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Unlocking the potential of green-engineered carbon quantum dots for sustainable packaging biomedical applications and water purification

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ABSTRACT

Carbon quantum dots (CQDs) with well-defined architectures offer highly fascinating properties such as excellent water-solubility, exceptional luminescence, large specific surface area, non-toxicity, biocompatibility and tuneable morphological, structural, and chemical features. This review comprehensively overviews recent breakthroughs and critical milestones in the green synthesis of CQDs from renewable sources and provides guidance for their sustainable development towards fulfilling the goals of green chemistry. It also discusses the interaction of CQDs with various biopolymers to improve the material performance and functionality. This paper also highlights the latest technological applications of CQDs in numerous fields, including sustainable packaging, biosensing, bioimaging, cancer therapy, drug delivery as well as water purification. Finally, it summarizes the main challenges and provides an outlook on the future directions of CQDs in packaging and biomedical fields. This review can act as a roadmap to guide researchers for tailoring the properties of CQDs for important composite and biomedical fields.

1. Introduction

Carbon has astonished scientists with its remarkable capacity to form diverse morphologies and dimensions. The evolution of carbon materials has progressed from traditional forms such as activated carbon, carbon black, carbon fibers to more cutting-edge nano-dimension morphology such as carbon nanotubes. The fundamental research and application of carbon-based materials remain highly regarded across chemistry, materials science, and other interdisciplinary fields due to their versatility and diverse functional properties. The adaptable nature of carbon materials enable their use in a wide range of applications, including energy storage [1–3], catalysis, nanotechnology, composites, and environmental remediation, making them indispensable for developing next-generation materials and sustainable technologies [4–6]. However, despite these creditable advantages, macroscopic carbon materials do not have a suitable band gap, which limits their potential use as fluorescent materials. Zero-dimensional carbon quantum dots (CQDs) are a recent addition to the carbon family, with sizes smaller than 10 nm. CQDs have garnered significant interest because of their unique and exceptional characteristics such as low toxicity, ease of synthesis, high water solubility, availability from inexpensive sources, efficient light harvesting, excellent stability under light, excellent biocompatibility, tunable emissivity, remarkable fluorescence characteristics, effective transfer of photoinduced electrons. These features have enabled their usage in cancer therapy and diagnostic devices [7,8], drug delivery [9], chemical sensing and biosensing [10,11], bioimaging [12], optoelectronics [13], electrocatalysts [14,15], food contaminant detection [16], and in agriculture as plant growth promoter [17], and improving plant stress tolerance [18]. The surface electronic structure of oxygen doped CQDs is modulated by varying isomerization precursors, showcasing excellent electrocatalyst performance [19]. CQDs have also gained recognition because of their significant environmental benefits such as biodegradability and potential to be synthesized from waste resources which reduces dependence on non-sustainable and toxic

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chemicals. Another key aspect that differentiates CQDs from other materials is their capability to effectively remove pollutants like dyes and heavy metals from water [20]. Furthermore, CQDs can be used as photocatalysts to break down organic contaminants in wastewater when exposed to visible light [21–23]. These unique properties position CQDs as a sustainable and versatile material for environmental remediation.

The field of CQDs is an active and prolific research area and many new papers are coming at a fast pace in literature. Significant research efforts have been directed towards exploring the potential applications of CQDs in food packaging and biomedical fields due to their multifunctional properties, including antibacterial, antioxidant, UV-barrier, fluorescent, and electrical conductivity features (Fig. 1). Hence, this is the right moment to compile a comprehensive and authoritative review that covers this important research area and provides new information that can lead to breakthroughs. Most currently published reviews have mainly focused on green synthesis of CQDs using renewable resources, neglecting the interaction of green-engineered CQDs within biopolymer composites [24–28].

This review distinguishes itself from other review articles in the field by comparatively and comprehensively exploring the integration and/or interaction of CQDs with various biopolymers and how this affects the improvement of mechanical, chemical and optical properties. This paper also seeks to unlock the technological potential of CQDs in various domains, including biomedical and food packaging. This study is an effort to highlight the environmental and economic benefits of green-engineered CQDs and their potential to revolutionize biopolymer composites for future applications.

2. Methods for the synthesis of CQDs

Carbon quantum dots (CQDs) can be synthesized using various methods, broadly classified into "top-down" and "bottom-up" approaches [30–33]. Top-down methods, such as laser ablation, chemical oxidation, and arc discharge, involve breaking down larger carbon structures into nanoscale materials. These methods can produce high-purity CQDs with controlled size and morphology but often require complex equipment, high energy consumption, and expensive precursors, limiting their scalability. In contrast, bottom-up approaches, including microwave-assisted carbonization, thermal decomposition, and solvothermal synthesis, assemble CQDs from small organic molecules. While these methods are more cost-effective and versatile, many rely on synthetic precursors and energy-intensive processes [32].

Recent advancements emphasize the importance of green synthesis as a sustainable alternative to conventional methods. This approach utilizes renewable and natural precursors, such as biomass, fruit peels, and crop residues, to minimize environmental impact while producing eco-friendly and biocompatible CQDs [26–29]. These natural sources are renewable, abundant, cost-effective, and non-toxic to the human and the environment [29,30]. As shown in Fig. 2 the number of research articles focused on green synthesis of CQDs has seen an exponential growth over the last decade.

Green synthesis methods, including hydrothermal, microwave-assisted, and pyrolysis techniques, align with sustainability goals by reducing toxic chemical use, energy consumption, and waste generation [30,32,34]. For instance, the hydrothermal method leverages water-based solvents under mild conditions to produce CQDs with tunable optical properties, while microwave-assisted synthesis enables rapid, energy-efficient production with minimal byproducts [31]. By focusing on renewable precursors and low-impact synthesis routes, green methods provide a viable pathway for scalable and sustainable nanomaterial production, addressing environmental and economic challenges in CQD manufacturing [32,34].

The increasing demand for environmental protection underscores the necessity of using renewable materials in the synthesis of CQDs. This trend emphasizes the importance of investigating simple, environmentally friendly, and biological methods over traditional chemical

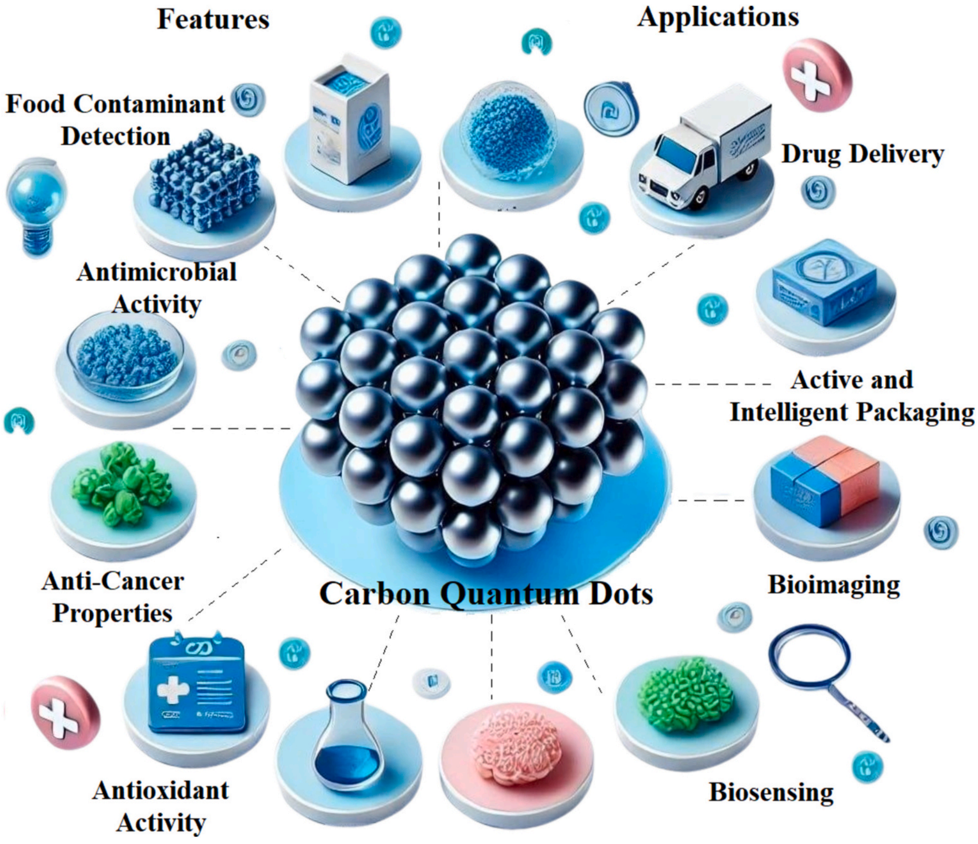

Fig. 1. An overview of diverse applications of carbon quantum dots (CQDs) in different fields.

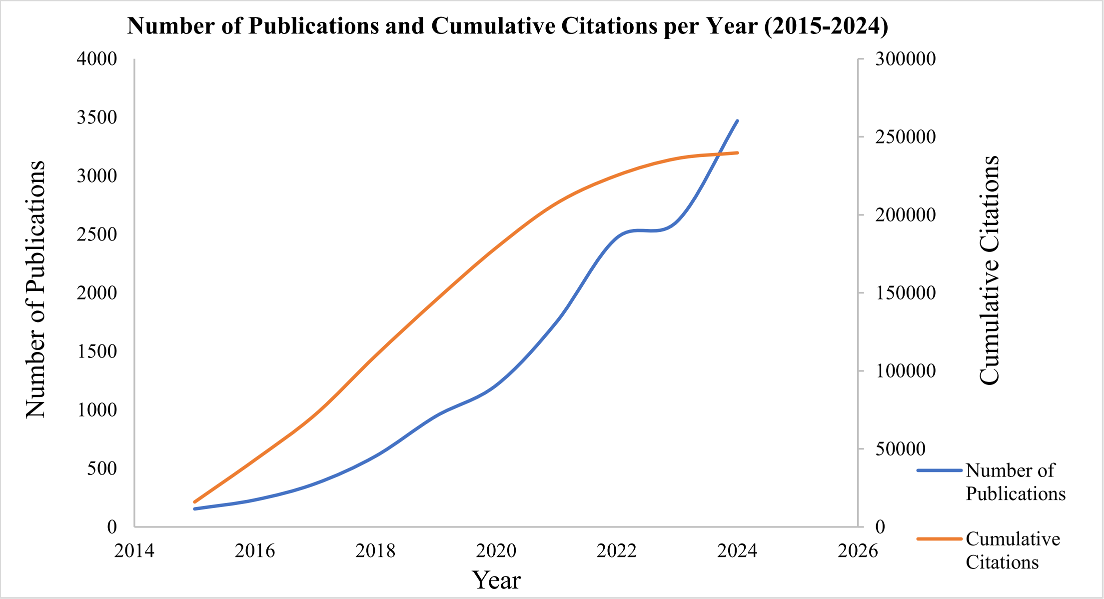

Fig. 2. The line graph representing the increasing trend in the number of publications on “CQDs” in the period of 2015 to 2024. These results were obtained from the Google Scholar database by using the keyword “carbon quantum dots” and “green synthesis” in the article title and abstract. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

methods. Sustainable synthesis of CQDs offers several advantages including improved biocompatibility, stability, scalability and sustainability [32]. However, there are some drawbacks associated with the green synthesis of CQDs including the complex process of separating CQDs from biomass [32], low luminescence (fluorescence) quantum yield [33] and the need for optimization to achieve the desired particle size and morphology [34]. In recent years, the development of machine learning (ML) has provided an exciting new avenue for researchers to overcome the challenges of optimizing the synthesis of CQDs. Guo et al. (2024) introduced a novel multi-objective optimization strategy utilizing a machine learning (ML) algorithm to intelligently guide the hydrothermal synthesis of CQDs, optimizing properties such as full-color photoluminescence (PL) wavelength and high PL quantum yields (PLQY) [35]. This aligns with the broader adoption of green synthesis strategies for CQDs generation, which commonly include hydrothermal/solvothermal, microwave-assisted polymerization, and pyrolysis methods [36]. Different methods used for the green synthesis of CQDs from various renewable sources were illustrated in Fig. 3.

2.1. Hydrothermal/solvothermal method

The hydrothermal method is cost-effective, straightforward, environmental-friendly, with high efficiency for the synthesis of CQDs. This technique relies on using water as the primary solvent, aligning with green chemistry principles by preventing or reducing the use of harmful organic solvents. Despite tremendous efforts to adopt this method in the synthesis of CQDs, it often requires careful optimization of reaction parameters such as temperature and duration to maximize product yield and performance while minimizing energy consumption [37].

Solvothermal synthesis method utilizes mild organic solvents such as ethanol, offering a greener alternative to conventional solvent-based methods. Similar to hydrothermal synthesis, solvothermal methods require meticulous control of reaction conditions to achieve desired results on size and morphology of CQDs. Both methods offer environmentally friendly benefits, aligning with the principles of green chemistry and striving to minimize environmental impacts while promoting sustainability in material production [38].

In a typical synthesis, Arkan et al., used a thermal-mediated technique in pressurized autoclave containers with reaction temperatures ranging from 120 to 240 °C for 3 and 12 h. Using quinine sulfate (fluorescence quantum yield: 54 %) as a reference, the synthesized CQDs from walnut oil had a good luminescence quantum yield of 14.5 % and exhibited outstanding photo and pH stabilities [37]. as Another study made an effort to synthesize CQDs from lemon juice at varying temperatures (160, 180, and 200 °C), and observed that higher reaction temperatures significantly improved the luminescence quantum yield properties of CQDs from 24 to 41 %. This study concluded that CQDs

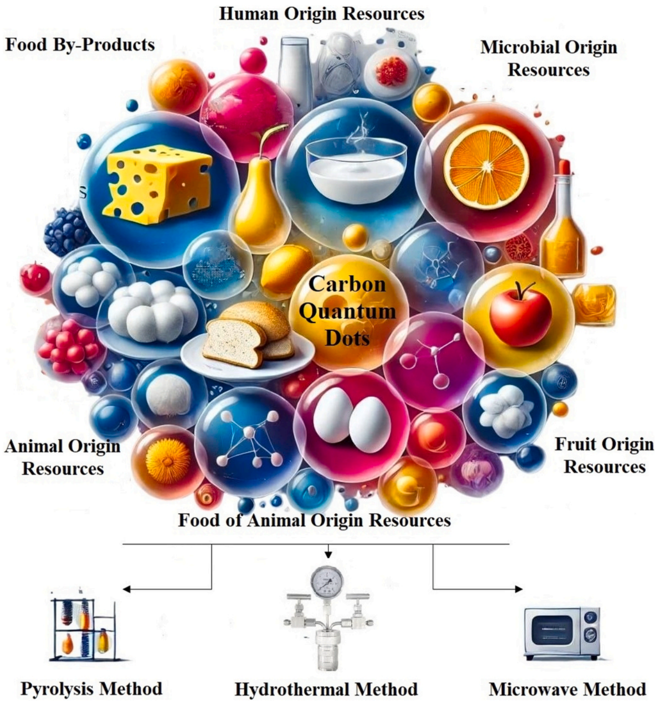

Fig. 3. Various methods used for the green synthesis of CQDs from several renewable sources. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

synthesized at temperatures above 180 °C exhibited significantly improved optical characteristics. The calculated bandgap energy at the temperature at 180 and 200 °C are 4.6 and 4.68 eV, respectively. This trend underscores the critical role of optimizing reaction temperature, as it directly influences the emission properties, with higher temperatures leading to stronger emissions. Similarly, reaction time also plays a crucial role, as prolonged exposure at elevated temperatures can further refine the size and uniformity of the CQDs, thus enhancing their overall stability and performance [39]. A recent study reported the synthesis of CQDs using pomegranate peel and sucrose as carbon sources via a hydrothermal method. The synthesis conditions, such as reaction temperature and duration, were optimized to yield CQDs with unique physical and chemical properties, including excellent water solubility and luminescence. The luminescence quantum yield of these CQDs was found to be 7.02 %. Additionally, the resulting CQDs displayed highly selective sensing capabilities, successfully detecting Fe^{3+} ions among various cations, including Co^{2+}, Al^{3+}, Hg^{2+}, Cu^{2+}, Zn^{2+}, Ni^{2+}, Ba^{2+}, Mn^{2+}, Li^{+}, K^{+}, and Fe^{2+}, all at the same concentration. Fe^{3+} ions were detected at a concentration of 7.488 μM, achieving a coefficient of determination (R^2) of 0.952 [40]. Another representation of this concept was presented by Ling et al. who used an innovative hydrothermal technique that effectively integrated the treatment of waste sulfuric acid from alkylation with the production of high-quality CQDs, providing an economical and controllable solution. This approach enabled precise control over the particle size and surface chemistry of the produced CQDs. Using a higher hydrothermal temperature (180-220 °C) varied the size of the CQD particles from 17.97 nm to 2.42 nm, and nitrogen-containing groups were introduced during the synthesis by adding nitrogen sources. As a result, the nitrogen-doped CQDs displayed enhanced photocatalytic degradation and improved performance in heavy metal detection. For example, the modified CQDs incorporated into graphite carbon nitride exhibited enhanced photocatalytic degradation and were effective in detecting Hg^{2+}. Furthermore, detecting heavy metals using CQDs has smaller ecological footprints compared to conventional industrial waste disposal methods, [41]. Jagannathan et al., employed the ultrasound-assisted hydrothermal method to synthesize white light-emitting CQD from corncob. After carbonizing the corncob by burning, it was treated with ultrasound for 6 h in hydrogen peroxide, followed by agitation in ammonia for 2 h. To produce CQDs with intercalated and exfoliated morphology, the carbon solution was heated at 70–80 °C for 12 h and subsequently subjected to hydrothermal treatment at 220 °C for another 12 h to yield colloidal solution of CQDs. The CQDs demonstrated a wide emission spectrum spanning from 380 nm to 650 nm and maintained high photoluminescence intensity, which remained stable after three months of storage and under different pH conditions. The presence of Si and N impurities in the biomass resulted in the formation of CQDs with a high luminescence quantum yield of 54 % and an extended photoluminescence lifetime at room temperature. The CQDs were highly sensitive to various analytes such as DNA, paracetamol, Pb^{2+}, Cu^{2+}, Fe^{3+}, and Cr^{3+}, with optical sensitivities and limits of detection quantified for each analyte. The CQDs also showed low relative standard deviation values, indicating high reproducibility. Flexible white light-emitting sheets fabricated from the CQDs demonstrated uniform brightness, excellent color reproducibility, and higher stability under various UV light excitations. These results highlighted the advanced characterization and potential applications of CQDs as multi-modal fluorescence sensors [42].

Fluorescent nitrogen-doped CQDs are a category of eco-friendly nanomaterials that hold significant potential for use in cell imaging and optoelectronic applications. A study conducted by Qi et al., (2021) used a natural amino acid, l-glutamic acid, as a precursor to synthesize two distinct types of nitrogen-doped CQDs through a one-step ultrasonic-assisted hydrothermal process at temperatures of 230 (N-CQDs-1) and 250 °C (N-CQDs-2). The findings indicated that N-CQDs-2 comprised of amorphous carbon with a substantial amount of pyroglutamic acid, whereas N-CQDs-1 consisted of solely amorphous carbon. Both N-doped CQDs demonstrated remarkable optical characteristics, including a luminescence quantum yield of 40.5 %, strong resistance to photobleaching, and excellent photostability. These properties are critical for cell imaging, as they ensure bright, stable fluorescence signals that enable prolonged and high-contrast visualization of cells without significant signal degradation. Nitrogen doping specifically enhances fluorescence intensity and stability, making these CQDs especially suitable for biomedical imaging. Additionally, the presence of pyroglutamic acid in N-CQDs-2 may further improve imaging efficiency by enhancing fluorescence and biocompatibility. The authors used both CQDs for imaging BV2 cells, and concluded that the ultrasonic-assisted hydrothermal method could be an effective and straightforward way to produce N-doped CQDs with controllable structures and morphologies for cell imaging applications [43].

Mitra et al., (2013) produced CQDs using polyethylene glycol 200 (PEG-200) a nontoxic polymer, in a NaOH solution at room temperature. Following this, a 'green' solvothermal modification was performed at elevated temperature and pressure to enhance the luminescence quantum yield through improved self-passivation of the surface. This two-step method resulted in the formation of CQDs with uniformly spherical shape and ultrasmall size of less than 1 nm. The photoluminescence properties of the CQDs were found to increase as the pH of the solution was raised from 1 to 7, before marginally decreasing at higher pH levels [44]. While hydrothermal treatment is a viable method for producing water-soluble CQDs from inexpensive organic materials, a major drawback of this technique is the typically lengthy processing times. Therefore, there is significant interest in developing a quicker and more straightforward approach for synthesizing CQDs [45].

2.2. *Pyrolysis*

Pyrolysis is another technique for producing CQDs through thermal breakdown and carbonizing the carbon precursors at higher temperatures (300–600 °C) in the absence of oxygen [46]. This process offers several benefits such as fewer processing steps, solvent-free condition, increased tolerance to various precursors, quicker reaction times, affordability, and scalability. Moreover, tailoring key parameters such as reaction temperatures, duration, and the pH of the reaction mix can enhance certain properties of CQDs particularly their optical capability, such as brightness and photostability for achieving higher luminescence quantum yield [47]. However, pyrolysis can result in CQDs with inconsistent sizes and shapes due to rapid thermal decomposition (Kong et al., 2024). Moreover, this process typically requires high temperatures, resulting in significant energy use and potentially leading to environmental concerns.

Murugan et al., (2019) synthesized CQDs through the pyrolysis of finger millet ragi (*Eleusine coracana*) as a carbon source. The resulting CQDs mostly had carbonyl and hydroxyl groups in their structures, which contributed to increased number of adsorption sites. The nanoscale particles had an average size of ~6 nm [48–50]. Similarly, Dager et al., synthesized monodispersed CQDs derived from fennel seeds using a single-step pyrolysis process at 500 °C for 3 h. The CQDs demonstrated excellent stability under both colloidal and environmental conditions, along with excitation-independent emission —a feature not typically achieved with CQDs from natural carbon sources. This behaviour was attributed to the high degree of carbonization and uniformity in surface states, which minimized surface defects and created a stable photoluminescent structure. The uniform structure enabled consistent emission across excitation wavelengths, marking a significant advancement in CQD synthesis from natural precursors [51]. Wang et al., synthesized two types of CQDs s—CQDs-1 which showed a single emission peak of blue fluorescence and CQDs-2 with a double emission peak of yellow fluorescence using a one-step pyrolysis method under different conditions. The authors combined citric acid and urea, ground the mixture to form a precursor, and heated the mixture in a Teflon-lined autoclave at 200 °C for 2 h. After cooling, the mixture was processed to produce a blue fluorescent CQDs-1 solution, which was then dried. For CQDs-2, the reaction was carried out in an open crucible for 40 min, resulting in yellow fluorescent CQDs-2 solution [52].

2.3. Microwave-assisted method

The utilization of microwave irradiation for synthesizing carbon nanoparticles has become widely used due to its efficiency, environmental friendliness, and cost-effectiveness. This method is known for its rapid action and ability to precisely control temperature, which make it useful for producing CQDs. Microwave-assisted synthesis offers a fast and economical route to obtaining CQDs by subjecting the reaction mixture containing carbon precursors to electromagnetic radiation within the wavelength range of 1 mm to 1 m [53], This technique is significantly quicker than hydrothermal method. As a result, microwave-based synthesis is gaining momentum as a leading strategy for the efficient and sustainable production of CQDs [54,55]. In a recent study led by Franco et al., (2020) explored the production of CQDs from *Vaccinium Meridionale Swartz* extract using microwave-assisted carbonization. This method is significant due to its remarkable efficiency in yielding substantial quantities of CQDs, producing over 80 % mass fraction of CQDs in just 5 min. Thermal gravimetric analysis (TGA) revealed that the resulting CQDs, with an average diameter of 30 nm, exhibited significant thermal stability, maintaining high resistance even in an air atmosphere up to 300 °C [56].

Additionally, a microwave-assisted method was used to produce fluorescent CQDs from roasted chickpea as the carbon source, without chemical additives. The CQDs exhibited excellent fluorescence properties, including high intensity and photostability, and water solubility. Characterization techniques confirmed their structural details and blue fluorescence emission under UV light. Besides, the CQDs showed promising sensitivity in detecting Fe^{3+} ions in certified reference materials (CRM-SA-C Sandy Soil C) [57].

3. Green renewable precursors for the synthesis of CQDs

Food and industrial waste have become a major global issue particularly over the last decades. However, waste can be a valuable carbon resource for synthesizing CQDs. Using these renewable materials helps mitigate environmental issues by reducing waste and converting low-value by-products into valuable nanomaterials [58,59]. Valorizing food and agro-industrial by-products promote sustainability, and improves the cost-effectiveness of CQDs production. A surface with abundant functional groups, uniform particle size, exceptional water solubility and stability, and excellent optical qualities are some of the features for CQDs made from agro-industrial by-products [60]. Limited research has explored the benefits of using waste materials and by-products for synthesizing CQDs.

Huang et al., (2019) synthesized biocompatible CQDs from the auto-hydrolyzated wheat straw and bamboo residues through hydrothermal treatment. The obtained CQDs had a size distribution of 2.0–6.0 nm and showed a blue-green fluorescence with a fluorescence quantum yield of approximately 13 %. The potential applications of synthesized CQDs in imaging cells and tumors were also demonstrated [61].

Polysaccharides, especially marine polysaccharides, are another carbon-based precursor group for producing CQDs [62]. Waste shrimp shells could be similarly used to synthesize CQDs using a one-step hydrothermal method at 180 °C for 12 h. The resultant CQDs exhibited excellent fluorescent stability with a fluorescence quantum yield of 27.14 %, and significant bio-imaging capabilities. They also showed strong antibacterial activity against both Gram-positive and Gram-negative bacteria. By increasing the concentration of CQDs from 20 μg/ml to 100 μg/ml, the activity against *E.coli*, *K.pneumonitae*, *B.ceresus*, and *S.aureus* increased from around 8, 9, 12, 10 to 19, 18, 22, 20 (in the unit of Zone of inhibition(mm)), respectively [63].

Additionally, the residues obtained from the pyrolysis of waste polyolefins were also investigated as precursors for CQDs. In this approach, the residue was pretreated through ultrasonication at 700 W for 2 h followed by hydrothermal treatment at 120 °C for 12 h using concentrated H_2SO_4 and HNO_3as the solvents. The obtained CQDs showed a fluorescence quantum yield of 4.84 % with intense fluorescence, and outstanding stability in an aqueous solution. Besides, they exhibited superior sensitivity and selectivity towards Cu^{2+} ions, with a linear detection range of 1–8.0 μM and a limit of detection of 6.33 nM [64]. CQDs can be synthesized using a variety of renewable biomass sources, including vegetable-based materials, animal-derived precursors, industrial by-products, and polysaccharides. These resources not only offer environmental and economic benefits but also demonstrate diverse functionalities and applications when processed through green synthesis methods. Table 1 highlights selected green synthesis methods using renewable carbon sources, emphasizing their advantages, outcomes, and potential applications.

4. Overview of carbon quantum dots (CQDs): mechanisms and properties

Since the discovery of CQDs in 2004, CQDs have attracted considerable interest in various fields such as biology, chemical sensing, nanomedicine, and photoelectron catalysis [74]. CQDs and inorganic quantum dots (QDs) represent two distinct categories of nanomaterials with unique characteristics. Inorganic QDs, composed of semiconductor materials, exhibit superior optical properties such as high fluorescence quantum yields and narrow-wavelength fluorescence emission. However, there are growing concerns regarding their toxicity and environmental impacts. In contrast, CQDs derived from carbonaceous sources, possess notable biocompatibility, negligible to low toxicity, and simple synthesis methods, making them safer alternatives. The quantum confinement effects of CQDs provide stable and tunable photoluminescence, enabling a wide range of photonic and electronic applications such as bioimaging [75], photovoltaics [76] and light-emitting devices [77]. For applications that prioritize biocompatibility, safety, and sustainability, CQDs surpass inorganic QDs as the preferred choice. CQDs exhibit a diverse array of physical and chemical properties, owing to the extensive range of carbon sources and synthesis methods available. Despite their diversity, sustainably-derived CQDs share several fundamental characteristics, including high stability, tunable fluorescence, environmental friendliness, nontoxicity, and water solubility [78,79]. This section discusses the key features of CQDs useful in biomedical and packaging applications.

4.1. Physical and structural properties of CQDs

CQDs typically have sizes ranging from a few to tens of nanometers and can form in various shapes, such as irregular, spherical or rod-like structures [80]. The specific shape of CQDs is influenced by the synthesis conditions and the precursor materials used [80]. The structure of CQDs can be determined using a mixture of analytical techniques such as X-ray diffraction (XRD), scanning electron Microscopy (SEM), Raman spectroscopy, transmission electron microscopy (TEM) or high resolution HRTEM [81]. The surface of CQDs has been covered with many inherent functionalized groups such as hydroxyl (-OH), carboxyl (-COOH), and amino ($-NH_2$). These terminal functional groups facilitate chain formation or intermolecular cross-linking during chemical reactions. The hydrophilic character of these functional groups contribute to improved water solubility, enhanced adsorption properties and chemical reactivity, and enable them to conjugate with various polymeric, biological, and organic materials [82,83]. Zhu et al., and Yadav et al., demonstrated that the stability and shelf life of CQDs can be enhanced by introducing steric hindrance and electrostatic repulsion between particles [84,85]. CQDs have shown the remarkable capacity to absorb photons (i.e., electromagnetic radiation), which excited electrons to a higher energy level. This excitation leads to the emission of intense

Table 1
Selected Green Synthesis methods of CQDs using renewable carbon sources.

Method	Carbon Source	Advantages	Outcomes	Reference
Hydrothermal	Sugarcane molasses	Antioxidant proper photoluminescence	Yellow fluorescence emission, Fe^{3+} ion detection	[65]
Hydrothermal	Waste tea	Scavenging ability against radicals	Blue fluorescence, CrO_4^{2-} and Fe^{3+} ion detection	[66]
Hydrothermal	Pomegranate peel	Eco-friendly, controlled size	Luminescence (fluorescence) quantum yield: 7.02 %, selective sensing of Fe^{3+} ions	[67]
Solvothermal	Mango peel	Controlled morphology, low cost	Red fluorescence, Mesotron detection (limit: 4.7 nmol/L)	[68]
Hydrothermal	Corn stalk shell	Fluorescence properties	Detecting Alizarin red s (detection limit: 2.65 μM)	[69]
Hydrothermal	Watermelon juice	Luminescent, fluorescence	Detection of Pb^{2+} ions (detection limit: 190 pM)	[70]
Microwave-assisted	Orange peels	Bright green fluorescence	*E. coli* detection in milk (detection limit: 487 CFU/ml)	[71]
Microwave-assisted	Vaccinium extract	Rapid synthesis, high yield	Stable blue fluorescence, high thermal stability	[69]
Pyrolysis	Fennel seeds	Solvent-free, Scalable	Monodispersed CQDs, excitation-independent emission	[38]
Pyrolysis	Waste shrimp shell	Renewable, antibacterial activity	Luminescence (fluorescence) quantum yield: 27.14 %, biocompatibility, detection of Gram-positive bacteria	[63]
Microwave-assisted	Crab shell	Cytotoxicity (against HeLa cells), UV barrier (280 and 370 nm)	Fluorescence imaging (targeting to folate receptor-positive HeLa cells)	[72]
Ultrasonic assisted	L-glutamic acid	Biocompatible, nitrogen doping possible	Luminescence (fluorescence) quantum yield: 40.5 %, strong resistance to photobleaching	[73]

fluorescence. Notably, the fluorescence emission of CQDs can be precisely controlled and amplified by adjusting factors including dimensions, heteroatom incorporation, solvent polarity, surface oxidation state, pH, surface functional groups, and synthesis methods and excitation wavelengths [86,87].

4.2. Antimicrobial activity of CQDs

The antibacterial activities of CQDs has made them suitable for use in packaging and biomedical fields to prevent the development of foodborne pathogens and bacterial infections. Several mechanisms have been proposed to elucidate the antibacterial activities of CQDs, such as the generation of reactive oxygen species (ROS), disruption of the cell membrane, leakage of cytoplasmic content, and DNA damage. The effectiveness of CQDs in destroying microorganisms is greatly influenced by factors such as size, shape, surface charge, and specific chemical groups present on the surface. Different studies have demonstrated a substantial correlation between surface charge and functional groups and their antibacterial efficacy [88]. CQDs have shown antibacterial properties against several bacteria including *Staphylococcus aureus, Pseudomonas aeruginosa*, and *Escherichia coli*. Fig. 4a shows the antimicrobial mechanism of CQDs against *E. coli*. Additionally, CQDs have been used for imaging these microorganisms. For the visualization of microorganisms enable the determination of their gram type, survival rates, and biofilm structures [89,90].

The antimicrobial activity of CQDs have shown great potential for medical applications. Thus, adopting CQDs in medical therapy can reduce the risk of wound infections, promote faster healing, and prevent wound complications. Additionally, CQDs can be used as carriers in drug delivery systems to directly target bacterial infections with their antimicrobial capabilities. It can be reasonably expected that the antimicrobial activities of CQDs provide significant benefits to food packaging by preventing the growth of bacteria, molds, and other microorganisms on food surfaces, thus extending the shelf life of perishable items. Additionally, CQDs can be used in active and smart packaging systems that respond to specific triggers, alerting consumers or retailers to potential spoilage or contamination before the food is consumed [27,91,92].

In this regard, Kousheh et al., (2020) investigated the antibacterial activity of the bacterial nanocellulose film containing carbon dots (CDs) synthesized from cell-free supernatant of lactic acid bacteria (*L. acidophilus*). The bacterial nanocellulose films were immersed into varying concentrations of CDs solution (1–500 mg/cm^2) and held for 24 h to produce films with CDs loading capacity ranging between 0.76 and 72 mg/cm^2. Results showed the antimicrobial activity of CD-loaded films against *Listeria monocytogenes* and *E. coli* when CDs were loaded at a concentration of 72 mg/cm^2, while no significant activity was recorded at CDs concentrations of 50 mg/cm^2 or below [93]. Similarly, Riahi et al., (2022) synthesized chitosan derived CQDs. The CQDs exhibited substantial antioxidant activity and robust antibacterial activity against *E. coli* and *Listeria monocytogenes*, and antifungal activity against *Aspergillus niger* and *Pencillium chrysogenum.* Coating of the lemon with carboxymethyl cellulose containing CQDs resulted in prolonging the shelf-life for more than 21 days [94]. In another study, CDs derived from kelp/chitosan coating solution containing various concentrations of kelp-derived CDs (0, 1.5, 3 and 4.5 %) was used as an antibacterial coating for fresh-cut cucumber in modified-atmosphere packaging (MAP) system [95,96]. The CDs/chitosan coatings exhibited a dose-dependent increase in inhibition zone diameters against *S. aureus* and *E. coli*. Furthermore, these coatings effectively inhibited the growth of total bacteria, mold, and yeast in MAP fresh-cut cucumbers, resulting in improved storage quality and a significant extension of their shelf life [95]. Doping various elements into the structure of CQDs has been shown to boost their antibacterial activity. Based on this fact, modifying the structure of glucose-derived CQDs by doping boron, sulfur, and nitrogen atoms has resulted in improved antimicrobial activity. Among them, nitrogen-doped (N-doped) CQDs exhibited a significant increase in antimicrobial activity compared to pristine CQDs against a range of bacteria, fungi, and yeasts, including *E. coli* and *Candida. albicans* (Fig. 4b). The enhancement in antimicrobial activity could be attributed to stronger interactions between doped CQDs and microbial cells, resulting in increased production of reactive oxygen species (ROS) that damage the microbial cells. This antimicrobial effect can be visualized using SEM (Fig. 4c) [27].

Similarly, Ezati et al., (2022) investigated the potential of N-doped CQDs derived from glucose to enhance the functionality of cellulose nanofiber coatings for extending the shelf life of fruits. The coating applied on tangerines and strawberries significantly reduced mold growth at room temperature. In addition, the coating exhibited significant antibacterial efficacy against L. *monocytogenes*, *E. coli*, and *Aspergillus flavus,* effectively preventing fungal growth on the surface of coated tangerines and extending their preservation for 15 days (Fig. 5a). CQDs' ability to generate ROS was suggested as a key antimicrobial mechanism for extending the shelf life of fruits (Fig. 5b) [78].

Photodynamic inactivation technology has also been used to enhance the antibacterial activity of CQDs. In this context, Wen et al., (2023) developed a chitosan composite incorporating CQDs derived from turmeric plants (Fig. 6a). The composite film generated a

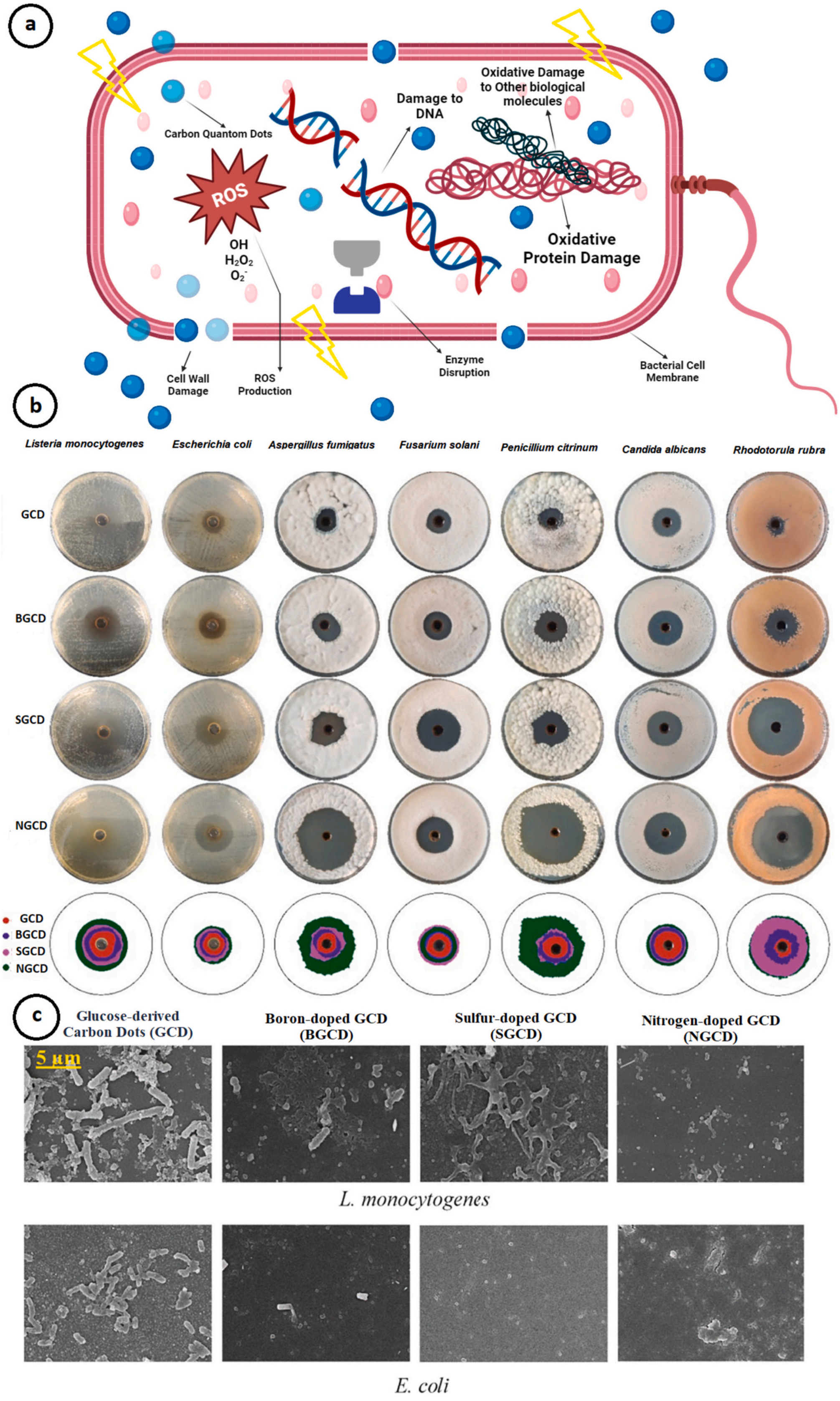

Fig. 4. a) The proposed antimicrobial mechanism of CQDs against *Escherichia coli*, b) disk diffusion assay findings of glucose-derived carbon dots (GCDs) against pathogenic organisms, including bacteria (*Listeria monocytogenes* and *Escherichia coli*), mold (*A. fumigatus, F. solani, and P. citrinum*), and yeast (*C. albicans and R. rubra*), c) scanning electron microscopy (SEM) images of L. *monocytogenes* (top) and *E. coli* (bottom) treated with GCDs with different doping elements. Reproduced from [27] with permission from Elsevier, copyright 2024.

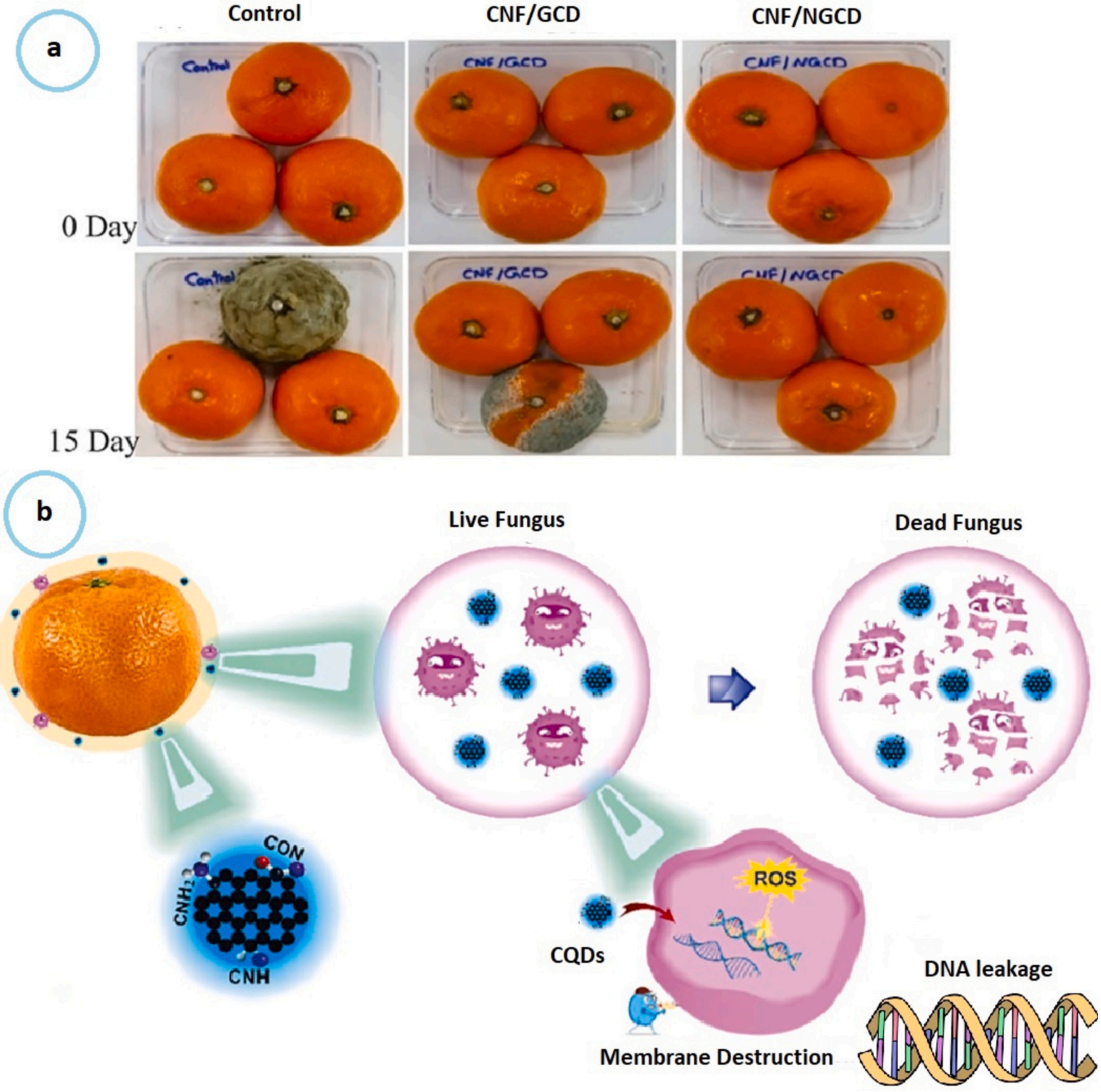

Fig. 5. a) Changes in the visual appearance of tangerines during storage at 25 °C after being coated with CQD and CNF-based films, b) A possible mechanism for the antifungal activity of N-doped CQD coatings on tangerines. Reproduced with permission from [78] Elsevier, copyright 2024.

significant amount of ROS after exposure to a 405 nm light source (Fig. 6b). Moreover, the incorporation of 0.5 % CQDs to the chitosan (CDs-CS2 film) led to a substantial reduction in *Staphylococcus aureus* and *E. coli* populations by approximately 3.19 and 2.05 Log10 CFU/ml, respectively, within 40 min (Fig. 6c). Applying these results to a broader concept, CDs-CS2 films effectively inhibited microbial growth and significantly delayed spoilage in pork during cold storage for a period of 10 days [97].

4.3. Antioxidant activity of CQDs

The antioxidant activity of CQDs, or their capacity to function as free radical scavengers, is another important feature that has only recently been discovered. The use of CQDs with antioxidant activity offers several benefits across various applications. CQDs with antioxidant properties can improve medical therapies by promoting wound healing and preventing the degradation of drugs due to oxidation. In addition, CQDs can neutralize harmful oxidative contaminants in water purification, thereby improving the water quality. The antioxidant properties of CQDs can extend the shelf life of perishable foods by preventing them from oxidation and spoilage [27].

The exceptional antioxidant capabilities of CQDs could stem from their surface hydroxyl groups, which actively participate in neutralizing free radicals. This process likely leads to the formation of more stable products, as observed in ABTS (2,2-azino-*bis*-3-ethylbenzothiazoline-6-sulphonic acid) and DPPH (2,2-Diphenyl-1-picrylhydrazyl) assays [98]. The results obtained indicated that the significant increase in antioxidant activity was attributed to the presence of amide groups resulting from nitrogen doping, along with hydroxyl groups and a stable dispersion in the aqueous medium. The generation of reactive oxygen species (ROS) may largely contribute to the antioxidant activity of carbon quantum dots (CQDs). These free radicals can be neutralized and diminished through hydrogen donation, electron transfer, and adduct formation involving peroxynitrite, nitric oxide, hydroxyl, and superoxide anions from the CQDs through both intracellular and extracellular interactions [72,99–101]. In a recent study, composite carrageenan

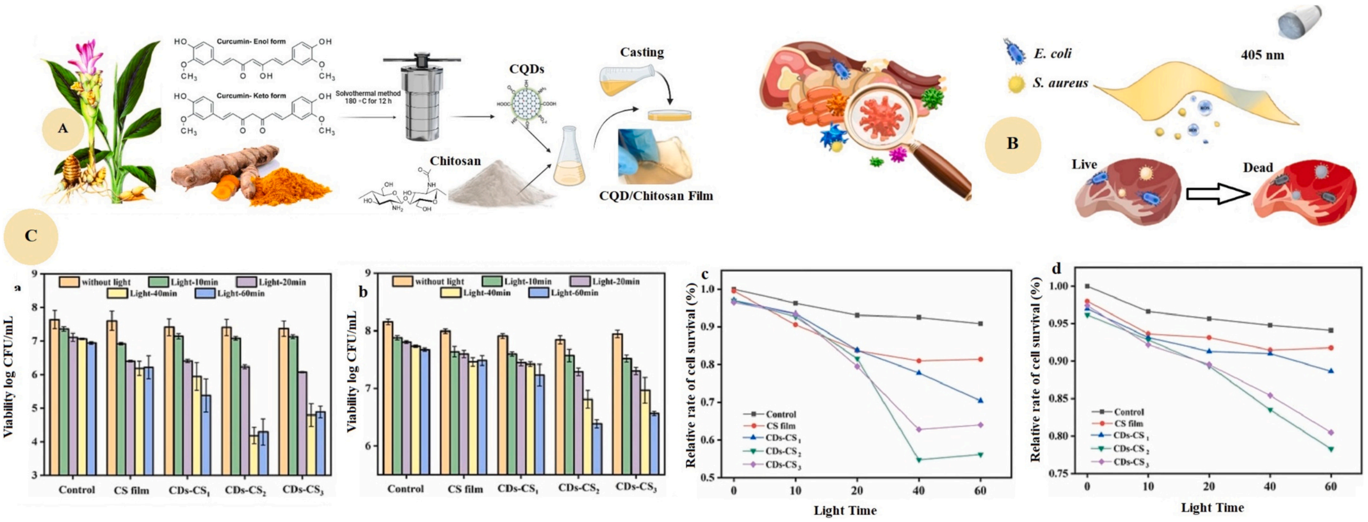

Fig. 6. A) Schematic representation of the composite film structure, B) Proposed mechanism of the composite film's antimicrobial activity for pork preservation, C) Antibacterial activity of the pure CS and CDs-CS composite films against (a) *S. aureus* and (b) *E. coli*. Curves of bacterial inhibition effect of composite film on (c) *S. aureus* and (d) *E. coli* under different light time Reproduced from [97]with permission from Elsevier, copyright 2024.

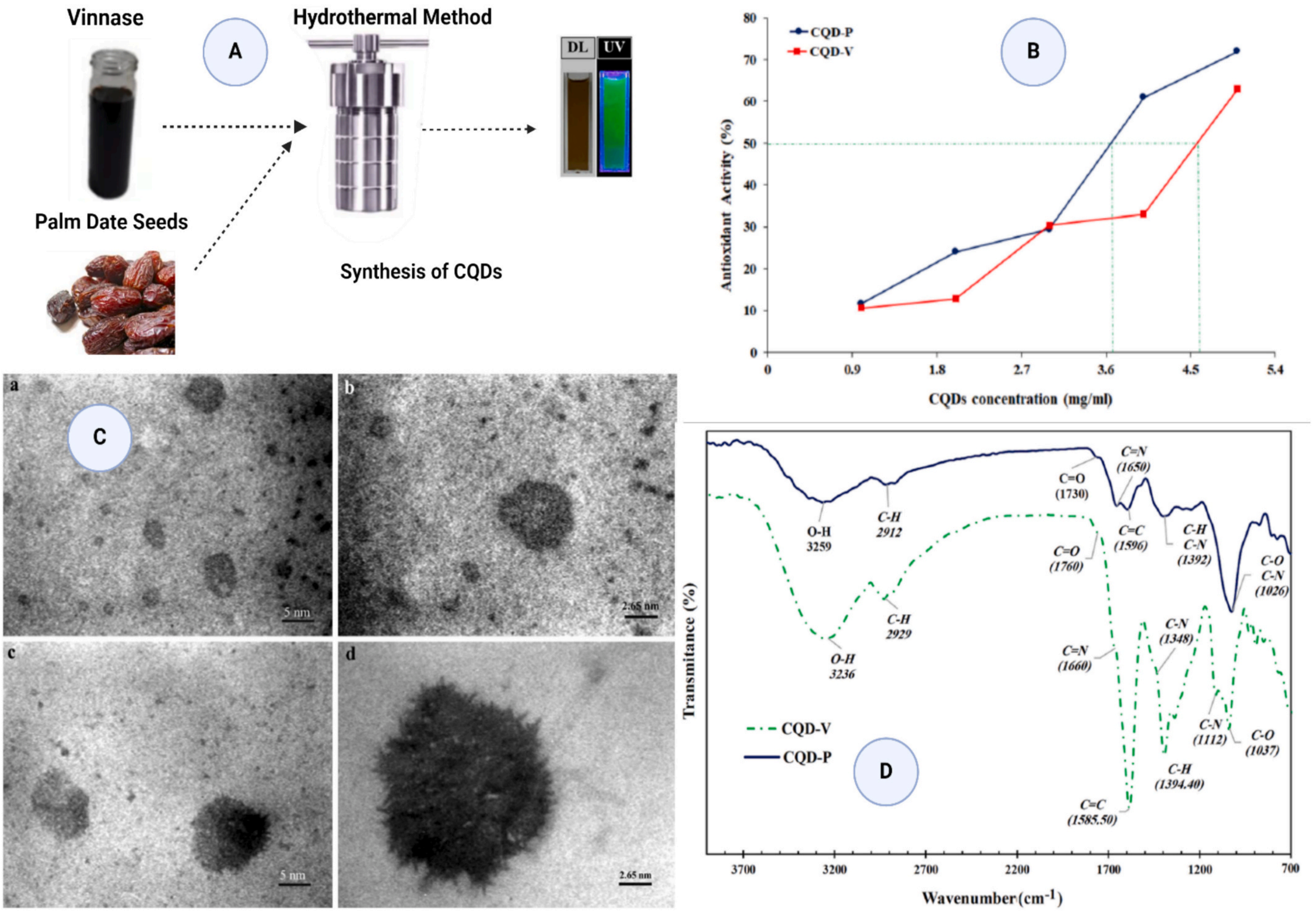

Fig. 7. Characterization of CQDs derived from vinasse and date seeds as agricultural by-products; A) synthesis of CGDs; B) DPPH scavenging antioxidant activity of CQDs; C) Transmission Electron Microscopy (TEM) images are presented at two magnifications for CQDs derived from both date seeds (a, b) and vinasse (c, d), revealing their size and morphology, D) Fourier-Transform Infrared Spectroscopy (FT-IR) results of the CQDs. Reproduced from [106] with permission from Elsevier, copyright 2024.

films with antioxidant and pH-dependent properties were developed by integrating anthocyanin from sweet potato peel (SPA) and TiO2-doped carbon dots (Ti-CDs). The Car/SPA/Ti-CD3% film effectively neutralized ABTS and DPPH radicals. Anthocyanin's phenolic hydroxyl groups, rich in electrons, play a key role in donating electrons and hydrogen atoms to reactive free radicals, neutralizing them [102]. The enhanced antioxidant efficiency of the films is linked to hydroxyl-rich functional groups on Ti-CD surfaces, which readily supply hydrogen to react with fatty acid-free radicals, stabilizing them and disrupting radical chain reactions. These films serve as effective antioxidant packaging materials, scavenging free radicals and delaying lipid oxidation in food [103]. In a study by Min et al., CDs were synthesized hydrothermally using potato peel as a source material. These CDs exhibited potent antioxidant and antimicrobial properties. When incorporated as fillers into gelatin-based films, the CDs were evenly distributed, demonstrating good compatibility within the biopolymer matrix. The antioxidant activity of the films was assessed using both ABTS and DPPH assays. Notably, ABTS yielded higher activity compared to DPPH, likely due to the hydrophilic nature of the CDs and the presence of surface hydroxyl groups. The addition of 2 % and 4 % CDs significantly enhanced the free radical scavenging capacity of the gelatin films, reaching 99.2 % and 99.6 % in ABTS and 72.8 % and 93.6 % in DPPH, respectively. This improved antioxidant performance can be attributed to the presence of free radical scavenging functional groups on the CD surface [104]. Green tea was utilized as a precursor for the green synthesis of CQDs nanoparticles, with curcumin incorporated to form CQDs/Cur nanocomposites. The CQDs/Cur exhibited superior antioxidant activity compared to free curcumin and CQDs, with efficacy increasing alongside CQDs concentration. Within the experimental concentration range, the ABTS radical scavenging rate of CQDs/Cur improved significantly, rising from 21.3 % to 79.3 %. These findings highlight the synergistic potential of combining curcumin with green tea-derived CQDs to enhance free radical scavenging capabilities [105]. Similarly, the antioxidant capacity of CQDs synthesized from vinasse (CQD-V) which is the byproduct of bioethanol processing from date seeds (CQD-P) was investigated. Both CQD-P and CQD-V showed higher antioxidant capacity (Fig. 7a). However, DPPH scavenging assays showed slightly higher antioxidant activity for CQD-V ($IC_{50} = 4.5$ mg/ml) than CQD-P ($IC_{50} = 3.6$ mg/ml) [106] (Fig. 7b). Transmission Electron Microscopy (TEM) images are presented at two magnifications for CQDs derived from both date seeds and vinasse revealed their small size and morphology (Fig. 7c). Fig. 7d shows the Fourier-Transform Infrared Spectroscopy (FT-IR) results for the CQDs synthesized from both precursors. The FT-IR spectra confirm the successful synthesis of CQDs with uniform spherical shapes and the incorporation N and P-doped CQDs. The FT-IR spectra revealed characteristic peaks associated with O-H, C=O, and C-O groups, confirming oxygen incorporation and enhanced water solubility. Additionally, the presence of C-H, C=C, C=N, and C-N peaks indicate the formation of polyaromatic structures and nitrogen doping.

In another study, Ezati et al., (2022) utilized CQDs derived from glucose in a chitosan/gelatin matrix to create an antifungal coating film for avocados. The CQDs showed significant antioxidant activity within minutes in both ABTS and DPPH assays. UV–vis spectra of the solutions with added CQDs showed a notable decrease in absorbance as the CQD concentration increased compared to the control solution. The characteristic absorption bands of ABTS at 734 nm and DPPH at 517 nm gradually diminished with rising CQD concentrations. At CDs with concentrations of 50 and 100 μg/ml, the antioxidant activity measured using ABTS and DPPH assays was approximately 95 % [107]. A composite film of enoki mushroom-derived carbon dots (mCDs), gelatin, and carrageenan showed enhanced free radical release and superior antioxidant activity compared to gelatin or carrageenan films alone, as measured by DPPH and ABTS assays. At 75 μg/ml, mCDs achieved 27 % and 50.3 % antioxidant activity against ABTS and DPPH radicals, respectively, with higher concentrations further improving this effect. Incorporating 1 wt% mCDs into the gelatin/carrageenan film significantly increased ABTS scavenging activity to ~65 % and DPPH scavenging to ~15 %, compared to ~5 % and ~ 7 % for the pure film [108]. Rajamanikandan et al., (2022) produced CQDs through a simple hydrothermal method using agricultural waste from *Ananas comosus*. The antioxidant potential of the CQDs was investigated through various assays and following results were yielded: DPPH radical scavenging (23.3 % at the concentration of 5 mg/ml), superoxide anion radical scavenging (40 % at the concentration of 5 mg/ml), hydroxyl radical scavenging (50.2 % at the concentration of 5 mg/ml), and hydrogen peroxide radical scavenging (93.4 % at the concentration of 5 mg/ml). These findings highlighted the potential of agricultural waste as a source for both optical switching devices and valuable medicinal properties, as demonstrated by the successful extraction of therapeutic compounds [109]. Moreover, different studies have demonstrated the broad-spectrum antioxidant capabilities of CQDs derived from coconut husk, selenium-doped CQDs, and graphene CDs [110–112]. Li et al., (2019) synthesized CQDs through a Maillard reaction between glucose and lysine during the roasting of mackerel and investigated their antioxidant properties. Their findings showed that the CQDs effectively scavenged both methyl and hydroxyl radicals produced from methylene blue (MB)/visible-light photosensitization system. A 90 % decline in the hydroxyl radical signal was observed when the mackerel CQDs were applied under the concentration of 15 mg/ml. In addition, the reaction rate constant decreased by 41.4 %, demonstrating a significant drop in MB degradation rate due to the methyl radical scavenging capability of the CQDs [113]. Wang et al. conducted a research on CQDs extracted from baked lamb, highlighting their potential in eliminating free radicals and protection against oxidative damage in vitro [114]. Overall, these studies demonstrated that CQDs can enhance the safety, efficacy, and longevity of products due to their antioxidant properties.

5. Emerging applications of green-engineered CQDs in sustainable food packaging

The use of CQDs in food packaging has the potential to revolutionize the industry by providing innovative solutions for extending shelf life, reducing food waste, and ensuring food safety. Fig. 8 shows the potential uses of CQDs in active and intelligent packaging applications. An important role of CQDs in food packaging their ability to enhance the barrier properties of packaging materials, thereby preventing oxygen and moisture from reaching the food products [27]. This enhancement is attributed to the unique structural and optical properties of CQDs. The UV-light blocking ability and photostability of CQDs, arising from their surface functional groups and conjugated structures, reduce the degradation of the packaging material when exposed to light. These properties are linked to electron transitions, specifically ππ* or nπ*, as well as excited-state intramolecular proton transfer via O-H-O and O-H-N configurations, and extensive conjugated structures. Furthermore, the dense and uniform dispersion of CQDs within the polymer matrix minimizes the permeation pathways for oxygen and moisture by increasing the tortuosity of the diffusion path. The interaction of CQDs with the polymer network, facilitated by their functional groups and dopants, strengthens the matrix, further improving its barrier properties.

It can also provide antimicrobial and antioxidant properties to packaging materials, ensuring the safety and quality of the food products [115–117]. In this regard, the chitosan solution containing CQDs derived from seaweed was utilized as an antibacterial coating on freshly sliced cucumbers. The inhibition zones against *S. aureus* and *E. coli* increased from 9.10 mm to 13.01 mm and from 9.32 mm to 12.77 mm respectively with 4.5 % CQD concentrations. Furthermore, the inhibition zone diameter of the CQDs and chitosan coating with 4.5 % CQDs concentration against *S. aureus* was larger than that against *E. coli,* which shows that the Gram-positive bacterium *S. aureus* was more sensitive to the coating than the Gram-negative bacterium *E. coli* was [95]. The UV-blocking properties of CQDs is another interesting property that contributes to the prevention of the oxidation and degradation of nutrients

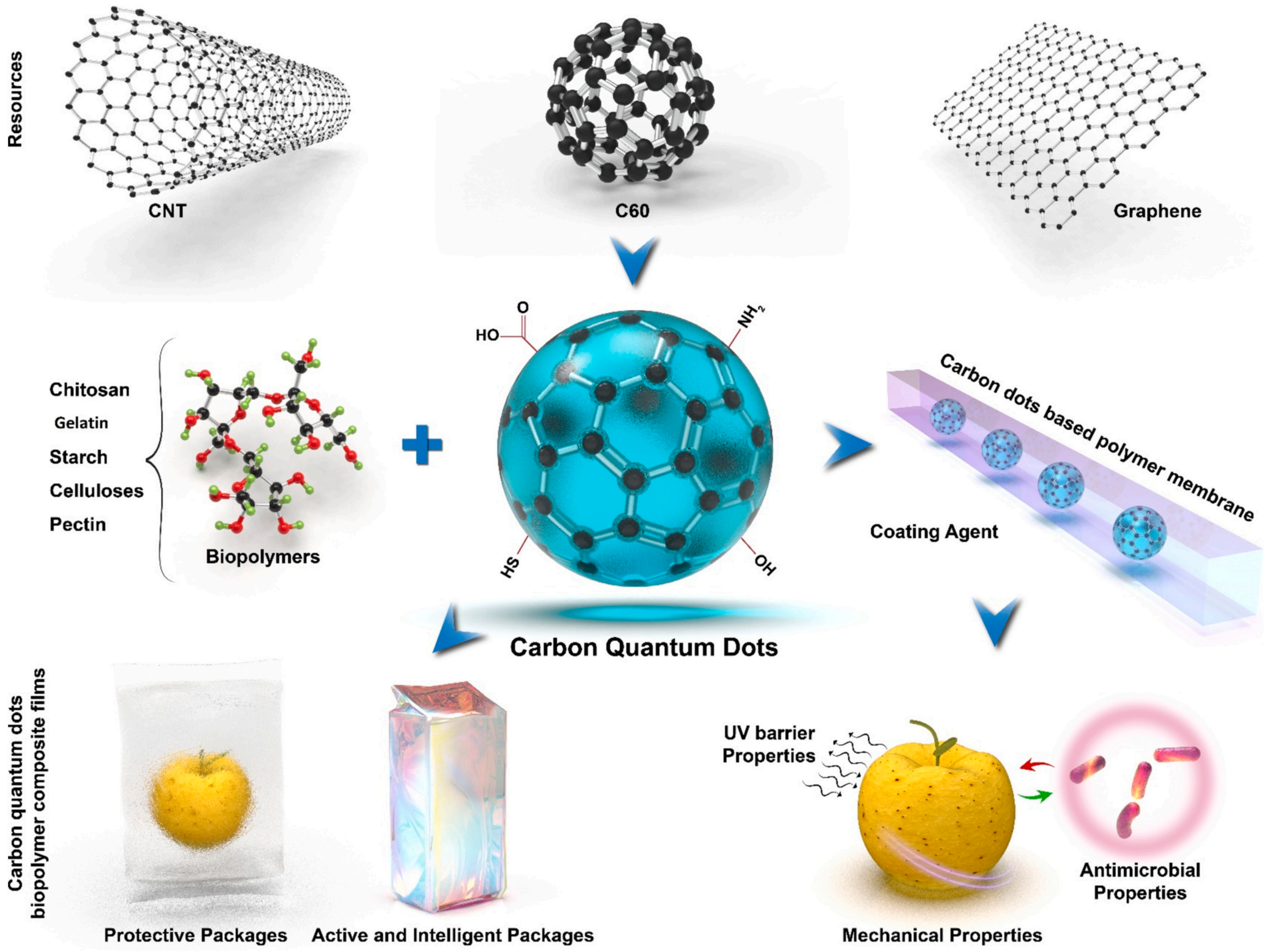

Fig. 8. The potential uses of CQDs derived from either synthetic (CNT, C60 and graphene) or renewable (chitosan, gelatin, starch, cellulose and pectin) as coating agents, active agents, and intelligent agents for food packaging applications.

in food. Furthermore, CQD can also be utilized as a sensor to detect food spoilage and contamination, ensuring the safety and quality of food products. Moreover, CQD enables intelligent packaging that monitors temperature and freshness, and provides traceability information, enhancing consumer experience [118,119]. Additionally, CQD can contribute to promote circular economy by reducing the food waste [97]. The development and implementation of CQD in food packaging requires extensive research and development to maximize both the performance and cost-effectiveness of the technology [120]. It is also essential to address regulatory and certification processes to meet industry standards and requirements [82]. Toxicity is a significant factor in determining the capacity-environmental impact of CQDs processes poses a significant challenge in integrating CQDs into current packaging systems. The potential toxicity of CQDs necessitates a careful examination of their release from packaging materials [121,122]. Numerous factors affect the release of active substances from films or active packaging into food simulants. These factors include the nature of the food additives, the compatibility of the active material with the film, the solubility of the film, and the amount or concentration of the substance. For example, the amount of carbon dots derived from mushrooms and the food additives had an impact on their release speed from a gelatin/carrageenan-based polymer matrix. As the concentration of carbon dots increased from 1.0 % to 6.0 %, the release rates of enoki mushroom-derived carbon dots in all simulants improved with the higher concentration. The release rates of carbon dots sourced from enoki mushrooms were found to be lower in 95.1 % and 50.2 % ethanol compared to 10.0 % ethanol and water. Carbon dots are small nanoparticles, which may raise concerns for certain consumers [108].

CQDs have also shown significant potential in enhancing the mechanical properties of packaging films. For instance, the addition of 2 wt % of CQDs into gelatine film improved the tensile strength from 60.7 to 65.3 MPa due to the synergistic interaction between gelatin and CQD through hydrogen bonding and interfacial interaction [104]. A recent study demonstrated that enoki-mushroom-derived CQDs significantly enhanced the mechanical and functional properties of gelatin/carrageenan films. The tensile strength of the films increased from ~52.8 MPa (for pure gelatin/carrageenan) to ~81.2 MPa with the addition of 5 wt% CQDs. Additionally, the incorporation of CQDs imparted dose-dependent antioxidant properties, with 75 μg/ml of CQDs providing ~27 % and 50.3 % antioxidant activity against ABTS and DPPH free radicals, respectively. CQDs also improved the films' UV blocking properties exponentially without compromising transparency. While the pristine films showed high transparency to visible light, the addition of CQDs significantly reduced UV light transmittance as CQD concentration increased. Despite these improvements, the water vapor permeability and hydrophobicity of the films remained largely unaffected, highlighting the multifunctional benefits of CQDs as additives [108]. Incorporating tea residue-derived CQDs into polyvinyl alcohol (PVA) films enhanced their UV blocking capabilities with minimal impact on mechanical properties. Pristine PVA films demonstrated higher stress-strain parameters, including load at break (4929.12 gf), extension (63.44 mm), tensile strain (249.78 %), and tensile stress (194.06 kg cm − 2). The addition of CQDs caused slight, nonsignificant changes to these properties, suggesting the CQD-PVA films remain suitable for diverse applications [123].

Various polymers such as cellulose [94], pectin [124], PVA [125,126], gelatin [104], carrageenan [127], nanocellulose [128] and zein [100,129] have been utilized to prepare composite films as networks for CQD addition. The effect of CQDs on various properties of biopolymers in the development of active and intelligent food packaging is summarized in Table 2. The interaction of CQDs with different biopolymers is discussed in the following section.

5.1. Interaction of CQDs with chitosan biopolymer

Chitosan is a biopolymer obtained from chitin via deacetylation, consisting of amino glucose and *N*-acetylaminoglucose molecules that are interconnected by glycosidic bonds [136]. Chitosan has been ranked as the second most abundant polysaccharide after cellulose and has garnered significant importance due to its distinct functional and biological characteristics, widespread availability, non-toxicity, biocompatibility, biodegradability, and cost-effectiveness. It is primarily sourced from a variety of origins, such as marine waste, fungi, insects, and agricultural byproducts. While marine waste is commonly considered as a typical source for chitosan, its usage is declining due to factors such as seasonal availability and the release of harmful effluents. Consequently, there is a growing need for alternative sources to create sustainable and economically viable chitosan production methods [137,138]. Chitosan-based photodynamic bactericidal food packaging films incorporating turmeric-derived fluorescent CQDs were developed. At 0.5 wt% CQD concentration, the tensile strength increased from 31 to 38 MPa, with a similar improvement in elongation at break. Increasing CQD content to 1 wt% enhanced UV-blocking capability by reducing light transmission in the UV region. The composite films also exhibited reduced water solubility, reaching a minimum of 7.72 %, likely due to hydrogen bonding between CQDs' phenolic hydroxyl groups and chitosan's amino groups. Under 405 nm light, the films generated significant ROS, reducing *S. aureus* and *E. coli* colonies by 3.19 and 2.05 Log10 CFU/ml within 40 min [97].

Another study developed a packaging film to preserve minced pork for a longer period by incorporating CQDs produced from green tea into a network combined chitosan and gelatin polymers [139]. The chitosan/gelatin films supplemented with GQDs exhibited potent antioxidant properties (99.2 % for ABTS and 63.87 % for DPPH) and robust antibacterial activity against both *E. coli* and L. *monocytogenes*, and UV-barrier properties, especially for extending shelf life and preserving meat's visual quality during storage at 20 °C for 48 h [139].

5.2. Interaction of CQDs with gelatin biopolymer

Gelatin, a biopolymer derived from collagen, is composed of glycine, proline, 4-hydroxyproline, and forms a triple helix structure. This

Table 2
The utilization of CQDs in the development of active and intelligent food packaging systems and their impact on the composite structure.

Type of biopolymer	Source of CQD	Percentage of added CQDs	Food Packaging Application	Characteristics	References
Carrageenan	Sweet potato peel	3 wt%	Intelligent packaging for detecting spoilage of shrimp	The film has great UV protection effects (285 nm), antioxidant (81.1 ± 0.8 % and 100 % in DPPH and ABTS), and antibacterial activities (*L. monocytogenes* and *E. coli*) and intelligent sensing capacity.	[103]
Poly vinyl alcohol (PVA)	Lemon peel	3 wt%	–	The developed lemon peel CQDs exhibit excellent fluorescence, antioxidant (98.9 %), and antibacterial activities (against *S. aureus, B.* cereus, *S. enterica, L. monocytogenes,* and *E. coli*), improved UVC (99.9 %), UVB (99.9 %) and UVA (99.1 %) blocking effects.	[130]
Chitosan	Nitrogen-doped CQDs	7 wt%	The composite film for extending shelf life of pork and blueberries	Compared with the chitosan film, the chitosan/nitrogen-CDs composite film is strong and flexible, with high photodynamic antibacterial rates of 91.2 % and 99.9 % for *E. coli* and *S. aureus* and greatly extend the shelf life of food products.	[131]
Gelatin/ Persian gum	Grape leaves	30 %*w/w*	Nanocomposites film for coating the trout fillet	Adding CQDs to the films reduced UV transfer rates (from 80.1 % to 19 %) but increased the antioxidant activity (94.08 %), showed antibacterial activity against *E. coli* and *S. aureus,* nanocomposite film showed no cell toxicity.	[132]
Chitosan/Gelatin	Banana peel	3 wt%	Active packaging for extending the shelf life of minced meat	The composite film exhibited a marginal reduction in transparency but significant enhancement in its UV protection capabilities (to 0.07 % in 280 nm), potent antibacterial activity against foodborne pathogens (*L. monocytogenes*), antioxidant activity (74 % DPPH and 99 % ABTS)	[133]
Gelatin	Potato peels	4 wt%	–	The gelatin/CDs coating has UV-barrier (310 nm), antioxidant (99.6 % in the ABTS and 93.6 % in DPPH), low cytotoxicity, and antibacterial characteristics (agains L. *monocytogenes)*.	[104]
Carboxymethyl cellulose	Chitosan	5 wt%	Active packaging for preserving lemon	The CQD has high antioxidant, antibacterial, and antifungal performance (against *E. coli, Penicillium chrysogenum, L. monocytogenes,* and *Aspergillus niger*) and increased CMC film tensile strength (by up to 27.6 %) and elongation modules (by up to 61.5 %).	[94]
Pectin/gelatin	Turmeric	20 %	Bio-nanocomposite film for extending the shelf-life of fish	This film exhibited potent antioxidant (77.31 % ABTS and 53.96 DPPH) and antimicrobial properties (total bacteriological counts of fish meat) while enhancing its UV-blocking performance without compromising its transparency.	[134]
Cellulose	Glucose	8 %	Edible coating extended the shelf-life of tangerines and strawberries	The material demonstrated antibacterial property, antioxidant activity (99–99 % of ABTS and 80–85 % of DPPH) increased water-contact angle and UV-blocking (365 nm) without compromising transparency.	[78]
Chitosan	Silk sericin	20 %	Bio-nanocomposite film for preserving litchi fruit	The bio-nanocomposite demonstrates effective UV radiation shielding (200–315 nm), enhanced flexibility, superior antibacterial properties (against *E. coli* and *S. aureus*), excellent biocompatibility as well as, notable antioxidant characteristics (78 % of ABTS and 67 % of DPPH).	[135]
PVA	Tea residue	3 mg/ml	Composite film for grape packaging	The film absorbed UV light and remission in the visible region (230–315 nm).	[123]

unique structure makes gelatin an ideal dispersion medium for nano biological materials as metal and chalcogen particles can easily integrate within its atomic chains [140,141]. Recently Bakeshlouy Afshar et al., (2024) revealed that the addition of CQDs to starch and gelatin networks not only improved the barrier properties and mechanical quality of the packaging, but also created an additional protective layer against microbial contamination [142]. Min et al. (2022) found that incorporating a low concentration of CQDs (2 wt%) into gelatin films enhanced their mechanical strength. The resulting gelatin film exhibited a tensile strength of 60.7 MPa, surpassing that of carbohydrate-based films such as chitosan, carrageenan, and agar [104]. This enhancement is attributed to strong interactions within the gelatin/CQD matrix, facilitated by improved hydrogen bonding even at low CQD concentrations. Incorporating CQDs at 2.0 % and 4.0 % significantly boosted the film's ABTS radical scavenging ability to 99.0 % and 99.6 %, respectively.

The addition of CQDs and sulfur-doped CQDs to the pectin/gelatin film (Fig. 9a) reduced its transparency from 89.5 % to 61.1 % (Fig. 9b). However, it significantly improved its ability to block UV radiation. The CQD-added composite film effectively blocked UVB rays (280–320 nm) and significantly reduced UVA exposure (320–400 nm), making it well-suited for packaging materials that require UV protection. Furthermore, the inclusion of CQD and sulfur-doped CQD in the pectin/gelatin film boosted its free radical scavenging ability to 96.6 % and 90.1 % in the ABTS assay, and to 79.5 % and 75.6 % in the DPPH assay (Fig. 9c). Interestingly, the film with sulfur-functionalized CQD also demonstrated strong antimicrobial activity against food-borne pathogens such as L. *monocytogenes* (Fig. 9d) and *E. coli* (Fig. 9e) [143].

5.3. Interaction of CQDs with starch biopolymer

Starch is a commonly used polymer for the development of environmentally friendly food packaging products due to its functional attributes, including high biodegradability, low price, accessibility, safety, and simplicity to use [144,145]. In addition, starch is non-allergenic

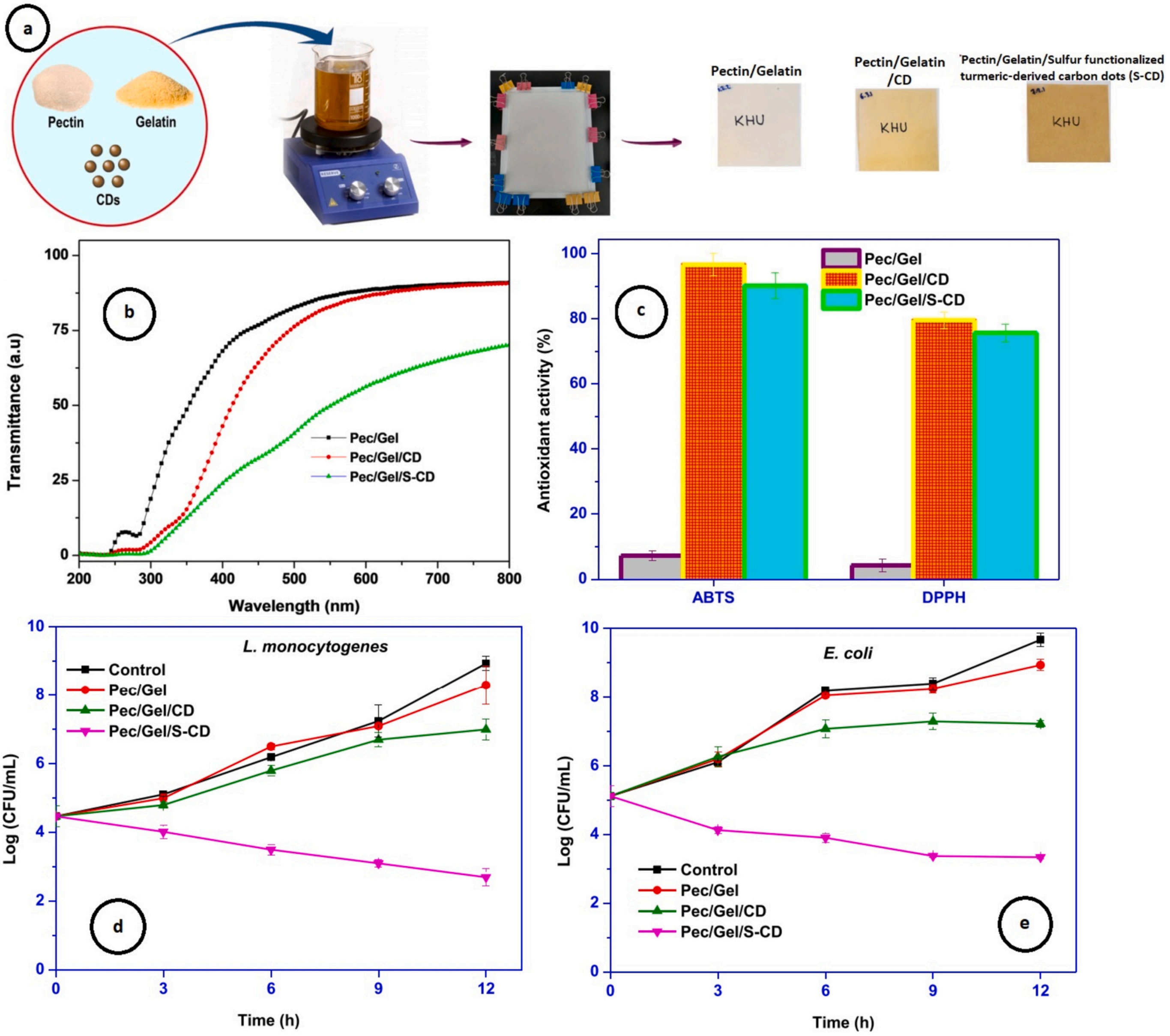

Fig. 9. a) Schematic representation for the preparation of carbon dot incorporated pectin/gelatin-based film, b) light transmittance spectra of the pectin/gelatin-based films, c) antioxidant activity of the pectin/gelatin-based films determined by ABTS and DPPH methods, d) Antibacterial activity of the pectin/gelatin-based films against L. *monocytogenes* and e) *E. coli.* Reproduced from [143] with permission from Elsevier, copyright 2024.

because of its mechanical properties and resistance to gas entry which is useful for various aspects of the food industry [146,147]. To address the drawbacks of starch films, several key solutions are suggested. These include using plasticizers and creating thermoplastic starch, chemically modifying starch, utilizing engineered polymers with starch, incorporating nanofiller compounds, and producing nanocomposites [148,149]. Starch biopolymers containing CQDs exhibited promising capabilities in active food packaging systems [150]. In this regard, a bilayer 3D-printed film composed of a gelatin-PVA/CQD layer and a corn starch-PVA-cinnamon essential oil layer was fabricated with the aim of providing both an external barrier and internal controlled-release capabilities for preserving food.

An innovative film was produced through the inclusion of banana peel-based CQDs in different layers of films to enable potent antioxidant and UV blocking properties, thereby maximizing the preservation of the microcapsules' sensory qualities. Furthermore, it effectively prolonged the mangoes' durability to 28 days by inhibiting the development of browning and decay [151]. In another study, researchers developed intelligent starch-based biopolymer films capable of pH monitoring. This was achieved by incorporating CQDs and an anthocyanin extracted from *Clitoria ternatea* flower (CTE) into the film to give responsiveness in the pH changes of pork. The produced films exhibited outstanding mechanical strength(tensile strength: 9.8 MPa), thermal stability (residual mass: 10.7 %) and improved antioxidant properties (from 7 % to 72 %) due to synergistic interaction between CQD and CTE [152]. Polyethylenimine-modified CQDs were conjugated with fluorescein isothiocyanate (FITC) in a separate study, resulting in pH-sensitive CQDs capable of measuring the acidity of foods like yogurt and detect the presence of Cu^{2+} ions through fluorescent sensing [153,154].

5.4. Interaction of CQDs with cellulose biopolymer

Cellulose is one of the most available elements when it comes to biodegradable and renewable polymers. Cellulose is derived from diverse sources including crops, wood, cotton, some microorganisms, and agricultural/food waste [155]. Cellulose is recognized as an important renewable resource that can replace some petroleum-based materials due to its exceptional properties, such as non-toxic nature, outstanding mechanical strength, and environmental compatibility and lightweight nature [156,157]. Moreover, cellulose in micro- or nanoscale structures, such as micro-fibrillated cellulose, cellulose nanoparticles, and microcrystalline cellulose, can be incorporated as reinforcements to enhance the mechanical and functional properties of nanocomposite films [158].

CQDs have been shown significant potential to increase the functionality of cellulose-based films [159]. Rezvan and Shekarchizadeh (2024) investigated the development of TEMPO-oxidized nanocellulose containing amine-modified CQDs specifically tailored for UV radiation filtering and active packaging applications. The incorporation of amine-modified CQDs into the oxidized nanocellulose film yielded a significant reduction in water vapor permeability (2.54 to 1.89×10^{-9} g/Pa/s/m^2). Moreover, this composite film also demonstrated an exceptional ability to absorb 99.8 % of UVA rays [160].

Riahi et al. (2022) developed carboxymethyl cellulose (CMC)-based films incorporating chitosan-derived CQDs for active food packaging. The CQDs exhibited strong antioxidant, antibacterial, and antifungal activities against *E. coli*, *L. monocytogenes*, *A. niger*, and *P. chrysogenum*, with low cytotoxicity to L929 cells even at 500 μg/ml. Their addition to CMC films resulted in a transparent, UV-blocking material with a 27.6 % increase in tensile strength and a 61.5 % increase in elongation at break. The films demonstrated high antimicrobial and antioxidant activity and effectively preserved lemons for 21 days without visible infection. These properties make CMC/CQD films promising for extending food shelf life and preventing spoilage [94].

Composite films made from cyanobacteria-derived CQDs, PVA, and nanocellulose demonstrated exceptional water resistance and significantly improved UV/infrared light barrier properties in different research studies. These findings strongly indicated that these composite films hold significant promise for use as flexible packaging materials [128]. Another study found that the tensile strength reduced and the elongation at break increased when CQDs were added to films made from bacterial nanocellulose [93].

6. Emerging biomedical applications of green-engineered CQDs

Effective fluorescence bioimaging of living cells and tissues requires a fluorescent contrast agent that is both safe and compatible with biological systems. While commercially available organic fluorophores offer high emission luminescence (fluorescence) quantum yield, their use is restricted by specific limitations. To overcome the limitations of existing materials, the development of novel fluorescent materials with enhanced optical emission and friendly biological properties is essential for advancing cell bioimaging applications. CQDs offer many compelling advantages, including affordability, abundant availability, excellent photostability, and favorable biological characteristics such as low toxicity, high stability in aqueous environments, and superior biocompatibility. These properties make CQDs highly promising for applications in biosensing, drug delivery, and bioimaging [161,162].

6.1. Bioimaging and diagnostic devices

CQDs have been extensively studied for both in vitro and in vivo bioimaging applications over the past few decades. However, CQDs exhibit temperature dependency, with limitations in their ability to internalize at low temperatures (e.g., 4 °C), restricting their use under low-temperature imaging conditions. Despite these limitations, the potential benefits of CQDs in biological labelling and bioimaging have led to extensive research efforts in this area [163] (Table 3). The matching

Table 3
Biomedical applications and eco-friendly fabrication of CQDs.

Resources of CQD	Synthetic method	Application	Reference
Maple tree leaves	Hydrothermal	Facilitating glycerol electrooxidation and providing probes for cesium detection	[166]
Banana peel	Hydrothermal	Bioimaging agents	[38]
Onion	Thermal	Real-time visualization of cellular processes and enhanced tissue regeneration	[167]
Crab shell powder	Sono-chemical assisted	Bioimaging and drug delivery applications	[72]
Walnut oil	Hydrothermal	Anti-cancer cytotoxicity and pro-apoptotic properties	[37]
Curcumin	Hydrothermal	Bioimaging	[168]
Grounds from coffee	Microwave assisted	Detection of pollutants	[169]
Pulp derived from sugarcane bagasse	Chemical exfoliation	Advancements in bioimaging techniques for visualizing biological processes at cellular and molecular levels, development of next-generation biosensors and drug delivery application	[170]
Milk	Hydrothermal	Bioimaging	[36]
Pollens bee	Hydrothermal	Biomedical imaging and chemical catalysis	[171]
Aloe vera	Hydrothermal	For detecting tartrazine, a food colorant by Fluorescence quenching technique used	[172]
Ginger	Hydrothermal	Suppression of human hepatocellular cancer cells	[173]
Sweet potato	Hydrothermal	Identification of 6-mercaptopurine, a pharmaceutical compound used in cancer treatment	[174]

characteristics of CQDs with many polysaccharides make them highly promising materials for the development of new hydrogels for cancer imaging and therapy. The CQDs have stable luminescence which enables sensitive and reliable detection, while the polysaccharide provides biocompatibility, allowing safe interaction with biological systems. Karakoçak et al., (2020) utilized an hyaluronan (HA)-conjugated N-doped CQDs (HA-N-CQDs) composite to image cancer cells and investigated their practical application in cancer research. The HA-N-CQD conjugate was formed through the carbodiimide coupling which linked amine groups from N-CQDs to the carboxylic groups from HA chains (Fig. 10a). Although the conjugated HA-N-CQDs exhibited ~30 % lower quantum efficiency compared to the original N-CQDs, they still maintained sufficient fluorescence (Fig. 10b). Confocal microscopy revealed that the internalization of HA-N-CQDs was enhanced, which was mediated by CD44 receptors. To test the specificity of HA-N-CQDs for human tumor cells, breast cancer tissue with high CD44 expression was implanted into adult mice. The findings indicated that HA-N-CQDs were suitable for imaging CD44-specific tumors in preclinical human cancer models and may also serve as effective carriers for targeted drug delivery to CD44-rich cells (Fig. 10c).

The effectiveness of human hair-derived CQDs as a bioimaging probe for cell labelling was also investigated [165]. CQDs derived from human hair were further modified with poly-L-lysine to create poly-L-lysine/CQDs (PLLCQDs). The resulting PLLCQDs demonstrated several advantageous properties, including strong fluorescence intensity, excellent photostability, and remarkable water solubility. These PLLCQDs exhibited strong blue emission with a luminescence (fluorescence) quantum yield of 28 %. When exposed to UV light (365 nm), the synthesized PLLCQDs emitted blue fluorescence. Moreover, the cytotoxicity of both the bulk system (hair precursor) and PLLCQDs was assessed using the L929 fibroblast cell lines. The MTT assay revealed a cell viability of 99.47 % for the L929 cells, indicating that PLLCQDs can be effectively used for cell labelling agents. Similarly, the in vivo bioimaging potential of CQDs synthesized from biorefinery byproducts was explored by intravenously injecting a CQD solution into mice bearing Smmc-7721 cancer cells. No fluorescence was observed in vital organs such as the heart, spleen, and lungs. However, strong fluorescence was observed in the tumor region, indicating the accumulation of CQD particles, which highlighted their potential for cell imaging applications [61].

6.2. Biosensors

Green-engineered CQDs can be used as biosensors due to their water solubility, non-toxicity, biocompatibility, ability to emit multiple colors after excitation, cell membrane permeability, resistance to photodegradation, and no cytotoxicity. The CQD-based biosensors enable real-time visual monitoring of glucose, phosphate, nucleic acid, cellular iron, potassium ions, and pH levels [163]. Green CQDs derived from maple leaves were used as a probe for detecting cesium ions using an electron transfer mechanism. Additionally, they acted as a catalyst for the electrooxidation of glycerol [175]. CQDs offer versatility in sensing glycerol due to their modifiable surface chemistry. CQDs can be tailored to react only with certain analytes by attaching specific ligands or receptors to their surfaces. This level of customization enables CQDs to function as adaptable detection tools for a wide range of substances, including environmental pollutants and biomolecules [176]. For example, titanium dioxide has been used to remove organic contaminants and enhance the production of hydrogen gas through water splitting [177]. Pandey et al., (2020) synthesized CQDs from curry leaves using a hydrothermal method. These CQDs were then employed for the sensitive detection of cadmium ions (Cd^{2+}). Their findings revealed that the CQDs exhibited remarkable selectivity for Cd^{2+} detection, achieving a low detection limit of 0.29 nM per liter and a detection range spanning from 0.01 to 8.00 mM per liter [178]. Arumugam et al., developed a simple, single-step hydrothermal method to synthesize CQDs from broccoli which were used for the sensitive detection of silver ions (Ag^{+}). The method relies on the quenching of the CQDs' photoluminescence by

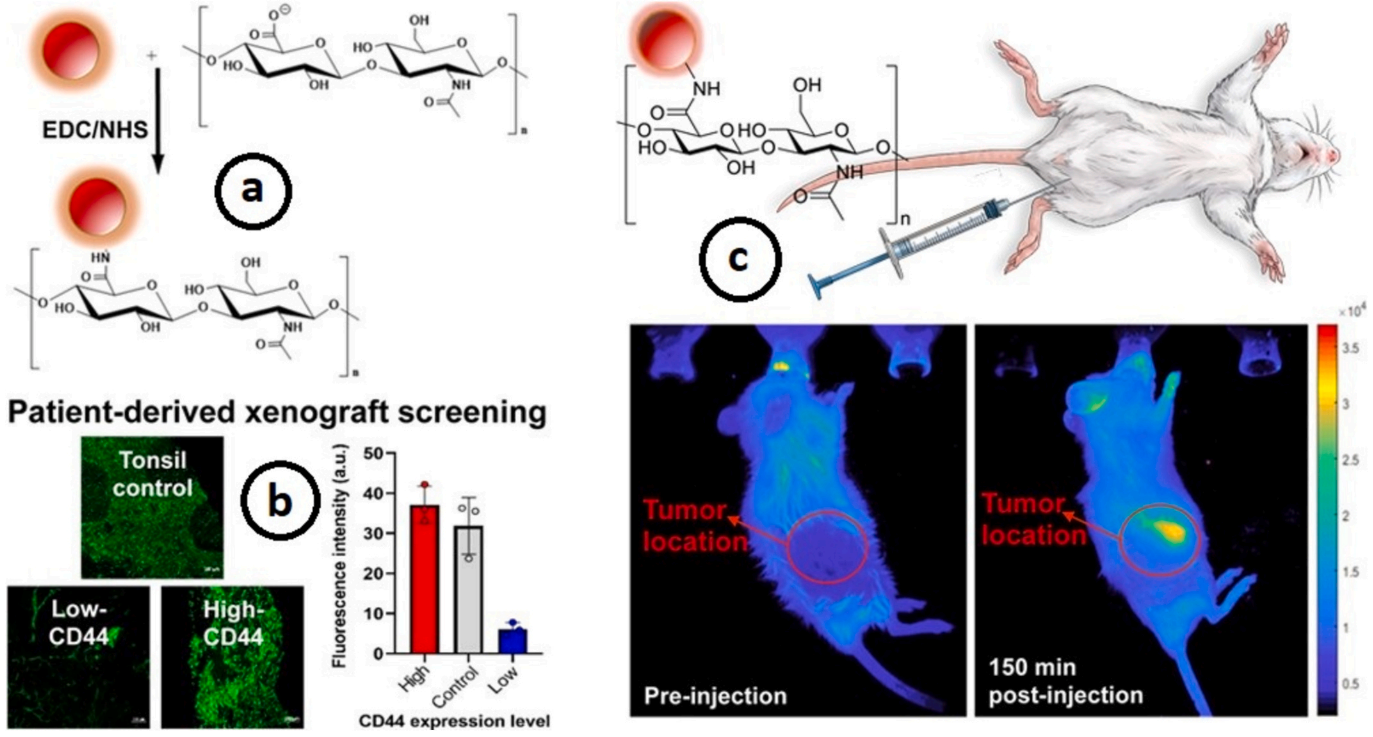

Fig. 10. a) Reaction scheme of conjugating nitrogen-doped CQDs with hyaluronic acid (HA), b) Tissue screening for CD44 expression and fluorescence intensity comparison of the CD44 expression of all three tissues, c) In vivo fluorescent images of mice bearing patient-derived WHIM4 tumor cells (up to 226.8 mm^3 in volume) after intravenous injections of HA-N-CQDs. The HA-N-CQDs were detectable at the tumor site at 150 min postinjection. Reproduced with permission from [164], copyright 2021, American Chemical Society.

Ag^+. The study demonstrated a significantly low detection limit of 0.5 μmol/L and a strong linear correlation between the intensity of light emitted by the CQDs and the concentration of Ag^+ ions [179].

Besides, the potential of glutathione conjugated CQDs (GSH-CQDs) as a sensitive platform was evaluated for the precise and specific detection of levodopa by leveraging the optical properties and detecting capabilities. The surface of N-CQDs was modified with glutathione (GSH) through EDC(1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride) /NHS (N hydroxysuccinimide) coupling reaction. The findings indicated that the green-synthesized GSH-CQDs effectively detected levodopa through fluorescence quenching after excitation at 365 nm, which was clearly observable to the naked eye. In alkaline environments, levodopa is converted into dopaquinone, which then interacts with the thiol group of GSH. This interaction triggers photoinduced electron transfer between the fluorescent GSH-CQDs and dopaquinone, resulting in the fluorescence quenching of GSH-CQDs. The ability of this GSH-CQDs sensor in monitoring levodopa in human serum was confirmed with impressive precision and recovery rates ranging from 100.20 % to 103.33 % [180]. Trumpie et al., (2012) showed that amorphous CQDs can be employed effectively as labels in lateral flow and microarray immunoassay formats. These CQDs offer a cost-effective alternative to other labels while providing enhanced sensitivity and stability. The signal produced by these CQDs can be visually interpreted (as black on a white background) or can be quantified using a flatbed scanner coupled with an image analysis software [181].

Fig. 11 illustrates the nucleic acid lateral flow immunoassays (NALFIA), CQD-based nucleic acid microarray immunoassay (NAMIA) as well as nucleic acid lateral flow microarray immunoassay (NALMIA) and their potential applications in diagnostic testing. These CQDs were synthesized affordably using soot and readily available sources of carbon like printer inks or automotive tires. The findings suggested that CQDs could be used as highly sensitive, non-invasive detectors, potentially enhancing diagnostic techniques and advancing human health. Qi Zhuang et al., (2019) developed a highly luminescent N-doped/CQDs sensor for detecting melamine, utilizing a 'turn-on' fluorescence mechanism. This sensor used iron ions to quench the fluorescence of CQDs, which is then restored by the presence of melamine, leading to a 'turn-on' signal. The fluorescence intensity of N-doped CQDs can be effectively suppressed by Fe^{3+} ions, and this quenching can be reversed after re-introducing melamine [182].

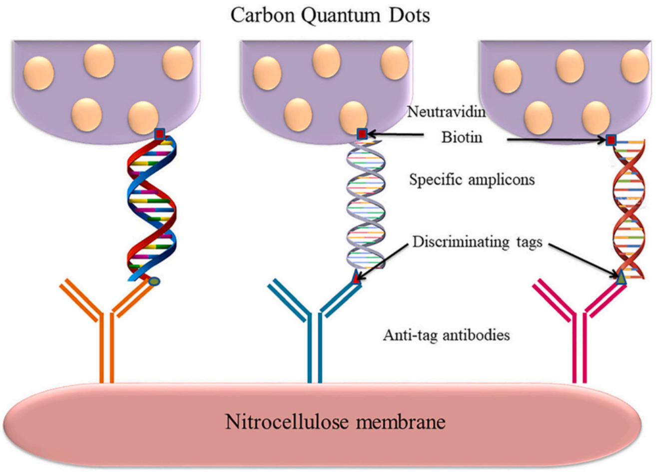

Fig. 11. Illustration of a NALFIA, NAMIA, or NALMIA. Neutravidin adsorbed onto carbon nanoparticles detects biotin-labelled amplicons; the discriminating tag is recognized by its respective antibody, which is immobilized onto nitrocellulose membranes or pads. Reprinted with permission from Springer Nature [181].

6.3. *Targeted drug delivery systems*

Targeted drug delivery are methods for transporting drugs with therapeutic effects to their intended location within an organism [183]. Drug delivery systems require innovative designs that precisely target specific locations within the body and facilitates interaction between the drug and the intended organ. The use of nanostructured materials within the drugs can potentially improve the efficiency of a drug delivery system by increasing absorption, distribution, and elimination of medications. Using nanotechnology in a drug delivery system also enables the delivery of poorly water-soluble allows the simultaneous delivery of multiple drugs or therapies, facilitates the transport of large macromolecule drugs, and tracks the location of drugs through within the body [184].

Researchers are increasingly interested in using CQDs for designing targeted drug delivery systems due to their exceptional merits. CQDs offer fluorescence properties that enable real-time tracking and sensing which are highly valuable in drug delivery applications. CQDs are safe and biocompatible contrast agents that effectively facilitate the release of drugs, especially those with poor water solubility.

Yang et al., (2017) used CQDs that were passivated with polyamine-containing organosilane molecules to deliver the anticancer drug doxorubicin (DOX). The abundance of surface amine groups allowed CQDs to covalently bind with DOX with a remarkably high drug loading capacity of 62.8 %. Moreover, the surface hydroxyl groups of CQDs improved the water-dispersibility of the CQD-DOX complexes. In addition to acting as a drug carrier, the fluorescent properties of CQDs facilitated the real-time monitoring of the drug release throughout the body. When the CQDs-DOX complexes were internalized by MCF-7 breast cancer cells, DOX gradually detaches from the CQD's surface and entered the cell nucleus, while the CQDs remained within the cytoplasm. Furthermore, in vivo studies indicated that the CQDs-DOX complexes demonstrated superior tumor inhibition compared to free DOX molecules, likely due to their extended accumulation in tumor tissues [45]. In another study, pasteurized milk was subjected to hydrothermal processing to synthesize CQDs for delivery of lisinopril (Lis) to HeLa cells. The findings from the combination of cytotoxicity tests and confocal laser scanning microscopy images demonstrated that HeLa cells effectively absorbed the Lis-CQDs without any noticeable cytotoxic effects. The green-engineered CQDs exhibited significant potential as drug carriers, demonstrating excellent biocompatibility and a sustained release of Lis from the CQDs. This observation suggested that the CQDs could be used as a promising system for drug delivery and/or bioimaging applications [185]. Using a similar concept, organophilic CQDs were successfully used to transport curcumin, which is another anticancer molecule. A drug delivery system was made using CQD to deliver curcumin with exceptional loading efficiency and rapid penetration into HeLa cells [186]. Similarly, the delivery of DOX was achieved using CQD/mesoporous silica nanocarriers [187]. Functionalized and surface-passivated CQDs were used to administer DOX to MCF-7 cancer cells. In addition, CQDs and hydroxyapatite hybrid nanorods were used in order to effectively deliver DOX to HeLa cells and PC-3 human prostate cancer cells [188,189]. A novel delivery system utilizing a CQD/calcium alginate hydrogel film was designed to deliver the glycopeptide antibiotic vancomycin within the gastrointestinal tract. CQDs and calcium alginate were combined to create a hydrogel film for the controlled release of the glycopeptide antibiotic vancomycin in the gastrointestinal tract. The CQD/calcium hydrogel film demonstrated a significant drug uptake capacity of 96 % and a slower release rate of 56 % over 120 h at very acidic pH 1.5 after incorporating β-cyclodextrin. This makes it a promising candidate for use as a drug delivery system for the controlled release of vancomycin in the stomach, presenting a potential option for oral administration of the antibiotics [190].

6.4. Photodynamic cancer therapy and treatment

Photodynamic therapy (PDT) is a non-invasive cancer treatment that uses a photosensitizer, light, and oxygen to selectively target and destroy cancer cells. Despite its advantages, conventional photosensitizers often face challenges such as poor selectivity, hydrophobicity, and limited photophysical properties. Carbon nanomaterials, including CQDs, have emerged as promising alternatives due to their excellent photoluminescence, biocompatibility, and hydrophilicity, which enhance PDT efficacy [191].

For instance, encapsulating indocyanine green (ICG) within CQDs has been shown to address ICG's limitations, such as low photostability and poor quantum yield. The resulting ICG@CQD system demonstrated improved photostability and reactive oxygen species (ROS) generation, significantly inhibiting tumor growth in vivo in melanoma models [192]. Similarly, N-doped CQDs have been employed in PDT for oral squamous cell carcinoma, where they effectively induced apoptosis via mitochondrial pathways under laser irradiation, demonstrating both in vitro and in vivo efficacy [193]. CQDs have also shown potential in multifunctional therapeutic systems. For example, a 5-ALA-CQD-Glu-β-CD nanocarrier loaded with DOX demonstrated enhanced cytotoxicity and ROS generation in breast cancer cells, combining chemotherapy and PDT for synergistic effects [194]. These studies underscore the potential of CQDs as innovative photosensitizers and nanocarriers in advancing green, efficient PDT applications for cancer therapy.

7. Applications of carbon quantum dots in water purification

The availability of sustainable, sufficient, and pure water is crucial in today's world. Among the various methods employed to purify water, nanotechnology serves a significant function [195]. CQDs possessing oxygen-based functional groups, exhibit highly desirable properties as semiconductor nanoparticles. This unique combination makes them promising nanomaterials for a wide range of applications, including: Photocatalysis, ion sensing, heavy metal detection, adsorption treatment, supercapacitors, membrane fabrication, as well as water pollution treatment [196]. CQDs are utilized at nearly every stage of wastewater treatment, primarily for the purpose of monitoring harmful substances. Various site-specific investigations have been carried out using functionalized CQDs [197]. For instance, CQDs can be applied as adsorbents for decontamination of Cd (II) [198]. A novel approach for synthesizing biocompatible CQDs photocatalysts was developed using a readily available and inexpensive plant source, garden thyme. This one-step calcination method yielded CQDs in both pure and fluorine and boron co-doped forms, with particle sizes below 10 nm and an impressive luminescence (fluorescence) quantum yield of 40 %. The effectiveness of these CQDs in removing the organic pollutant Rhodamine B (RhB) was evaluated, revealing a strong correlation between CQD size and removal rates. Trapping experiments confirmed that hydroxyl radicals were the primary reactive species responsible for RhB oxidation under visible light irradiation when using the F, B co-doped CQDs. This research demonstrates the feasibility of producing highly efficient, eco-friendly, and cost-effective photocatalysts from readily available plant materials, paving the way for sustainable and environmentally friendly wastewater treatment solutions [199,200]. Moreover, Yang et al., (2019) investigated the removal of benzopyrene (BaP) in environmental water sample using CDs-modified magnetic nanocomposites. CDs/fatty acid-coated magnetic nanoparticles (CDs/C11-Fe_3O_4), used for detecting BaP in large-volume water samples in compliance with China's environmental protection standards, show great potential for water remediation [201]. Another study focused on nitrogen-doped CQDs (N-CQDs) to assess their surface activity by removing Pb^{2+} and Cd^{2+} ions from wastewater. N-CQDs exhibit exceptional efficacy in removing Pb^{2+} and Cd^{2+} ions (with 75 % and 37 %, respectively) through surface adsorption due to their extensive surface area, versatile surface chemistry, and non-corrosive nature [202].

Researchers in China developed a method for detecting hexavalent chromium (Cr(VI)) in wastewater from the vanadium extraction industry. This method utilizes amino-functionalized CQDs as fluorescent probes, enabling visual detection of Cr(VI) using a portable UV lamp. The CQDs-based method provides a sensitive and selective quantitative analysis of Cr(VI) in complex solutions, including industrial wastewater. It exhibits a linear range spanning four orders of magnitude and a detection limit of 140 nmol/L, significantly lower than the discharge limit for Cr(VI) in China. This innovative chemo-sensing approach offers on-site detection and quantitative Cr(VI) concentration determination in wastewater. Its high sensitivity and selectivity make it a promising tool for monitoring hazardous materials in various industrial effluents, contributing to environmental safety and resource management [203].

8. Conclusion and future prospects

Carbon quantum dots (CQDs) have been extensively investigated in recent years due to their light-emissive characteristics, UV-blocking properties, chemical inertness, and easy interaction with biopolymers. CQDs can be produced from abundant and green precursors including vegetables, animals and industrial by-products. While CQDs have shown enormous promise in several fields including bioimaging, electronics, medicines, and drug delivery, their bright future in an emerging and conceptually new area of sustainable packaging has not been thoroughly reviewed. Despite the immense potential for CQDs in packaging and biomedical applications, many industries or clinics are still reluctant and uncertain to exploit them in tangible consumer goods due to a limited understanding of how they integrate with different biopolymers. CQDs offer numerous advantages to improve food packaging, including mechanical strength, water resistance, heat transfer, barrier protection, and antimicrobial and antioxidant properties. Using CQDs to create intelligent packaging systems is a promising field, with potential for developing systems that monitor food freshness and offer active antimicrobial and antioxidant protection. This paper attempts to unlock the potential of converting food industry waste materials and by-products into valuable CQDs, which can contribute to a more sustainable and economically viable global food system. Despite huge successes in green engineering CQDs, several critical challenges still need to be addressed. The development of new strategies to chemically bind CQDs at the interface of biopolymers without any loss in their intrinsic optical properties is currently a new trend in this field. Current knowledge has offered limited insights into the biological fate of green-engineered CQDs when they enter the human body. Other hurdles that contribute to the narrow commercial availability of CQDs include the high costs and complexity of most laboratory-synthesized CQDs. Given the unfulfilled need to develop cost-effective CQDs, additional data and detailed studies are still required to drive a synthesis of multi-kilogram quantities of CQDs from renewable materials. There is a lack of essential understanding of underlying molecular mechanisms at the nanoscale level, and it must be acknowledged that relying on trial-and-error experimentation will not yield the critical information needed to achieve this understanding. The future research mission is also encouraged to gain a deep understanding of the CQD-biopolymer interactions, and develop new applications based on the unique properties of CQDs. With the scarcity of space for landfilling and due to increasing quantities of industrial by-products, the dominant trends in the future synthesis of CQDs are likely to undergo further shifting from conventional carbon resources towards renewable carbon resources, building a gateway towards a more sustainable future. This review also sheds light on the most recent developments and fundamental interface engineering of CQDs utilizing surface modifications. A key problem of using CQDs in biomedical devices is their extremely small sizes which can be absorbed through the skin or inhaled, potentially impacting human health. Despite achieving remarkable progress to fine-tune CQDs for specific medical applications, fundamental details of their structural changes and tentative reaction mechanisms with certain biomolecules are still largely elusive and further research is required to evaluate their in-vitro and in-vivo profiles. A key reason for limited commercial success in incorporating CQDs into food packaging containers is the primary concern over their potential release from the containers into the food products. Despite the seemingly plausible biological nature of CQDs, it is crucial to conduct further research and ascertain their safe biological fates into the gastrointestinal tract. The overwhelming conclusion conveyed through this review is that the field of green-engineered CQDs has a promising future in sustainable packaging and biomedical fields and will undoubtedly continue to inspire further studies.

CRediT authorship contribution statement

Yasaman Esmaeili: Writing – original draft, Methodology, Investigation. **Farzad Toiserkani:** Writing – original draft, Methodology. **Zeinab Qazanfarzadeh:** Writing – review & editing, Visualization. **Mehran Ghasemlou:** Writing – review & editing, Visualization. **Minoo Naebe:** Writing – review & editing, Visualization, Validation. **Colin J. Barrow:** Writing – review & editing, Visualization, Validation. **Wendy Timms:** Writing – review & editing, Visualization, Validation, Supervision. **Shima Jafarzadeh:** Writing – review & editing, Visualization, Validation, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] Fu S, Tang B, Wang Z, An G, Zhang M, Wang K, et al. Hydrophobic carbon quantum dots with Lewis-basic nitrogen sites for electrocatalyst CO2 reduction to CH4. Chem Eng J 2024;500:157207.
[2] Xu Y, Hou W, Huang K, Guo H, Wang Z, Lian C, Zhang J, Wu D, Lei Z, Liu Z, Wang L. Engineering Built-In Electric Field Microenvironment of CQDs/g-C_3N_4 Heterojunction for Efficient Photocatalytic CO_2 Reduction. Adv. Sci. 2024;11:2403607.
[3] Ni Q, Zhang S, Wang K, Guo H, Zhang J, Wu M, et al. Carbon quantum dot-mediated binary metal–organic framework nanosheets for efficient oxygen evolution at ampere-level current densities in proton exchange membrane electrolyzers. J Mater Chem A 2024;12:31253–61.
[4] Naebe M, Lin T, Wang X. Carbon nanotubes reinforced electrospun polymer nanofibres. Nanofibers 2010;11:8160.
[5] Zabihi O, Ahmadi M, Shafei S, Seraji SM, Oroumei A, Naebe M. One-step amino-functionalization of milled carbon fibre for enhancement of thermo-physical properties of epoxy composites. Compos A Appl Sci Manuf 2016;88:243–52.
[6] Rabiee N, Dokmeci MR, Zarrabi A, Makvandi P, Saeb MR, Karimi-Maleh H, et al. Green biomaterials: Fundamental principlesvol. 1. Taylor & Francis; 2023. p. 1–4.
[7] Liu J, Li R, Yang B. Carbon dots: a new type of carbon-based nanomaterial with wide applications. ACS Central Sci 2020;6:2179–95.
[8] Ghasemlou M, Pn N, Alexander K, Zavabeti A, Sherrell PC, Ivanova EP, et al. Fluorescent Nanocarbons: from synthesis and structure to Cancer imaging and therapy. Adv Mater 2024;36:2312474.
[9] Kong J, Wei Y, Zhou F, Shi L, Zhao S, Wan M, et al. Carbon quantum dots: properties, preparation, and applications. Molecules 2024;29:2002.
[10] Hamed M, Chinnam S, Bedair A, Emara S, Mansour FR. Carbon quantum dots from natural sources as sustainable probes for metal ion sensing: preparation, characterizations and applications. Talanta Open 2024;23:100348.
[11] Jafarzadeh S, Oladzadabbasabadi N, Dheyab MA, Lalabadi MA, Sheibani S, Ghasemlou M, et al. Emerging trends in smart and sustainable Nano-biosensing: the role of green nanomaterials. Ind Crop Prod 2025;223:120108.
[12] Qin K, Zhang D, Ding Y, Zheng X, Xiang Y, Hua J, et al. Applications of hydrothermal synthesis of *Escherichia coli* derived carbon dots in in vitro and in vivo imaging and p-nitrophenol detection. Analyst 2020;145:177–83.
[13] Yuan F, Wang Y-K, Sharma G, Dong Y, Zheng X, Li P, et al. Bright high-colour-purity deep-blue carbon dot light-emitting diodes via efficient edge amination. Nat Photon 2020;14:171–6.
[14] Sher F, Ziani I, Smith M, Chugreeva G, Hashimzada SZ, Prola LDT, et al. Carbon quantum dots conjugated with metal hybrid nanoparticles as advanced electrocatalyst for energy applications–A review. Coord Chem Rev 2024;500:215499.
[15] Hu B, Huang K, Tang B, Lei Z, Wang Z, Guo H, et al. Graphene quantum dot-mediated atom-layer semiconductor electrocatalyst for hydrogen evolution. Nano-Micro Lett 2023;15:217.
[16] Kumar JV, Rhim JW. Fluorescent carbon quantum dots for food contaminants detection applications. J Environ Chem Eng 2024 Jan;22:111999.
[17] An Z, Zhang H, Li W, Yang X, Kang Y, Zheng M, et al. Large-scale preparation of peanut-bran-derived carbon dots and their promoting effect on Italian lettuce. ACS Agricult Sci Technol 2021;2:215–21.
[18] Wu H, Li Z. Recent advances in nano-enabled agriculture for improving plant performance. Crop J 2022;10:1–12.
[19] Xie L, Liang C, Wu Y, Wang K, Hou W, Guo H, Wang Z, Lam YM, Liu Z, Wang L. Isomerization Engineering of Oxygen-Enriched Carbon Quantum Dots for Efficient Electrochemical Hydrogen Peroxide Production. Small 2024;7:2401253.
[20] Dhariwal J, Rao GK, Vaya D. Recent advancements towards the green synthesis of carbon quantum dots as an innovative and eco-friendly solution for metal ion sensing and monitoring. RSC Sustain 2024;2:11–36.
[21] Das GS, Shim JP, Bhatnagar A, Tripathi KM, Kim T. Biomass-derived carbon quantum dots for visible-light-induced photocatalysis and label-free detection of Fe (III) and ascorbic acid. Sci Rep 2019;9:15084.
[22] Ibraheem Shelash Al-Hawary S, Saleh RO, AlBajalan AR, Fayzullaev N, Alshuhri M, Hayif Jasim Ali S, et al. Synthesis of N, N′-alkylidene bisamides and Suzuki–Miyaura coupling reaction derivatives with Pd organometallic catalyst anchored to channels of mesoporous silica MCM-41. Sci Rep 2024;14:7688.
[23] Fayzullayev N, Muradov K, Fayzullaev O, Umirzakov R, Pardaeva S. About mechanism of acetone formation from acetylene on polyfunctional catalyst. In: Abstracts of Papers of the American Chemical Society. Vol. 223: Amer Chemical Soc 1155 16th St, NW, Washington, DC 20036 USA; 2002. U22–.
[24] Nazar M, Hasan M, Wirjosentono B, Gani BA. Fabrication and characterization of bio-nanocomposite from sweet potato starch and *Moringa oleifera* leaf extract loaded with carbon quantum dots from *Coffea arabica* grounds. Results Eng 2024;23:102448.
[25] Latif Z, Shahid K, Anwer H, Shahid R, Ali M, Lee KH, et al. Carbon quantum dots (CQDs) modified polymers: a mini review of non-optical applications. Nanoscale 2024;16:2265–88.
[26] Gupta D, Priyadarshi R, Tammina SK, Rhim J-W, Agrawal G. Fruit processing wastes as sustainable sources to produce multifunctional carbon quantum dots for application in active food packaging. Food Bioproc Tech 2024;1-25.
[27] Ezati P, Priyadarshi R, Rhim J-W. Prospects of sustainable and renewable source-based carbon quantum dots for food packaging applications. Sustain Mater Technol 2022;33:e00494.
[28] Qasim M, Clarkson AN, Hinkley SF. Green synthesis of carbon nanoparticles (CNPs) from biomass for biomedical applications. Int J Mol Sci 2023;24:1023.
[29] Sheibani S, Jafarzadeh S, Qazanfarzadeh Z, Wijekoon JO, Nafchi AM. Sustainable strategies for using natural extracts in smart food packaging. Int J Biol Macromol 2024;267:131537.
[30] Jafarzadeh S, Zargar M, Forough M. Renewable and recyclable polymeric materials for food packaging: a new open special issue in materials. Materials 2022;15:5845.
[31] Hadidi M, Jafarzadeh S, Ibarz A. Modified mung bean protein: optimization of microwave-assisted phosphorylation and its functional and structural characterizations. LWT 2021;151:112119.
[32] Omran BA, Whitehead KA, Baek K-H. One-pot bioinspired synthesis of fluorescent metal chalcogenide and carbon quantum dots: applications and potential biotoxicity. Colloids Surf B Biointerf 2021;200:111578.
[33] Kharissova OV, Kharisov BI, Oliva González CM, Méndez YP, López I. Greener synthesis of chemical compounds and materials. R Soc Open Sci 2019;6:191378.
[34] Rana A, Yadav K, Jagadevan S. A comprehensive review on green synthesis of nature-inspired metal nanoparticles: mechanism, application and toxicity. J Clean Prod 2020;272:122880.
[35] Guo H, Lu Y, Lei Z, Bao H, Zhang M, Wang Z, et al. Machine learning-guided realization of full-color high-quantum-yield carbon quantum dots. Nat Commun 2024;15:4843.
[36] Wang L, Zhou HS. Green synthesis of luminescent nitrogen-doped carbon dots from milk and its imaging application. Anal Chem 2014;86:8902–5.
[37] Arkan E, Barati A, Rahmanpanah M, Hosseinzadeh L, Moradi S, Hajialyani M. Green synthesis of carbon dots derived from walnut oil and an investigation of their cytotoxic and apoptogenic activities toward cancer cells. Adv Pharm Bull 2018;8:149.
[38] Atchudan R, Edison TNJI, Shanmugam M, Perumal S, Somanathan T, Lee YR. Sustainable synthesis of carbon quantum dots from banana peel waste using hydrothermal process for in vivo bioimaging. Physica E 2021;126:114417.
[39] Deme G, Belay A, Andoshe DM, Barsisa G, Tsegaye D, Tiruneh S, et al. Effect of hydrothermal reaction temperature on fluorescent properties of carbon quantum dots synthesized from lemon juice for adsorption applications. J Nanomater 2023;2023:1701496.
[40] Eskalen H, Uruş S, Kavgacı M, Kalmış HV, Tahta B. Carbon quantum dots derived from pomegranate peel: highly effective Fe (III) sensor. Biomass Convers Biorefinery 2024;14:1201–14.
[41] Ling C, Wang Z, Li C, Wang W. Eco-friendly and sustainable synthesis of carbon quantum dots from waste sulfuric acid of alkylation. J Industr Eng Chem 2024;143:447–54.
[42] Jagannathan M, Dhinasekaran D, Soundharraj P, Rajendran S, Vo D-VN, Prakasarao A, et al. Green synthesis of white light emitting carbon quantum dots:

fabrication of white fluorescent film and optical sensor applications. J Hazard Mater 2021;416:125091.

[43] Qi C, Wang H, Yang A, Wang X, Xu J. Facile fabrication of highly fluorescent N-doped carbon quantum dots using an ultrasonic-assisted hydrothermal method: optical properties and cell imaging. ACS Omega 2021;6:32904–16.

[44] Mitra S, Chandra S, Pathan SH, Sikdar N, Pramanik P, Goswami A. Room temperature and solvothermal green synthesis of self passivated carbon quantum dots. RSC Adv 2013;3:3189–93.

[45] Yang J, Gao G, Zhang X, Ma Y-H, Jia H-R, Jiang Y-W, et al. Ultrasmall and photostable nanotheranostic agents based on carbon quantum dots passivated with polyamine-containing organosilane molecules. Nanoscale 2017;9:15441–52.

[46] Tajik S, Dourandish Z, Zhang K, Beitollahi H, Van Le Q, Jang HW, et al. Carbon and graphene quantum dots: A review on syntheses, characterization, biological and sensing applications for neurotransmitter determination. RSC Adv 2020;10:15406–29.

[47] Wang J, Qiu J. A review of carbon dots in biological applications. J Mater Sci 2016;51:4728–38.

[48] Jafarzadeh S, Ariffin F, Mahmud S, Alias AK, Najafi A, Ahmad M. Characterization of Semolina biopolymer films enriched with zinc oxide nano rods. Italian J Food Sci/Rivista Italiana di Scienza degli Alimenti 2017:29.

[49] Jafarzadeh Shima, Whan Rhim Jong, Alias Abd Karim, Ariffin Fazilah, Mahmud Shahrom. Application of antimicrobial active packaging film made of semolina flour, nano zinc oxide and nano-kaolin to maintain the quality of low-moisture mozzarella cheese during low-temperature storage. 2019.

[50] Jafarzadeh S, Alias A, Ariffin F, Mahmud S, Najafi A, Sheibani S. Characterization of a new biodegradable edible film based on semolina loaded with nano kaolin. Int Food Res J 2017:24.

[51] Murugan N, Prakash M, Jayakumar M, Sundaramurthy A, Sundramoorthy AK. Green synthesis of fluorescent carbon quantum dots from *Eleusine coracana* and their application as a fluorescence 'turn-off' sensor probe for selective detection of Cu^{2+}. Appl Surf Sci 2019;476:468–80.

[52] Wang C, Yang M, Shi H, Yao Z, Liu E, Hu X, et al. Carbon quantum dots prepared by pyrolysis: investigation of the luminescence mechanism and application as fluorescent probes. Dyes Pigments 2022;204:110431.

[53] Singh R, Kumar R, Singh D, Savu R, Moshkalev S. Progress in microwave-assisted synthesis of quantum dots (graphene/carbon/semiconducting) for bioapplications: a review. Mater Today Chem 2019;12:282–314.

[54] Sharma A, Das J. Small molecules derived carbon dots: synthesis and applications in sensing, catalysis, imaging, and biomedicine. J Nanobiotechnol 2019;17:92.

[55] Li M, Wang M, Zhu L, Li Y, Yan Z, Shen Z, et al. Facile microwave assisted synthesis of N-rich carbon quantum dots/dual-phase TiO_2 heterostructured nanocomposites with high activity in CO_2 photoreduction. Appl Catal Environ 2018;231:269–76.

[56] Franco CA, Candela CH, Gallego J, Marin J, Patiño LE, Ospina N, et al. Easy and rapid synthesis of carbon quantum dots from Mortino (Vaccinium Meridionale Swartz) extract for use as green tracers in the oil and gas industry: lab-to-field trial development in Colombia. Industr Eng Chem Res 2020;59:11359–69.

[57] Başoğlu A, Ocak Ü, Gümrükçüoğlu A. Synthesis of microwave-assisted fluorescence carbon quantum dots using roasted–chickpeas and its applications for sensitive and selective detection of Fe^{3+} ions. J Fluoresc 2020;30:515–26.

[58] Jafarzadeh S, Jafari SM, Salehabadi A, Nafchi AM, Kumar USU, Khalil HA. Biodegradable green packaging with antimicrobial functions based on the bioactive compounds from tropical plants and their by-products. Trends Food Sci Technol 2020;100:262–77.

[59] Jafarzadeh S, Yildiz Z, Yildiz P, Strachowski P, Forough M, Esmaeili Y, et al. Advanced macromolecular technologies in biodegradable packaging using intelligent sensing to fight food waste; A review. Int J Biol Macromol 2024;261:129647.

[60] Wang C, Shi H, Yang M, Yan Y, Liu E, Ji Z, et al. Facile synthesis of novel carbon quantum dots from biomass waste for highly sensitive detection of iron ions. Mater Res Bull 2020;124:110730.

[61] Huang C, Dong H, Su Y, Wu Y, Narron R, Yong Q. Synthesis of carbon quantum dot nanoparticles derived from byproducts in bio-refinery process for cell imaging and in vivo bioimaging. Nanomaterials 2019;9:387.

[62] Torres FG, Gonzales KN, Troncoso OP, Cañedo VS. Carbon quantum dots based on marine polysaccharides: types, synthesis, and applications. Mar Drugs 2023;21:338.

[63] Elango D, Packialakshmi JS, Manikandan V, Jayanthi P. Sustainable synthesis of carbon quantum dots from shrimp shell and its emerging applications. Mater Lett 2022;312:131667.

[64] Kumari A, Kumar A, Sahu SK, Kumar S. Synthesis of green fluorescent carbon quantum dots using waste polyolefins residue for Cu^{2+} ion sensing and live cell imaging. Sens Actuat B Chem 2018;254:197–205.

[65] Huang G, Chen X, Wang C, Zheng H, Huang Z, Chen D, et al. Photoluminescent carbon dots derived from sugarcane molasses: synthesis, properties, and applications. RSC Adv 2017;7:47840–7.

[66] Chen K, Qing W, Hu W, Lu M, Wang Y, Liu X. On-off-on fluorescent carbon dots from waste tea: their properties, antioxidant and selective detection of CrO_4^{2-}, Fe^{3+}, ascorbic acid and L-cysteine in real samples. Spectrochim Acta A Mol Biomol Spectrosc 2019;213:228–34.

[67] Sarswat PK, Free ML. Light emitting diodes based on carbon dots derived from food, beverage, and combustion wastes. Phys Chem Chem Phys 2015;17:27642–52.

[68] Sun X, Liu Y, Niu N, Chen L. Synthesis of molecularly imprinted fluorescent probe based on biomass-derived carbon quantum dots for detection of mesotrione. Anal Bioanal Chem 2019;411:5519–30.

[69] Li Z, Wang Q, Zhou Z, Zhao S, Zhong S, Xu L, et al. Green synthesis of carbon quantum dots from corn stalk shell by hydrothermal approach in near-critical water and applications in detecting and bioimaging. Microchem J 2021;166:106250.

[70] Rawat P, Nain P, Sharma S, Sharma PK, Malik V, Majumder S, et al. An overview of synthetic methods and applications of photoluminescence properties of carbon quantum dots. Luminescence 2023;38:845–66.

[71] Hu X, Li Y, Xu Y, Gan Z, Zou X, Shi J, et al. Green one-step synthesis of carbon quantum dots from orange peel for fluorescent detection of *Escherichia coli* in milk. Food Chem 2021;339:127775.

[72] Dehvari K, Liu KY, Tseng P-J, Gedda G, Girma WM, Chang J-Y. Sonochemical-assisted green synthesis of nitrogen-doped carbon dots from crab shell as targeted nanoprobes for cell imaging. J Taiwan Inst Chem Eng 2019;95:495–503.

[73] Yao Y-Y, Gedda G, Girma WM, Yen C-L, Ling Y-C, Chang J-Y. Magnetofluorescent carbon dots derived from crab shell for targeted dual-modality bioimaging and drug delivery. ACS Appl Mater Interfaces 2017;9:13887–99.

[74] Šafranko S, Goman D, Stanković A, Medvidović-Kosanović M, Moslavac T, Jerković I, et al. An overview of the recent developments in carbon quantum dots—promising nanomaterials for metal ion detection and (bio) molecule sensing. Chemosensors 2021;9:138.

[75] Kumar A, Kumar D, Saikia M, Subramania A. A review on plant derived carbon quantum dots for bio-imaging. Mater Adv 2023;4:3951–66.

[76] Achem CU, Onimisi MY, Danladi E, David I, Babatunde RA. Influence of nitrogen-doped carbon quantum dots on titanium dioxide for photovoltaic applications: optical and structural insight. Mater Res Innov 2024;28:106–19.

[77] He P, Shi Y, Meng T, Yuan T, Li Y, Li X, et al. Recent advances in white light-emitting diodes of carbon quantum dots. Nanoscale 2020;12:4826–32.

[78] Ezati P, Rhim J-W, Molaei R, Priyadarshi R, Han S. Cellulose nanofiber-based coating film integrated with nitrogen-functionalized carbon dots for active packaging applications of fresh fruit. Postharv Biol Technol 2022;186:111845.

[79] Akmalaiuly K, Fayzullayev N. Heterogeneo-catalytic synthesis of vinyl chloride and chloroprene from acetylene. Известия НАН РК Серия хиМии и технологии 2020:5–13.

[80] Acharya B, Behera A, Behera S, Moharana S. Carbon quantum dots: a systematic overview of recent developments in synthesis, properties, and novel therapeutic applications. Inorgan Chem Commun 2024;9:112492.

[81] Li H, Kang Z, Liu Y, Lee S-T. Carbon nanodots: synthesis, properties and applications. J Mater Chem 2012;22:24230–53.

[82] Kumar L, Gaikwad KK. Carbon dots for food packaging applications. Sustain Food Technol 2023;1:185–99.

[83] Aprila ZA, Hindersah R, Sofyan ET. The effect of organic matter on soil organic carbon and water spinach grown in gold mine tailings. Curr Res Agric Sci 2023;10:41–9.

[84] Zhu P, Liu Y, Tang Y, Zhu S, Liu X, Yin L, et al. Bi-doped carbon quantum dots functionalized liposomes with fluorescence visualization imaging for tumor diagnosis and treatment. Chin Chem Lett 2024;35:108689.

[85] Yadav N, Mudgal D, Mishra V. Nanobiotic formulations utilizing Quinoline-based-Triazole functionalized carbon quantum dots via click chemistry for combatting clinical-resistant bacterial pathogens. Indian J Microbiol 2024:1–15.

[86] Farshbaf M, Davaran S, Rahimi F, Annabi N, Salehi R, Akbarzadeh A. Carbon quantum dots: recent progresses on synthesis, surface modification and applications. Artific Cells Nanomed Biotechnol 2018;46:1331–48.

[87] Wang Y, Hu A. Carbon quantum dots: synthesis, properties and applications. J Mater Chem C 2014;2:6921–39.

[88] Dong X, Liang W, Meziani MJ, Sun Y-P, Yang L. Carbon dots as potent antimicrobial agents. Theranostics 2020;10:671.

[89] Lin F, Bao Y-W, Wu F-G. Carbon dots for sensing and killing microorganisms. C 2019;5:33.

[90] Sajadizadeh H, Zamindar N, Esmaeili Y, Lorenzo JM, Pateiro M, Goksen G, et al. Antimicrobial activity of Oliveria decumbens vent. Essential oil and Ferula asa-foetida extract on Turkey breast meat: antimicrobial activity of Oliveria decumbens vent. Essential Oil Ferula ASA Foetida Extract J Food Measurem Characteriz 2024;18:1218–28.

[91] Paidari S, Esmaeili Y, Ibrahim SA, Vahedi S, Al-Hilifi SA, Zamindar N. Application of nanoparticles to enhance the microbial quality and shelf life of food products. In: Microbial biotechnology in the food industry: Advances, challenges, and potential solutions. Springer; 2024. p. 75–102.

[92] Esmaeili Y, Zamindar N, Mohammadi R. The effect of polypropylene film containing nano-hydroxyapatite on physicochemical and microbiological properties of button mushrooms (Agaricus bisporus) under modified atmosphere packaging. J Food Measurem Characteriz 2023;17:773–86.

[93] Kousheh SA, Moradi M, Tajik H, Molaei R. Preparation of antimicrobial/ultraviolet protective bacterial nanocellulose film with carbon dots synthesized from lactic acid bacteria. Int J Biol Macromol 2020;155:216–25.

[94] Riahi Z, Rhim J-W, Bagheri R, Pircheraghi G, Lotfali E. Carboxymethyl cellulose-based functional film integrated with chitosan-based carbon quantum dots for active food packaging applications. Prog Org Coat 2022;166:106794.

[95] Fan K, Zhang M, Fan D, Jiang F. Effect of carbon dots with chitosan coating on microorganisms and storage quality of modified-atmosphere-packaged fresh-cut cucumber. J Sci Food Agric 2019;99:6032–41.

[96] Fan K, Zhang M, Chen H. Effect of ultrasound treatment combined with carbon dots coating on the microbial and physicochemical quality of fresh-cut cucumber. Food Bioproc Tech 2020;13:648–60.

[97] Wen F, Li P, Yan H, Su W. Turmeric carbon quantum dots enhanced chitosan nanocomposite films based on photodynamic inactivation technology for antibacterial food packaging. Carbohydr Polym 2023;311:120784.

[98] Zhang W, Chavez J, Zeng Z, Bloom B, Sheardy A, Ji Z, et al. Antioxidant capacity of nitrogen and sulfur codoped carbon nanodots. ACS Appl Nano Mater 2018;1:2699–708.

[99] Khan A, Ezati P, Kim J-T, Rhim J-W. Biocompatible carbon quantum dots for intelligent sensing in food safety applications: opportunities and sustainability. Mater Today Sustain 2023;21:100306.

[100] Moradi M, Molaei R, Kousheh SA, Guimarães TJ, McClements DJ. Carbon dots synthesized from microorganisms and food by-products: active and smart food packaging applications. Crit Rev Food Sci Nutr 2023;63:1943–59.

[101] Roy S, Ezati P, Rhim J-W, Molaei R. Preparation of turmeric-derived sulfur-functionalized carbon dots: antibacterial and antioxidant activity. J Mater Sci 2022;57:2941–52.

[102] Mei LX, Nafchi AM, Ghasemipour F, Easa AM, Jafarzadeh S, Al-Hassan AA. Characterization of pH sensitive sago starch films enriched with anthocyanin-rich torch ginger extract. Int J Biol Macromol 2020;164:4603–12.

[103] Riahi Z, Khan A, Rhim J-W, Shin GH, Kim JT. Carrageenan-based active and intelligent packaging films integrated with anthocyanin and TiO2-doped carbon dots derived from sweet potato peels. Int J Biol Macromol 2024;259:129371.

[104] Min S, Ezati P, Rhim J-W. Gelatin-based packaging material incorporated with potato skins carbon dots as functional filler. Ind Crop Prod 2022;181:114820.

[105] Wen F, Li P, Zhang Y, Zhong H, Yan H, Su W. Preparation, characterization of green tea carbon quantum dots/curcumin antioxidant and antibacterial nanocomposites. J Mol Struct 2023;1273:134247.

[106] Alamdari NG, Almasi H, Moradi M, Akhgari M. Characterization of carbon quantum dots synthesized from vinasse and date seeds as agro-industrial wastes. Waste Biomass Valoriz 2023;14:3689–703.

[107] Ezati P, Rhim J-W, Molaei R, Rezaei Z. Carbon quantum dots-based antifungal coating film for active packaging application of avocado. Food Packag Shelf Life 2022;33:100878.

[108] Roy S, Ezati P, Rhim J-W. Gelatin/carrageenan-based functional films with carbon dots from enoki mushroom for active food packaging applications. ACS Appl Polym Mater 2021;3:6437–45.

[109] Rajamanikandan S, Biruntha M, Ramalingam G. Blue emissive carbon quantum dots (CQDs) from bio-waste peels and its antioxidant activity. J Cluster Sci 2022;1-9.

[110] Rosenkrans ZT, Sun T, Jiang D, Chen W, Barnhart TE, Zhang Z, et al. Selenium-doped carbon quantum dots act as broad-Spectrum antioxidants for acute kidney injury management. Adv Sci 2020;7:2000420.

[111] Zhao L, Wang Y, Li Y. Antioxidant activity of graphene quantum dots prepared in different electrolyte environments. Nanomaterials 2019;9:1708.

[112] Chunduri L, Kurdekar A, Patnaik S, Dev BV, Rattan TM, Kamisetti V. Carbon quantum dots from coconut husk: evaluation for antioxidant and cytotoxic activity. Materials Focus 2016;5:55–61.

[113] Li J, Cao L, Li D, Yu C, Tan M. Carbon dots from roasted mackerel (*scomberomorus niphonius*) for free radical scavenging. Lwt 2019;111:588–93.

[114] Wang H, Xie Y, Na X, Bi J, Liu S, Zhang L, et al. Fluorescent carbon dots in baked lamb: formation, cytotoxicity and scavenging capability to free radicals. Food Chem 2019;286:405–12.

[115] Garavand F, Cacciotti I, Vahedikia N, Rehman A, Tarhan Ö, Akbari-Alavijeh S, et al. A comprehensive review on the nanocomposites loaded with chitosan nanoparticles for food packaging. Crit Rev Food Sci Nutr 2022;62:1383–416.

[116] Mohammadi-Moghaddam T, Kariminejad M, Hadad S, Jafarzadeh S, Shahrampour D. Physical properties, antioxidant activity, and antimicrobia l properties of edible film prepared from black plum peel extract as a valuable byproduct of plum processing. J Food Chem Nanotechnol 2023;9:156–62.

[117] Jafarzadeh S, Alias AK, Ariffin F, Mahmud S, Najafi A, Ahmad M. Fabrication and characterization of novel semolina-based antimicrobial films derived from the combination of ZnO nanorods and nanokaolin. J Food Sci Technol 2017;54:105–13.

[118] Jafarzadeh S, Nooshkam M, Qazanfarzadeh Z, Oladzadabbasabadi N, Strachowski P, Rabiee N, et al. Unlocking the potential of 2D nanomaterials for sustainable intelligent packaging. Chem Eng J 2024;490:151711.

[119] Azlim NA, Mohammadi Nafchi A, Oladzadabbasabadi N, Ariffin F, Ghalambor P, Jafarzadeh S, et al. Fabrication and characterization of a pH-sensitive intelligent film incorporating dragon fruit skin extract. Food Sci Nutr 2022;10:597–608.

[120] Liu Z, de Souza TS, Holland B, Dunshea F, Barrow C, Suleria HA. Valorization of food waste to produce value-added products based on its bioactive compounds. Processes 2023;11:840.

[121] Havrdova M, Hola K, Skopalik J, Tomankova K, Petr M, Cepe K, et al. Toxicity of carbon dots–effect of surface functionalization on the cell viability, reactive oxygen species generation and cell cycle. Carbon 2016;99:238–48.

[122] Rashid NZMN, Radzun KA, Saharuddin AN, Rusmidi MHH, Ismail A, Razak WRWA, et al. Effects of agricultural grade nutrient modulation on the biomass production and carbon fixation rate of Isochrysis sp. microalgae. Asian J Agric Rural Developm 2023;13:248–56.

[123] Patil AS, Waghmare RD, Pawar SP, Salunkhe ST, Kolekar GB, Sohn D, et al. Photophysical insights of highly transparent, flexible and re-emissive PVA@WTR-CDs composite thin films: a next generation food packaging material for UV blocking applications. J Photochem Photobiol A Chem 2020;400:112647.

[124] Arias Velasco V, Caicedo Chacón WD, Carvajal Soto AM, Ayala Valencia G, Granada Echeverri JC, Agudelo Henao AC. Carbon quantum dots based on carbohydrates as nano sensors for food quality and safety. Starch-Stärke 2021;73:2100044.

[125] El-Shamy AG, Zayied H. New polyvinyl alcohol/carbon quantum dots (PVA/CQDs) nanocomposite films: structural, optical and catalysis properties. Synth Met 2020;259:116218.

[126] Park SW, Im SH, Hong WT, Yang HK, Jung YK. Lignin-derived carbon quantum dot/PVA films for totally blocking UV and high-energy blue light. Int J Biol Macromol 2024;268:131919.

[127] Wang Y, Liu Y, Zhao L, Sun L, Zhao X, Xia Y. κ-Carrageenan-derived carbon dots for highly selective and sensitive detection of Fe 3+ and oxytetracycline. J Mater Sci 2021;56:1272–85.

[128] Xu L, Li Y, Gao S, Niu Y, Liu H, Mei C, et al. Preparation and properties of cyanobacteria-based carbon quantum dots/polyvinyl alcohol/nanocellulose composite. Polymers 2020;12:1143.

[129] Garavand F, Khodaei D, Mahmud N, Islam J, Khan I, Jafarzadeh S, et al. Recent progress in using zein nanoparticles-loaded nanocomposites for food packaging applications. Crit Rev Food Sci Nutr 2024;64:3639–59.

[130] Jayakumar A, Radoor S, Shin GH, Kim JT. Lemon peel-based fluorescent carbon quantum dots as a functional filler in polyvinyl alcohol-based films for active packaging applications. Ind Crop Prod 2024;209:117968.

[131] Chen S, Zeng Q, Tan X, Ye M, Zhang Y, Zou L, et al. Photodynamic antibacterial chitosan/nitrogen-doped carbon dots composite packaging film for food preservation applications. Carbohydr Polym 2023;314:120938.

[132] Khoshkalampour A, Ghorbani M, Ghasempour Z. Cross-linked gelatin film enriched with green carbon quantum dots for bioactive food packaging. Food Chem 2023;404:134742.

[133] Sul Y, Ezati P, Rhim J-W. Preparation of chitosan/gelatin-based functional films integrated with carbon dots from banana peel for active packaging application. Int J Biol Macromol 2023;246:125600.

[134] Fu B, Liu Q, Liu M, Chen X, Lin H, Zheng Z, et al. Carbon dots enhanced gelatin/chitosan bio-nanocomposite packaging film for perishable foods. Chin Chem Lett 2022;33:4577–82.

[135] Mei S, Fu B, Su X, Chen H, Lin H, Zheng Z, et al. Developing silk sericin-based and carbon dots reinforced bio-nanocomposite films and potential application to litchi fruit. Lwt 2022;164:113630.

[136] Garavand F, Rouhi M, Jafarzadeh S, Khodaei D, Cacciotti I, Zargar M, et al. Tuning the physicochemical, structural, and antimicrobial attributes of whey-based poly (L-lactic acid)(PLLA) films by chitosan nanoparticles. Front Nutr 2022;9:880520.

[137] Pavani M, Singh SK, Singha P. Chitosan from agro-waste for food packaging applications. In: Agro-waste derived biopolymers and biocomposites: innovations and sustainability in food packaging; 2024. p. 267–94.

[138] Ivanova S, Vesnina A, Fotina N, Prosekov A. Influence of coal mining activities on soil's agrochemical and biochemical properties. Qubahan Academ J 2023;3:387–99.

[139] Khan A, Ezati P, Rhim J-W. Chitosan/gelatin-based multifunctional film integrated with green tea carbon dots to extend the shelf life of pork. Food Packag Shelf Life 2023;37:101075.

[140] Zhang J-J, Gu M-M, Zheng T-T, Zhu J-J. Synthesis of gelatin-stabilized gold nanoparticles and assembly of carboxylic single-walled carbon nanotubes/au composites for cytosensing and drug uptake. Anal Chem 2009;81:6641–8.

[141] Jafarzadeh S, Jafari SM. Impact of metal nanoparticles on the mechanical, barrier, optical and thermal properties of biodegradable food packaging materials. Crit Rev Food Sci Nutr 2021;61:2640–58.

[142] Bakeshlouy Afshar M, Poursattar Marjani A, Gozali Balkanloo P. Introducing graphene quantum dots in decomposable wheat starch-gelatin based nano-biofilms. Sci Rep 2024;14:2069.

[143] Ezati P, Roy S, Rhim J-W. Pectin/gelatin-based bioactive composite films reinforced with sulfur functionalized carbon dots. Colloids Surf A Physicochem Eng Asp 2022;636:128123.

[144] Grzebieniarz W, Nowak N, Khachatryan G, Krzan M, Krystyjan M, Kosiński J, et al. The preparation and characterization of quantum dots in polysaccharide carriers (starch/chitosan) as elements of smart packaging and their impact on the growth of microorganisms in food. Materials 2021;14:7732.

[145] Zhang W, Azizi-Lalabadi M, Jafarzadeh S, Jafari SM. Starch-gelatin blend films: A promising approach for high-performance degradable food packaging. Carbohydr Polym 2023;6:21266.

[146] Sanchez T, Hla T. Structural and functional characteristics of S1P receptors. J Cell Biochem 2004;92:913–22.

[147] Babaee M, Garavand F, Rehman A, Jafarazadeh S, Amini E, Cacciotti I. Biodegradability, physical, mechanical and antimicrobial attributes of starch nanocomposites containing chitosan nanoparticles. Int J Biol Macromol 2022;195:49–58.

[148] Muñoz-Gimena PF, Oliver-Cuenca V, Peponi L, López D. A review on reinforcements and additives in starch-based composites for food packaging. Polymers 2023;15:2972.

[149] Jafarzadeh S, Nafchi AM, Salehabadi A, Oladzad-Abbasabadi N, Jafari SM. Application of bio-nanocomposite films and edible coatings for extending the shelf life of fresh fruits and vegetables. Adv Colloid Interface Sci 2021;291:102405.

[150] Abdulwahid RT, Aziz SB, Kadir MF. Environmentally friendly plasticized electrolyte based on chitosan (CS): potato starch (PS) polymers for EDLC application: steps toward the greener energy storage devices derived from biopolymers. J Energy Storage 2023;67:107636.

[151] Chen K, Zhang M, Bhandari B, Deng D. 3D printed cinnamon essential oil/banana peel carbon dots loaded corn starch/gelatin bilayer film with enhanced functionality for food packaging application. Food Chem 2024;1:1391762024.

[152] Koshy RR, Koshy JT, Mary SK, Sadanandan S, Jisha S, Pothan LA. Preparation of pH sensitive film based on starch/carbon nano dots incorporating anthocyanin for monitoring spoilage of pork. Food Control 2021;126:108039.

[153] Zhu X, Jin H, Gao C, Gui R, Wang Z. Ratiometric, visual, dual-signal fluorescent sensing and imaging of pH/copper ions in real samples based on carbon dots-fluorescein isothiocyanate composites. Talanta 2017;162:65–71.

[154] Abedi-Firoozjah R, Yousefi S, Heydari M, Seyedfatehi F, Jafarzadeh S, Mohammadi R, et al. Application of red cabbage anthocyanins as pH-sensitive pigments in smart food packaging and sensors. Polymers 2022;14:1629.

[155] Fashandi H, Abolhasani MM, Sandoghdar P, Zohdi N, Li Q, Naebe M. Morphological changes towards enhancing piezoelectric properties of PVDF electrical generators using cellulose nanocrystals. Cellulose 2016;23:3625–37.

[156] Jafarzadeh S, Nooshkam M, Zargar M, Garavand F, Ghosh S, Hadidi M, et al. Green synthesis of nanomaterials for smart biopolymer packaging: challenges and outlooks. J Nanostruct Chem 2023:1–24.

[157] Owolabi FA, Deepu AG, Thomas S, Shima J, Rizal S, Aprilia NAS, et al. Green composites from sustainable cellulose nanofibrils. 2020.

[158] Hermawan D, Lai TK, Jafarzadeh S, Gopakumar DA, Hasan M, Owolabi FT, et al. Development of seaweed-based bamboo microcrystalline cellulose films intended for sustainable food packaging applications. BioResources 2019;14:3389–410.

[159] Jafarzadeh S, Forough M, Kouzegaran VJ, Zargar M, Garavand F, Azizi-Lalabadi M, et al. Improving the functionality of biodegradable food packaging materials via porous nanomaterials. Comprehens Rev Food Sci Food Safety 2023;22:2850–86.

[160] Rezvan N, Shekarchizadeh H. UV-blocking active packaging film made from TEMPO-oxidized nanocellulose and amine-modified carbon quantum dot. J Food Measurem Characteriz 2024;18:676–87.

[161] Emam HE. Clustering of photoluminescent carbon quantum dots using biopolymers for biomedical applications. Biocatal Agric Biotechnol 2022;42:102382.

[162] Song K, Al-Hetty HRAK, Hsu C-Y, Mustafa YF, Kaur I, Alzubaidi LH, et al. Biosensors for detection contaminations in coffee samples: recent progress and challenges. Microchem J 2024;3:110472.

[163] Azam N, Najabat Ali M, Javaid Khan T. Carbon quantum dots for biomedical applications: review and analysis. Front Mater 2021;8:700403.

[164] Karakoçak BBM, Laradji A, Primeau T, Berezin MY, Li S, Ravi N. Hyaluronan-conjugated carbon quantum dots for bioimaging use. ACS Appl Mater Interfaces 2020;13:277–86.

[165] Kamble P, Malavekar D, Tiwari AP. Natural biowaste derived fluorescent carbon quantum dots: synthesis, characterization and biocompatibility study. J Fluoresc 2024;34:191–201.

[166] Chellasamy G, Arumugasamy SK, Govindaraju S, Yun K. Green synthesized carbon quantum dots from maple tree leaves for biosensing of cesium and electrocatalytic oxidation of glycerol. Chemosphere 2022;287:131915.

[167] Dastidar DG, Mukherjee P, Ghosh D, Banerjee D. Carbon quantum dots prepared from onion extract as fluorescence turn-on probes for selective estimation of Zn2+ in blood plasma. Colloids Surf A Physicochem Eng Asp 2021;611:125781.

[168] Pal T, Mohiyuddin S, Packirisamy G. Facile and green synthesis of multicolor fluorescence carbon dots from curcumin: in vitro and in vivo bioimaging and other applications. ACS Omega 2018;3:831–43.

[169] Xu H, Xie L, Hakkarainen M. Coffee-ground-derived quantum dots for aqueous processable nanoporous graphene membranes. ACS Sustain Chem Eng 2017;5:5360–7.

[170] Thambiraj S, Shankaran R. Green synthesis of highly fluorescent carbon quantum dots from sugarcane bagasse pulp. Appl Surf Sci 2016;390:435–43.

[171] Zhang J, Yuan Y, Liang G, Yu SH. Scale-up synthesis of fragrant nitrogen-doped carbon dots from bee pollens for bioimaging and catalysis. Adv Sci 2015;2:1500002.

[172] Xu H, Yang X, Li G, Zhao C, Liao X. Green synthesis of fluorescent carbon dots for selective detection of tartrazine in food samples. J Agric Food Chem 2015;63:6707–14.

[173] Li C-L, Ou C-M, Huang C-C, Wu W-C, Chen Y-P, Lin T-E, et al. Carbon dots prepared from ginger exhibiting efficient inhibition of human hepatocellular carcinoma cells. J Mater Chem B 2014;2:4564–71.

[174] Yin B, Deng J, Peng X, Long Q, Zhao J, Lu Q, et al. Green synthesis of carbon dots with down-and up-conversion fluorescent properties for sensitive detection of hypochlorite with a dual-readout assay. Analyst 2013;138:6551–7.

[175] Vibhute A, Patil T, Gambhir R, Tiwari AP. Fluorescent carbon quantum dots: synthesis methods, functionalization and biomedical applications. Appl Surf Sci Adv 2022;11:100311.

[176] Fakheri M, Fatemi S, Rahimi Kakolaki R. Comparative study of one-pot and facile methods to synthesize codoped CQDs with low band gap and photovoltaic properties. Can J Chem Eng 2023;101:4480–92.

[177] Zhang L-Y, Han Y-L, Yang J-J, Deng S-L, Wang B-Y. Construction and photocatalysis of carbon quantum dots/layered mesoporous titanium dioxide (CQDs/LM-TiO2) composites. Appl Surf Sci 2021;546:149089.

[178] Pandey SC, Kumar A, Sahu SK. Single step green synthesis of carbon dots from *Murraya koenigii* leaves; a unique turn-off fluorescent contrivance for selective sensing of Cd (II) ion. J Photochem Photobiol A Chem 2020;400:112620.

[179] Arumugam N, Kim J. Synthesis of carbon quantum dots from broccoli and their ability to detect silver ions. Mater Lett 2018;219:37–40.

[180] Park SW, Kim TE, Jung YK. Glutathione-decorated fluorescent carbon quantum dots for sensitive and selective detection of levodopa. Anal Chim Acta 2021;1165:338513.

[181] Posthuma-Trumpie GA, Wichers JH, Koets M, Berendsen LB, van Amerongen A. Amorphous carbon nanoparticles: a versatile label for rapid diagnostic (immuno)assays. Anal Bioanal Chem 2012;402:593–600.

[182] Zhuang Q, Li L, Ding Y, Zeng H, Wu Y. Highly luminescent nitrogen-doped carbon dots as “turn-on” fluorescence probe for selective detection of melamine. ChemistrySelect 2019;4:84–9.

[183] Nair A, Haponiuk JT, Thomas S, Gopi S. Natural carbon-based quantum dots and their applications in drug delivery: a review. Biomed Pharmacother 2020;132:110834.

[184] Molaei MJ. Carbon quantum dots and their biomedical and therapeutic applications: a review. RSC Adv 2019;9:6460–81.

[185] Mehta VN, Chettiar SS, Bhamore JR, Kailasa SK, Patel RM. Green synthetic approach for synthesis of fluorescent carbon dots for lisinopril drug delivery system and their confirmations in the cells. J Fluoresc 2017;27:111–24.

[186] Shu Y, Lu J, Mao Q-X, Song R-S, Wang X-Y, Chen X-W, et al. Ionic liquid mediated organophilic carbon dots for drug delivery and bioimaging. Carbon 2017;114:324–33.

[187] Wang Y, Cui Y, Zhao Y, He B, Shi X, Di D, et al. Fluorescent carbon dot-gated multifunctional mesoporous silica nanocarriers for redox/enzyme dual-responsive targeted and controlled drug delivery and real-time bioimaging. Eur J Pharm Biopharm 2017;117:105–15.

[188] Ardekani SM, Dehghani A, Hassan M, Kianinia M, Aharonovich I, Gomes VG. Two-photon excitation triggers combined chemo-photothermal therapy via doped carbon nanohybrid dots for effective breast cancer treatment. Chem Eng J 2017;330:651–62.

[189] Ma B, Zhang S, Liu R, Qiu J, Zhao L, Wang S, et al. Prolonged fluorescence lifetime of carbon quantum dots by combining with hydroxyapatite nanorods for bio-applications. Nanoscale 2017;9:2162–71.

[190] Sarkar N, Sahoo G, Das R, Prusty G, Swain SK. Carbon quantum dot tailored calcium alginate hydrogel for pH responsive controlled delivery of vancomycin. Eur J Pharm Sci 2017;109:359–71.

[191] Karagianni A, Tsierkezos NG, Prato M, Terrones M, Kordatos KV. Application of carbon-based quantum dots in photodynamic therapy. Carbon 2023;203:273–310.

[192] Mehravanfar H, Farhadian N, Abnous K. Indocyanine green-loaded N-doped carbon quantum dot nanoparticles for effective photodynamic therapy and cell imaging of melanoma cancer: in vitro, ex vivo and in vivo study. J Drug Target 2024:1–23.

[193] Sun L, Zhao Y, Yan J, Wang J, Cheng H, Wang Y, et al. Nitrogen-doped carbon dots as a highly efficient photosensitizer for photodynamic therapy to promote apoptosis in oral squamous cell carcinoma. Colloids Surf A Physicochem Eng Asp 2024;697:134409.

[194] Li X, Vinothini K, Ramesh T, Rajan M, Ramu A. Combined photodynamic-chemotherapy investigation of cancer cells using carbon quantum dot-based drug carrier system. Drug Deliv 2020;27:791–804.

[195] Gore PM, Purushothaman A, Naebe M, Wang X, Kandasubramanian B. Nanotechnology for oil-water separation. Adv Res Nanosci Water Technol 2019:299–339.

[196] Sridharan K, Ilango V, Samuel RS. Water purification by carbon quantum dots. Inorgan Organic Comp Water Wastewater Treatm 2022;2:113–60.

[197] Manikandan V, Lee NY. Green synthesis of carbon quantum dots and their environmental applications. Environ Res 2022;212:113283.

[198] Rahmanian O, Dinari M, Abdolmaleki MK. Carbon quantum dots/layered double hydroxide hybrid for fast and efficient decontamination of Cd (II): the adsorption kinetics and isotherms. Appl Surf Sci 2018;428:272–9.

[199] Mirzaeifard Z, Shariatinia Z. Economical, one-pot, and green synthesis of plant-based carbon quantum dots for efficient visible-light photocatalytic dye degradation and water purification. J Taiwan Inst Chem Eng 2024;163:105655.

[200] Hadidi M, Jafarzadeh S, Forough M, Garavand F, Alizadeh S, Salehabadi A, et al. Plant protein-based food packaging films; recent advances in fabrication, characterization, and applications. Trends Food Sci Technol 2022;120:154–73.

[201] Yang DeZhi YD, Tammina S, Li Xiao LX, Yang YaLing YY. Enhanced removal and detection of benzo [a] pyrene in environmental water samples using carbon dots-modified magnetic nanocomposites. 2019.

[202] Sabet M, Mahdavi K. Green synthesis of high photoluminescence nitrogen-doped carbon quantum dots from grass via a simple hydrothermal method for removing organic and inorganic water pollutions. Appl Surf Sci 2019;463:283–91.

[203] Li H-Y, Li D, Guo Y, Yang Y, Wei W, Xie B. On-site chemosensing and quantification of Cr (VI) in industrial wastewater using one-step synthesized fluorescent carbon quantum dots. Sens Actuators B 2018;277:30–8.