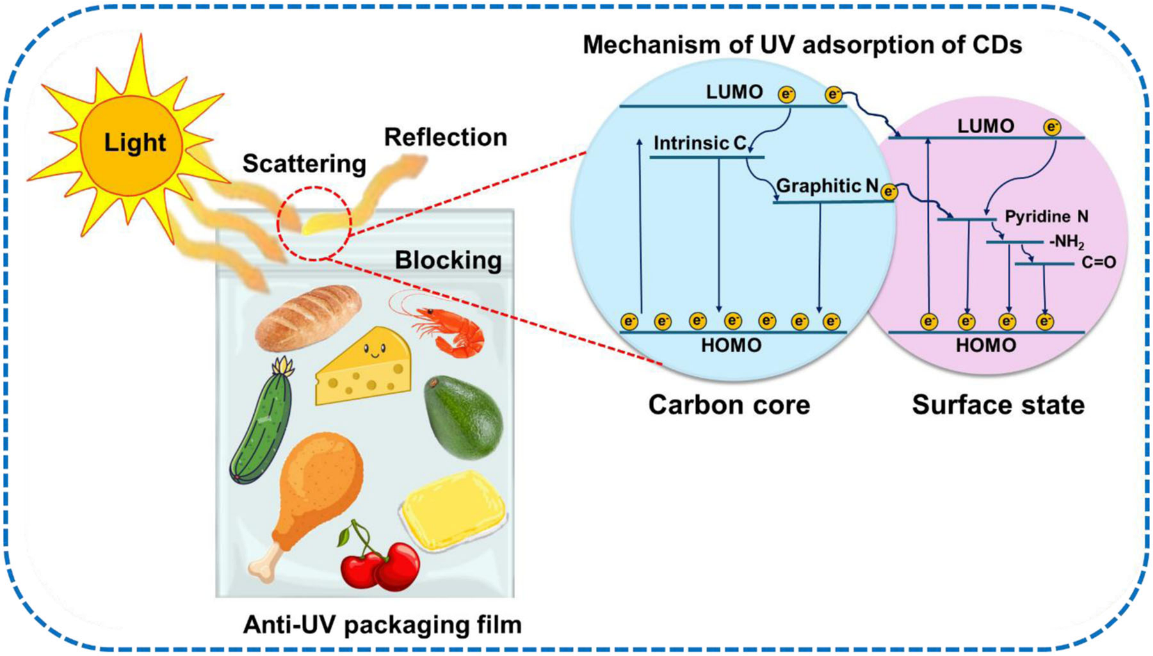

FIGURE 3 | Schematic representation of the UV-blocking mechanism of CDs-based packaging materials.

In another study, Min et al. (2023) developed a multifunctional gelatin/PVA-based film by incorporating CDs derived from spent coffee grounds and grapefruit seed extract (GSE) and applied it for UV-blocking food packaging applications. The pure gel/PVA film exhibited high transparency with 87.6% transmission at 660 nm (T_{660}) and excellent UV-blocking performance with 16.4% transmission at 280 nm (T_{280}). When CDs were incorporated, the T_{280} value decreased significantly to 0.2%, and T_{660} decreased only slightly, indicating the film effectively blocked UV light while minimally the effect of CDs on transparency. When both CDs and GSE were combined, the Gel/PVA/GSE/CD film exhibited an almost perfect UV-blocking effect with a T_{280} of only 0.1% while maintaining high transparency (T_{660} of 86.5%). In this regard, they tested the UV-blocking efficiency of Gel/PVA/GSE/CD films compared with LDPE film in preserving minced pork under UV light. Over time, UV exposure caused severe discoloration in the meat packaged in LDPE film, which darkened rapidly and developed a rancid odor within 24 h. In contrast, meat packaged in Gel/PVA/GSE/CD film showed minimal color change and no odor at all. The observed discoloration was attributed to UV-induced photooxidation that converts myoglobin to brown met-myoglobin. Measurements of the redness (a-value) of the meat showed that Gel/PVA/GSE/CD films significantly reduced color degradation compared to LDPE. This highlights the excellent UV-blocking ability of Gel/PVA/GSE/CD films to effectively prevent photooxidation, maintain food quality, and extend shelf life. These results highlight the promising applications of CDs-based films in protecting foods from harmful UV radiation.

The UV-blocking properties of CDs are affected by several factors, such as the size of the π-conjugated domains, the composition of the surface groups, and the oxygen/nitrogen ratio within the carbon core. Additionally, intramolecular proton transfer through O–H–N and O–H–O tunnels and appropriate junction structures contribute to the UV-blocking properties of the films (Min et al. 2023). Therefore, doping with elements, such as nitrogen, sulfur, or boron, can improve UV-blocking properties by modifying the electronic structure and increasing the light absorption. Similarly, surface functionalization with amino groups fine-tunes the functionality, biocompatibility, and dispersion properties. For instance, Khan, Ezati, and Rhim (2023) pioneered the incorporation of nitrogen- and phosphorus-doped green tea-derived CDs (NP-CDs) into chitosan/starch (CS/St) blends to fabricate multifunctional nanocomposite films. The resulting CS/St-CD$^{3\%}$ film exhibited remarkable UV-protection effects, blocking about 93.1% of UV-A and 99.7% of UV-B. It also exhibited significant antioxidant potential, scavenging about 97.9% of ABTS and 71.4% of DPPH radicals. The study highlighted that this film significantly extended the shelf life of meat products by utilizing the synergistic UV-blocking, antioxidant, and antibacterial properties imparted by CDs. In a recent study, a multifunctional packaging film was prepared by dispersing zinc-doped CDs derived from avocado peel (Zn-ACDs) into cellulose nanofibers/pullulan polymer matrix (Riahi, Khan, Rhim, et al. 2024). The polymer film loaded with 5 wt% Zn-ACDs presented 100% UV-blocking ability and excellent antioxidant activity (100.0% for ABTS and 68.0% for DPPH). The CNF/PUL/Zn-ACDs composite films markedly inhibited lipid oxidation of packed chicken and tofu samples at 10°C for 9 days due to the light-blocking and antioxidant abilities of the developed films.

Synergistic integration of the UV-blocking properties of CDs with their inherent antimicrobial and antioxidant activities has been reported as a promising strategy for extending the shelf life of meat (Ahmadi et al. 2024; Wu et al. 2025), chicken (Sasikumar et al. 2024), and meatballs (Zhao et al. 2024). These results comprehensively demonstrate that CDs-based films play an important role in preserving key quality factors of meat products, such as color, lipid stability, and freshness, in addition to effective UV protection. The common mechanism across studies is to block harmful UV radiation to prevent photooxidation,

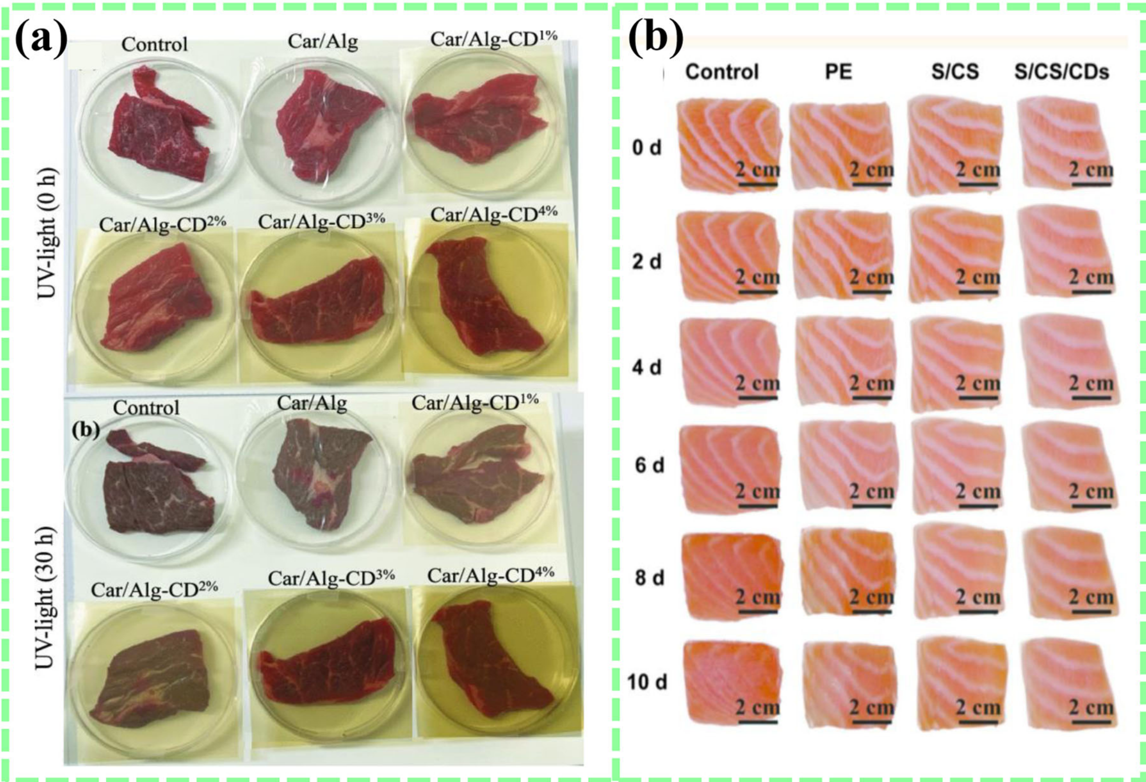

FIGURE 4 | (a) Photographs of red meat wrapped in Car/Alg-based films after UV exposure at 20°C for 30 h, and (b) visual changes in salmon fillets packed in starch/chitosan-based films after storage at 4°C for 10 days. *Source*: (a) Reprinted from Khan, Priyadarshi, et al. (2023); (b) reprinted from Wang et al. (2024).

which is supported by the antioxidant and antimicrobial properties of CDs. These combined protective effects help delay the degradation process of meat and maintain sensory and nutritional quality during storage. Therefore, CDs-enhanced UV-blocking films represent a multifunctional approach to meat preservation, which can be extended to other food categories with similar spoilage pathways.

6.2 | Seafood

Photodegradation significantly affects the quality of seafood and its products, resulting in deterioration in appearance, texture, flavor, and nutritional value. Seafood, which is often rich in polyunsaturated fatty acids, is particularly susceptible to photooxidation, which can further damage its quality. When these sensitive compounds are exposed to light, they oxidize, accelerating spoilage and nutrient loss. The use of UV-blocking packaging films provides an effective solution to mitigate these negative effects (Sani et al. 2024). For example, Fu et al. (2022) proposed the preparation of an active chitosan/gelatin nanocomposite film using CDs derived from chitosan–citric acid solution. The gelatin/chitosan/CDs film showed a significantly enhanced UV-blocking effect compared to the film composed of gelatin and chitosan. The bionanocomposite film containing CDs exhibited an average light transmittance of only 5.82% in the wavelength range of 200–400 nm, whereas the gelatin/chitosan film exhibited an average light transmittance of 34.87%. This remarkable UV blocking is attributed to the strong UV absorbance of CDs, which is evidenced by the UV–vis spectra, which exhibit distinct absorption peaks at 235 and 324 nm. These peaks correspond to the π–π^* transitions of C═C bonds and the n–π^* transitions of C—N and C═O bonds, respectively. In addition to UV protection, the gelatin/chitosan/CDs film exhibited enhanced functional properties, including potent antioxidant activity and strong antibacterial efficacy against *Escherichia coli* and *Staphylococcus aureus*. The gelatin/chitosan/CDs film showed promising results in the preservation of fish slices. It exhibited excellent antibacterial activity, keeping the total bacteria count below the acceptable limit for 10 days, compared to 6 days in the control group. The film also showed the ability to inhibit spoilage by effectively reducing lipid oxidation and pH increase. These results show that the film has the potential to improve food quality and extend shelf life.

Wang et al. (2024) developed eco-friendly, multifunctional CDs from radish residues (R-CDs) using one-pot hydrothermal method. The hydroxyl group-rich R-CDs were incorporated into starch- and chitosan-based films (S/CS/R-CDs films) to evaluate their application in salmon fillet protection. UV–vis scanning was performed in transmission mode to evaluate the UV-blocking properties of R-CDs. The results showed that the starch/chitosan film without R-CDs had a maximum UV transmittance of 58.37% in the UV spectrum (200–400 nm). When R-CDs were added at concentrations of 0.5%, 1.0%, and 1.5%, respectively, the UV transmittance gradually decreased to 49.33%, 46.13%, and 39.29%, respectively. At 1.5% R-CDs, the transmittance dropped to almost 0% below 280 nm, confirming the excellent UV-blocking ability of the film, making it suitable for food packaging to mitigate UV damage. Incorporating R-CDs into S/CS film can preserve the quality of salmon fillets by utilizing the UV blocking, antibacterial, and antioxidant properties of the film (Figure 4b). During storage, untreated salmon fillets showed rapid spoilage, characterized by discoloration, loosening of muscle fibers, rancid odor, and increased bacterial growth. On the other hand, salmon packed with S/CS/R-CDs-1.5% films maintained freshness for a longer period, and spoilage indicators, such as total viable count (TVC), pH, TVB-N, and TBA, values were significantly lower than those of the control and PE-treated samples.

In a recent study, a sustainable biopolymer film was developed using a chitosan/soy protein isolate (Cs/SPI) matrix enriched with purple hull pistachio anthocyanins (PHPA) and CDs derived from pistachio by-products (Hadavifar et al. 2025). Incorporation of PHP-CDs significantly reduced the UV transmittance in the range of 200–330 nm, which resulted in a perfect UV-blocking effect due to efficient photon absorption. In addition, fish samples wrapped with the PHP-CDs/PHPA-reinforced film exhibited superior preservation properties, including reduced microbial growth and lipid oxidation during storage. Similar results were observed in composite films combining konjac glucomannan (KGM) and sodium alginate (SA) with nitrogen-doped carbon quantum dots (N-CQDs) (Jiang et al. 2025). The film effectively preserved crayfish meat for up to 8 days at 4°C due to the synergistic effects of UV-shielding, antibacterial, and antioxidant properties by incorporation of N-CQDs.

Hybridization of CDs with some other active fillers can enhance the UV-blocking properties. For example, Khan et al. (2024a) developed carrageenan-based active/intelligent packaging films incorporating anthocyanin and ZnO-doped CDs (Zn-CD) derived from purple kohlrabi peels. The introduction of kohlrabi peel anthocyanins into carrageenan films was shown to block UV light. Therefore, the film composed of anthocyanin and 3 wt% Zn-CD exhibited impressive UV-blocking properties (85.2% for UV-A and 99.4% for UV-B) along with significant antioxidant activity. In the real-packaging test, the Car/KA@Zn-CD films were found to effectively extend the shelf life of shrimp while preserving its quality.

These studies confirm that UV significantly accelerates the spoilage of seafood with high content of photosensitive polyunsaturated fatty acids. CD-based films effectively reduce photodegradation and oxidative spoilage by blocking harmful UV rays and providing antioxidant and antimicrobial protection. Similar to meat products, the general preservation mechanism is to limit UV-induced lipid oxidation and microbial growth, thereby maintaining quality indicators such as color, texture, pH, and TVC. These common protective effects highlight the wide applicability of CD-based films in various food categories, reinforcing their role as multifunctional packaging materials for extending shelf life and ensuring food safety.

6.3 | Fruits and Vegetables

UV can damage fruits and vegetables during postharvest storage and transportation, leading to a loss of nutrients and sensory quality. UV damages fruits and vegetables through two main mechanisms, causing significant quality losses. First, photooxidation occurs when UV light induces reactions involving photosensitizers, destroying antioxidants and causing protein denaturation, lipid oxidation, pigment degradation, and off-flavor formation. This process breaks covalent bonds in organic compounds, generating singlet oxygen and free radicals that are detrimental to photosensitive molecules. The second mechanism is related to physiological and metabolic disturbances. UV light changes cell metabolites, disrupts photoreceptor pathways such as UVR8, and accelerates ripening and senescence through ethylene signaling. It also activates endogenous photosensitizers to promote the production of ROS. These disturbances are manifested by chlorophyll degradation, pigment accumulation, changes in respiration, energy metabolism, and synthesis of volatile flavor compounds. When these effects are combined, the visual and sensory appeal of fruits and vegetables decreases, thereby lowering their market value (Zhang and Jiang 2023).

To counteract these adverse effects, it is important to improve the UV-protection performance of packaging films and coatings. Such innovations are essential to protect the quality and extend the shelf life of fruits and vegetables, thereby keeping them attractive and consumable for a longer period. CD-based packaging films are frequently used for the preservation of foods exposed to UV, especially fresh fruits and vegetables. For instance, Patil et al. (2020) prepared a flexible UV-blocking and highly transparent composite film combining PVA and waste tea residue CDs (WTR-CDs) using a solvent casting method for grape preservation. Incorporating 3 mg of WTR-CDs into the film provided impressive UV-blocking performance, effectively filtering 20–60% of UV-A rays (315–400 nm) while completely blocking UV-B (280–315 nm) and UV-C (230–280 nm). The practical feasibility of PVA@WTR-CDs composite films as UV-blocking packaging was demonstrated using grapes as a model fruit. Grapes stored in cups wrapped with PVA@WTR-CDs films exhibited significantly less browning and shrinkage than those stored in unwrapped cups or cups wrapped with pristine PVA film after UV exposure for 30 h (Figure 5a). This study highlights the potential of PVA@WTR-CDs composite film as a sustainable and effective solution for UV protection in food packaging applications.

It is reported that PVA/CNC film showed limited UV-blocking ability, which could only transmit 71.97% of UV-A and 69.27% of UV-B, resulting in a low UPF of 1.43 (Lien and Van Nguyen 2024). To overcome this drawback, 0–1 wt% CDs derived from apple waste were incorporated into the PVA/CNC matrix to enhance its UV-blocking performance. As a result, the PVA/CNC/CD composites showed significant improvement, and the PVA/CNC/$CD^{1\%}$ film could only transmit 21.8% of UV-A and 9% of UV-B. This modification increased the UPF by 5.9 times compared to the unmodified PVA/CNC film. In practical applications, the PVA/CNC/$CD^{1\%}$ film effectively preserved the freshness of cherry tomatoes. Tomatoes wrapped with this composite film maintained their shape with minimal wrinkling and 6.5% weight loss even after exposure to 365 nm UV at room temperature for 15 days (Figure 5b). These lab-scale results highlight the potential of PVA/CNC/CD composites as highly effective UV-blocking materials, offering promising prospects for sustainable food packaging solutions. In another study, Khan et al. (2024b) showed that incorporating a hybrid structure of CDs with a metal-organic framework provided 95.7% protection against UV-

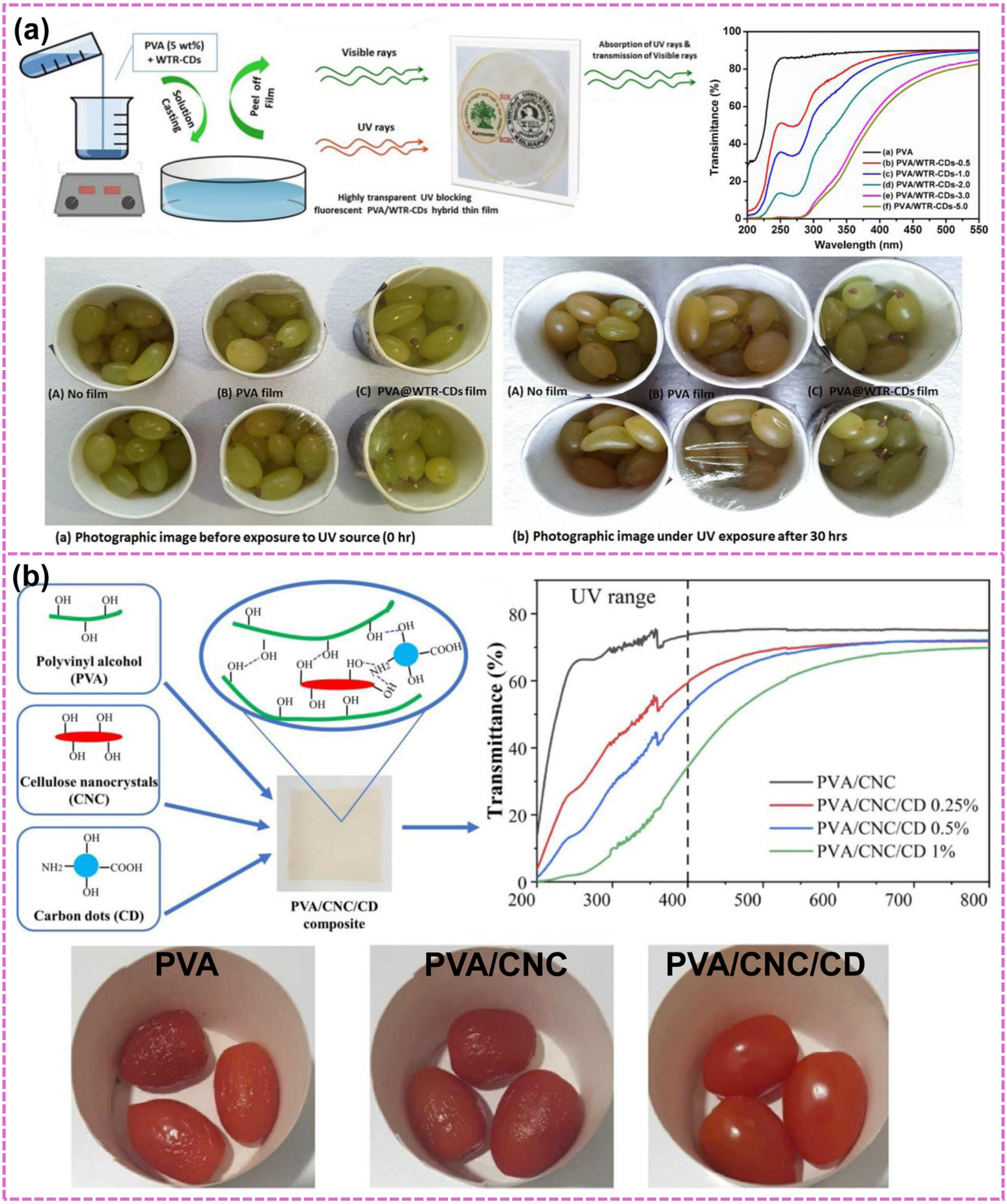

FIGURE 5 | (a) A schematic depicts the fabrication of pure PVA and PVA@WTR-CDs composite thin films, emphasizing their UV-blocking properties. Photographs illustrate the effectiveness of PVA@WTR-CDs films in preserving grape quality during UV exposure over time. (b) The UV-blocking capability of PVA/CNC films embedded with apple waste-derived CDs is highlighted. Visual assessments of cherry tomatoes subjected to UV radiation for 15 days demonstrate the PVA/CNC/CD film's ability to reduce weight loss and maintain quality under prolonged UV exposure. *Source*: (a) Reprinted from Patil et al. (2020); (b) reprinted from Lien and Van Nguyen (2024).

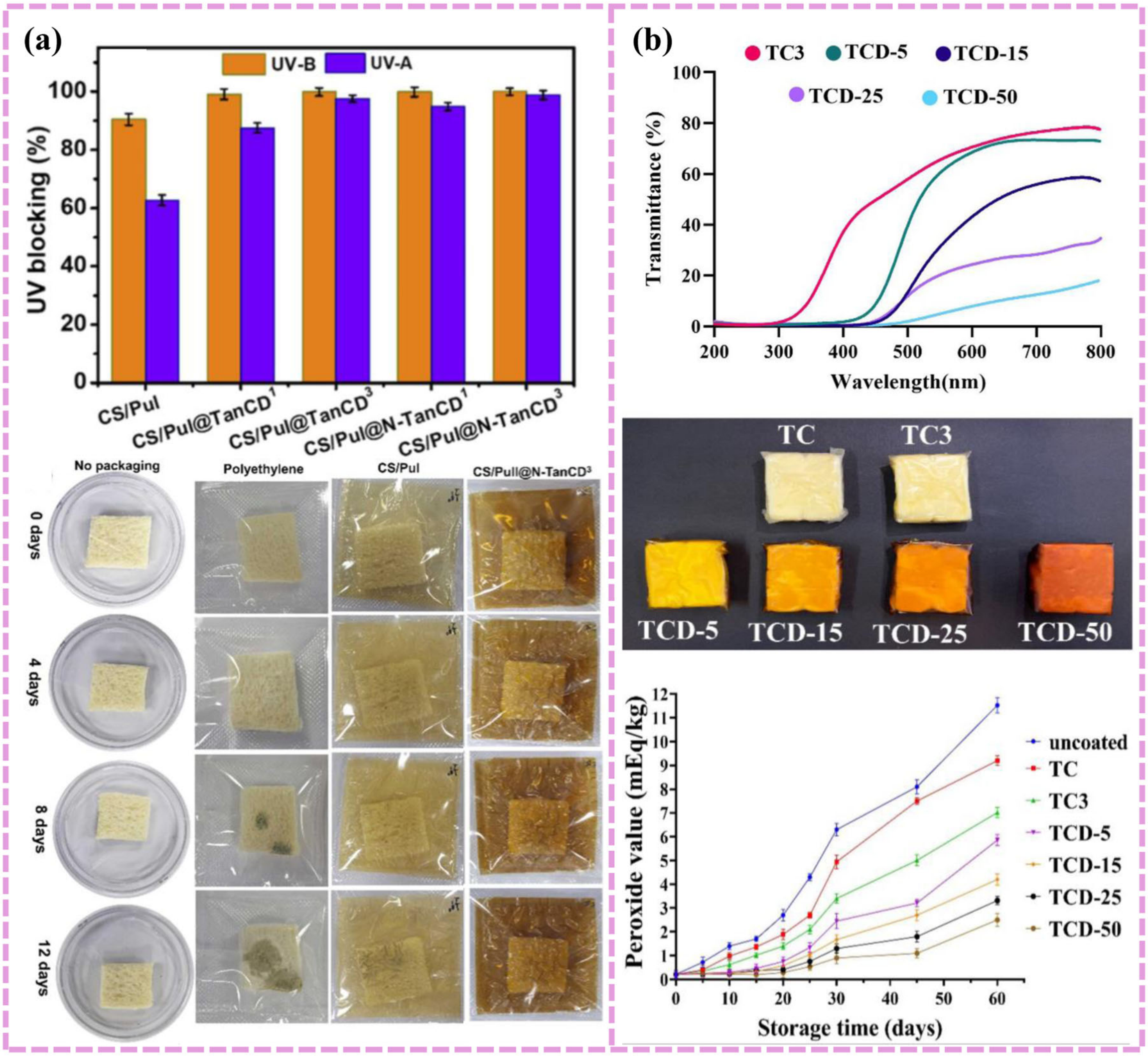

FIGURE 6 | (a) UV-blocking potential of the tangerine peel-based carbon dots loaded chitosan/pullulan film and the preservation effect of the proposed film for the packed bread. (b) The UV–vis transmittance curves of the oxidized dialdehyde tragacanth gum/casein (ratio 2:1) films containing varying concentrations of CDs (5%, 15%, 25%, and 50%) along with the effect of developed films on the prevention of oxidation of coated butter samples. *Source*: (a) Reprinted from Sul et al. (2025); (b) reprinted from Khoshkalampour et al. (2024).

B and 84.7% protection against UV-A. The use of composite films extended the shelf life and maintained the quality of packaged tomatoes stored at 4°C for 24 days.

Ezati, Rhim, Molaei, and Rezaei (2022) developed glucose-based CDs via a one-pot hydrothermal process and incorporated them into chitosan/gelatin films to enhance their UV-blocking properties. UV-blocking and transparency properties of CS/Gel/CD films were evaluated by measuring the light transmittance at 280 nm (T_{280}) and 660 nm (T_{660}). The results showed that the incorporation of CDs significantly enhanced the UV-blocking performance of the films. In particular, the addition of only 1 wt% CDs to the CS/Gel film resulted in an 82.5% reduction in T_{280} and a minimal decrease in T_{660}, indicating excellent UV-blocking properties with minimal impact on visible light transparency. The enhanced UV-blocking performance of the CD-incorporated film is attributed to the strong UV absorption properties of CDs, which exhibit a maximum absorption peak at 295 nm. In addition, CDs induced strong antioxidant, antibacterial, and antifungal effects, which improved the shelf life of stored avocados.

In a subsequent study, nitrogen-functionalized CDs were synthesized to significantly improve the UV-blocking properties of cellulose nanofiber-based films (Ezati, Rhim, Molaei, Priyadarshi, et al. 2022). These CD-incorporated films also showed strong antifungal activity, which helped extend the shelf life and maintain the freshness of tangerines and strawberries. Similarly, Riahi et al. (2022) investigated the UV-blocking potential of CMC films containing chitosan-based CDs. Their findings highlighted the versatility and effectiveness of CDs in enhancing the UV protection of food packaging. Specifically, CMC/CD$^{5\%}$ film provided complete UV-blocking performance superior to pure chitosan film. Additionally, lemons coated with CMC/CDs solution maintained their attractive appearance for up to 21 days, owing to the combined UV-protection, antibacterial, and antioxidant properties of CDs.

Hou et al. (2024) developed CDs from D-anhydrous glucose and ethylenediamine through a one-pot hydrothermal process and introduced them into polyvinyl alcohol-carboxymethyl cellulose film to improve their UV-blocking properties. The results showed that the UV-blocking rate increased with increasing CD content. Specifically, the UV-blocking rate reached 92.44% at 0.25 wt% CDs and 99.4% at 0.50 wt% CDs. When the CD content was 0.75 wt%, the film achieved a 100% UV-blocking rate. This high UV-blocking effect is mainly due to the inherent UV absorption properties of CDs. In addition, the CDs induced strong antioxidant and antibacterial effects, which improved the shelf life of strawberries.

CDs can be used as a modifier of packaging fillers to impart more functional properties to the developed packaging materials. In this regard, the research team aimed to synthesize alginate-based nanocomposite filled with CDs-modified halloysite nanotubes (HNTs-CDs) to improve their potential as active food packaging materials (Cinà et al. 2024). For this purpose, HNTs were chemically modified with CDs derived from L-tartaric acid and various amines through microwave-assisted pyrolysis. Interestingly, this study extensively investigated the effect of UV irradiation on the mechanical properties of the prepared films. As a result, UV exposure significantly reduced the stress at break of both the pristine alginate film and Alg/HNTs film by about 28% and 21%, respectively. Meanwhile, the stress at the break of the Alg/HNTs-CDs film remained stable even after UV irradiation, indicating excellent resistance to mechanical degradation by UV. This suggests that the photostability of the composite film was significantly enhanced by adding CDs to the HNT-reinforced alginate matrix. Further analysis of the optical transmittance properties of the films showed that the Alg/HNTs-CDs nanocomposite exhibited the lowest transmittance in the UV-B range (300 nm), which is because CDs are known to have strong absorption properties in the wavelength range of 200–300 nm. In addition, the Alg/HNTs-CDs coating effectively extended the shelf life of both apple slices and banana slices. This preservation effect is attributed to the synergistic effect of the antioxidant, antimicrobial, and barrier properties of the nanocomposites. In particular, the UV-blocking provided by the embedded CDs is likely to have played an important role in mitigating photodegradation processes within the fruit tissue, thereby supporting the retention of quality and visual appearance during storage. Several other studies have also confirmed that the UV-blocking capability of CDs combined with antioxidant and antimicrobial properties can effectively extend the shelf life of various fruits and vegetables (Althawab et al. 2024; Alzahrani 2024; Ananda et al. 2025; Gao et al. 2024; Guo et al. 2024; B. Liu et al. 2025; J. Zhang et al. 2025).

Overall, the integration of CDs into biopolymer-based packaging films has shown significant potential in mitigating UV-induced damage to fruits and vegetables by absorbing harmful radiation and preventing photooxidation and physiological stress. Similar to meat and seafood, these CD-based materials prevent lipid oxidation, microbial spoilage, and nutrient loss by leveraging their UV blocking, antioxidant, and antimicrobial functions. The consistent mechanism across food types, focusing on photosensitive compound blocking and oxidative stress modulation, demonstrates the broad efficacy of CD-functionalized films as a sustainable packaging solution for shelf life extension and food quality preservation.

6.4 | Bakery Products

Bakery products, such as bread, cookies, biscuits, and puddings, are among the most widely consumed daily foods worldwide. However, these products are mainly susceptible to spoilage due to factors such as oxidation, moisture absorption, and microbial contamination. The oxidation process that occurs due to the high-fat content of baked products leads to undesirable changes in sensory qualities, including texture deterioration, off-flavors, rancidity, and color changes. Oxidation also leads to the formation of harmful compounds with cytotoxic, mutagenic, and carcinogenic properties. These changes have a significant impact on the quality and shelf life of bakery products, ultimately influencing their consumer acceptance. Exposure to UV radiation can accelerate the deterioration of bakery products through photodegradative reactions such as lipid oxidation, and therefore, it is important to protect these products from oxidants such as UV light (Tripathi et al. 2024). One of the promising solutions is the use of CD-based active packaging, which can effectively protect bakery products from these harmful factors. In addition, the antifungal and antioxidant properties of CDs can actively preserve the quality of baked products during storage. In this regard, Sul et al. (2025) designed a UV-blocking packaging material incorporating citrus peel waste-derived CDs (TanCDs) to extend the shelf life of baked wheat bread. TanCDs were further doped with nitrogen (N-TanCDs) and used as active agents to prepare CS/Pul-based active packaging films. The UV–visible spectra showed that both TanCDs and N-TanCDs exhibited distinct and broad absorbance peaks at 291 and 290 nm, respectively, which corresponded to the π–π^* and n–π^* transitions of conjugated C–C bonds and carboxyl (C–O) groups. In terms of light transmittance, the T_{660} and T_{280} values of the neat CS/Pul film were 87.9% and 6.3%, respectively, indicating high transparency but moderate UV-blocking capacity. However, the incorporation of TanCDs and N-TanCDs into the composite film slightly decreased its transparency, with a decrease in T_{660} from 87.9% to 80.8%, whereas the T_{280} significantly decreased from 6.3% to 0.1%, indicating a significant enhancement in its UV-blocking performance. The improvement of UV-blocking properties was further evident from the optical transmittance spectra of the CD-loaded films. The UV-blocking ability increased with increasing CD concentration, whereas N-doped CDs (N-TanCDs) proved to be more effective than TanCDs (Figure 6a). In particular, the CS/Pul@N-TanCD^3 film was found to almost completely block UV-A (320–400 nm) and UV-B (280–320 nm). These CD-reinforced biopolymer films provided excellent UV protection due to the CDs' ability to reflect or absorb UV radiation. In addition, the presence of aromatic polyphenols in the CDs derived from tangerine peels further amplified their strong UV-blocking ability. CS/Pul/CDs film significantly extended the shelf life of bread slices, keeping them fresh for more than 12 days compared to 8 days when using commercial polyethylene bags and pure CS/Pul film. This improvement is attributed to the combined UV-blocking, antimicrobial, and antioxidant properties of Tan CDs incorporated into the film. Koshy et al. (2022) also introduce a novel CD-based active film designed for bread packaging. The film was prepared using an environmentally friendly approach using SPI and AgNP-immobilized

CDs as active agents. The developed film is ideal for bakery products such as bread due to the synergistic UV-blocking, antioxidant, and antimicrobial properties imparted by the integrated particles.

Recently, Thanawutthiphong et al. (2025) explored the potential of elemental doping to enhance the properties and functionality of CDs for active food packaging. Specifically, they synthesized sulfur-nitrogen-doped CDs (S,N-doped CDs) from citric acid and cysteine and incorporated them into a polyvinyl alcohol matrix to fabricate transparent UV-blocking film. As a result, the nanocomposite film exhibited excellent UV-blocking performance, especially in the UVC and UVA ranges, with more than 95% UVA blocking efficiency. Additionally, the film exhibited enhanced antibacterial properties, reducing both Gram-positive and Gram-negative bacteria by more than 99.999%, and the DPPH radical scavenging activity reached 89%. The combined functional properties of the S,N-doped CDs significantly extended the shelf life of bread slices packaged with PVA-CDs, which remained mold-free until Day 6, whereas mold growth occurred after Day 4 in the control and PVA only samples.

On the basis of the above discussion, it can be suggested that the incorporation of CDs into biopolymer films for bakery packaging has shown excellent potential in preventing UV-induced oxidation and microbial spoilage. CD plays a protective role through their strong UV absorption and enhanced antioxidant and antifungal properties, which are consistent with the mechanisms observed in meat, seafood, fruits, and vegetables. CD-based packaging significantly contributed to extending shelf life and maintaining consumer preference by protecting bakery products from photodegradation and preserving sensory and nutritional characteristics. These results support the versatile applicability of CD-functionalized packaging as a versatile and sustainable solution for UV protection in food systems.

6.5 | Dairy Products

Dairy products, such as milk, cheese, and butter, are highly prone to photodegradation due to their high-fat content and react negatively when exposed to light, resulting in off-flavors and deterioration in quality. In addition, photosensitive vitamins (vitamins A and B12) in dairy products are reduced when exposed to UV light, thereby reducing their nutritional value. To address these issues, UV-blocking packaging films have become an important solution to preserve the quality and extend the shelf life of dairy products. Khoshkalampour et al. (2024) proposed a novel film based on casein/modified tragacanth gum reinforced with CDs to extend the shelf life of butter. CD NPs were hydrothermally synthesized from milk permeate and then incorporated (5%–50% w/w) into optimized cross-linked casein films to produce advanced casein-based nanocomposites. The incorporation of CDs into the film matrix significantly minimized UV transmittance, resulting in a 99.09% reduction in UV-C and a 97.46% reduction in UV-A. This excellent UV-blocking performance can be attributed to the unique UV absorbance properties of the synthesized CDs. UV–visible spectral analysis supported this property, showing a prominent absorption peak at 280 nm. This peak was associated with the n–π^* transition of the C═O bond and the π–π^* transition of the C═C bond, indicating the presence of aromatic sp^2 carbon domains within the CDs structure. More importantly, incorporating CDs into the packaging films significantly improved the oxidative stability and shelf life of butter. CDs exhibited strong UV-blocking and antioxidant properties, effectively reducing the peroxide value (PV) level over 60 days. Butter samples coated with films containing CDs exhibited lower PV (2.5–5.86 mEq/kg) compared to uncoated butter (11.53 mEq/kg), indicating reduced primary lipid oxidation (Figure 6b).

In a recent study, the effect of CDs from coconut husk was evaluated on the functional properties of a carrageenan-based biopolymer system (Sangeetha et al. 2024). Carrageenan films exhibited high transparency against harmful UV rays with a transmittance of 71.2%. On the other hand, the composite films incorporating 1%–3% CDs showed significantly reduced UV transmittance with values of 43.7%, 30.1%, and 27.3%, respectively. The enhanced UV-blocking properties of the composite films can be attributed to the chromophore present in the lignin-based CDs, which effectively absorb UV rays. These results indicate that CD-incorporated films have superior UV-blocking properties compared to pure carrageenan films, making them a promising option for dairy product packaging.

The research results summarized above suggest that CD-incorporated packaging films provide a powerful and effective strategy to counteract the adverse effects of UV exposure on dairy products. These mechanisms are similar to those observed in other food categories, where CDs reduce oxidative spoilage, inhibit photodegradation, and extend shelf life. Therefore, the application of CD-functionalized films to dairy packaging further enhances their versatility and potential as sustainable and broad-spectrum solutions to improve food quality and safety under UV exposure.

7 | Conclusion and Outlook

Photooxidation is a key factor in the deterioration of a wide range of foods, including meat, seafood, dairy, oils, fruits, vegetables, baked goods, and beverages. This process can result in a loss of nutritional value and sensory quality and can also produce harmful byproducts. Exposure to UV radiation, particularly in the UV-A and UV-B range, poses significant risks to food safety and quality. To address these challenges, UV-protection packaging materials have been developed, offering several benefits to both food producers and consumers. These materials act as effective barriers to UV radiation, protecting perishable foods from spoilage and extending their shelf life. This not only reduces food waste but also improves the sustainability of the food supply chain. UV-protection films also preserve the sensory properties and nutritional value of packaged foods, ensuring that consumers receive high-quality and nutritious products. This review explored how newly developed CDs could be applied as highly effective UV-protective fillers in various biopolymer-based films and coating materials for packaging. By incorporating these UV-protective materials, manufacturers can maintain the integrity, safety, and appeal of food products. Despite significant progress in understanding the UV-protection capabilities of CDs in active food packaging systems, several challenges remain.

A comparative review of the available literature suggests that CDs are promising UV absorbers, but their effectiveness is highly dependent on the source material and concentration. This variability limits their widespread application in a variety of packaging environments. A major challenge to future progress in this field is the reliance on "generic" CDs that are either undefined or poorly characterized by their structures. To address this issue, more precise control of the synthesis and comprehensive structural characterization of CDs is required to ensure consistent performance in UV-protection applications. In addition, the use of brown-colored CDs (obtained from pyrolysis or thermal approaches) may limit its widespread application in food packing. Then, a critical consideration in active packaging is to identify the optimal CD concentration that balances UV protection and transparency to provide the desired protective properties while maintaining the aesthetic appeal of the packaging and meeting consumer expectations for visual quality. Further exploration of CDs as an active UV-protection filler requires comprehensive studies to evaluate the effects of precursor materials, structural properties, polymer formulations, and functionalization methods on their performance in food packaging. Future development of active packaging systems should prioritize investigations into manufacturing techniques, integration strategies, and the optimization of CD concentrations to maximize efficacy and practical applications. Finally, it will be necessary to develop CD-based UV-protection packaging materials that are environmentally sustainable, safe for human health, and cost-effective for large-scale commercial production.

Author Contributions

Zohreh Riahi: conceptualization, writing–original draft, visualization, formal analysis, investigation. **Ajahar Khan**: investigation, formal analysis, visualization, writing–original draft. **Mohsen Ebrahimi**: writing-original draft. **Jong-Whan Rhim**: writing–review and editing. **Gye Hwa Shin**: writing–review and editing. **Jun Tae Kim**: conceptualization, funding acquisition, project administration, supervision, writing–review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be made available on request.

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