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Photoluminescent Carbon Dots for Intelligent Food Packaging: A Review on Sensing Mechanisms and Applications

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Abstract

Ensuring food safety and quality has become a global priority, demanding innovative solutions to detect early signs of spoilage or contamination. Intelligent food packaging systems offer a promising approach through real-time monitoring of food quality. Among various sensing materials, carbon dots (CDs) have emerged as a novel class of fluorescent nanomaterials with exceptional optical properties, high water solubility, low toxicity, and tunable photoluminescence. This review discusses the synthesis strategies of CDs particularly focusing on green synthesis using biomass waste and their photoluminescence mechanisms including quantum confinement, surface state, carbon core state, and molecular state emissions. The application of CDs in smart packaging is highlighted, especially in detecting spoilage indicators such as ammonia, hydrogen sulfide, Total Volatile Basic Nitrogen (TVBN), and pH changes. Various studies demonstrate the ability of CDs embedded in biopolymer matrices to produce distinct color changes in response to food spoilage, making them effective visual sensors. These findings support the development of eco-friendly, sensitive, and low-cost nano sensors for next-generation intelligent packaging technologies.

Keywords: Carbon dots, photoluminescent, intelligent, food packaging, sensing

1 Introduction

Preventing food contamination is vital for ensuring both food safety and maintaining its quality, making it a top priority for producers and consumers alike [1]. Packaging plays a key role as a protective barrier against external influences, contributing significantly to food preservation and safety [2]. To strengthen food safety measures, there is an urgent need for rapid, sensitive, and accurate detection systems to enhance current food safety monitoring technologies. In response to this need, smart or intelligent sensing technologies are gaining attention, offering real-time monitoring of food quality changes or microbial contamination throughout storage and distribution processes [3].

Nanotechnology provides a simple and fast detection method for food safety measurements, which may offer the opportunity to overcome food safety challenges through the food supply chain [4]. One of the efficient nanomaterials is carbon dots (CDs) based material. In recent years, there has been a substantial growth in research focused on ratiometric fluorescent probes based on CDs [5]. CDs are a novel class of zero-dimensional luminescent carbon nanomaterials with particle sizes smaller than 10 nanometers. They are characterized by their diverse range of raw material sources, straightforward and cost-effective synthesis processes, excellent water solubility, low toxicity, remarkable optical properties, strong biocompatibility, ease of surface modification, and high chemical stability [6].

Detection of Ammonia (NH_3) has attracted huge attention of researchers among various types of volatile species due to its dangerous effect on human health and the environment [7]. Many approaches and techniques have been presented to detect hydrogen sulfide (H_2S) gas, for instance, optical mass spectrometry, gas chromatography, electrochemical, piezoelectric sensors, and other instruments. However, these instruments or devices come with several drawbacks, including high cost, susceptibility to malfunction in harsh environments, limited stability, high energy consumption, lack of flexibility, bulky design, restricted applicability for in-situ and continuous monitoring, absence of real-time detection capabilities, and complex operation procedures [8]. Among these, fluorescence-based nanosensors exhibit the advantages of simplicity, sensitivity and high efficiency.

The development of sensors based on CDs is very important in the effort to detect spoilage indicators in food, such as changes in pH [9], NH_3 [10], TVBN [11], and H_2S [12]. These indicators are generally produced during the food spoilage process due to microorganism activity or enzymatic reactions, so their presence is an early marker of deterioration in food quality and safety [13]. Therefore, it is highly required to fabricate and design a highly sensitive, miniaturized, long term reliable, low power-consuming and room temperature efficient sensor, which can easily detect and monitor the food present in the environment in real time.

A focused literature search was conducted to identify relevant studies on photoluminescent carbon dots applied in intelligent food packaging. The search was performed using the ScienceDirect database, covering publications from 2020 to 2025. The following search string was applied to titles, abstracts, and keywords "Photoluminescent" OR "Fluorescent" AND "Carbon Dots" AND "Intelligent" OR "Smart" AND "Food Packaging". Studies were included if they met one or more of the following criteria: (i) applied carbon dots in food-contact materials, (ii) incorporated CDs into polymer matrices such as PVA, chitosan, carrageenan, or cellulose-based films, (iii) evaluated CDs for detecting spoilage-related analytes (NH_3, H_2S, pH, TVBN), or (iv) reported in-package or real-food testing. Studies focusing solely on biomedical uses, environmental sensing, theoretical modeling, or CDs not intended for food-related applications were excluded.

2 Overview of Carbon Dots

CDs have a nearly spherical (quasi-spherical) structure with a size of less than 10 nm, which consists of an sp^2-bonded nanocrystalline carbon core and an sp^3-bonded amorphous outer layer. CDs display various distinctive superior properties, such as customisable optical capabilities, good biocompatibility, very low to almost no cellular toxicity, relatively low production cost, high solubility in water, ease of synthesis, as well as large specific surface area. This combination of characteristics makes CDs highly potential for use in various engineering and biomedical fields [14].

CDs, as a new class of fluorescent carbon nanomaterials, have attracted growing attention in recent years. Various methods have been successfully developed to synthesise CDs with high efficiency and consistent characteristics. In general, there are two main approaches in the synthesis of high-quality CDs based on carbon sources, namely ‘top-down’ and ‘bottom-up’ methods, as seen in the **Fig. 1.** The top-down approach involves the decomposition of carbon materials through chemical, physical, or electrochemical techniques. In contrast, the bottom-up approach is based on chemical synthesis that includes pyrolysis and several other chemical reactions to carbonise small organic molecules, artificial compounds, or biomass [15].

Green synthesis of CDs refers to production processes that utilise environmentally friendly materials and/or energy-efficient methods. These processes generally involve the use of natural precursors such as plant materials, microorganisms, food waste, or other waste streams, with the aim of avoiding the use of toxic chemicals as well as complex and expensive equipment. Plant waste, which is generated in large quantities by various food sectors, is a very suitable starting material for the synthesis of CDs due to its biocompatibility, cheapness, and non-toxicity [16]. In addition, carbon derived from microorganism biomass also offers extensive opportunities for CDs production. Microbial biomass is abundantly available in nature, easily obtained at low cost, and can be efficiently processed [17].

3 Photoluminescent Mechanisms of Carbon Dots

CDs are a class of carbon-based nanomaterials that have garnered significant attention due to their unique and tunable photoluminescent (PL) properties, which make them highly attractive for a wide range of applications such as bioimaging, sensors, light-emitting devices, and drug delivery. The optical characteristics of CDs are influenced by various factors including their elemental composition, morphology, particle size distribution, and the specific synthetic methods employed [18]. Among these, particle size plays a crucial role due to the quantum confinement effect (QCE), where the electronic properties of the nanoparticles change as their size approaches or becomes smaller than the exciton Bohr radius. As reported by Ye et al. (2013), the quantum confinement effect causes a blue shift in emission for smaller CDs, while increasing the particle size leads to a red shift in emission, allowing modulation of photoluminescence across a wide spectral range, from ultraviolet (UV) to near-infrared (NIR). if the emission wavelength shows strong excitation dependence and marked sensitivity to environmental factors such as pH or ionic strength, surface states are likely dominant; conversely, excitation-independent and environmentally stable emission generally indicates core-state involvement.

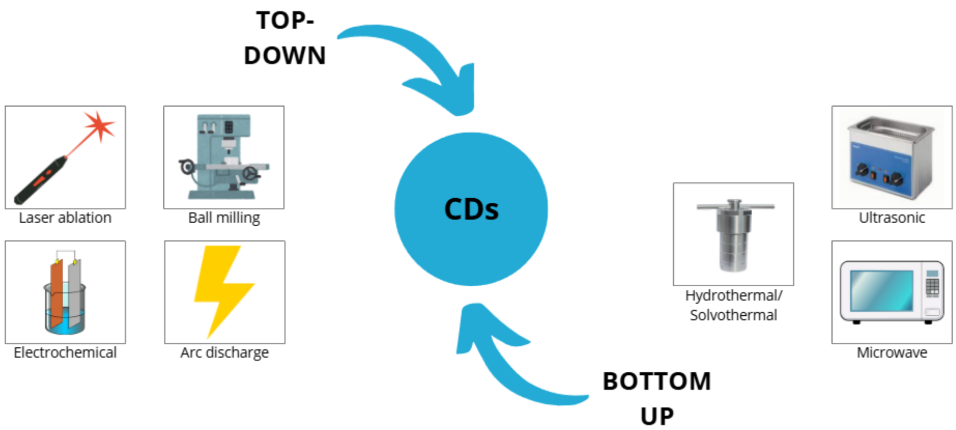

Figure 1. General scheme of the synthesis method for CDs through top-down and bottom-up approaches, including laser ablation, ball milling, electrochemistry, arc discharge, hydrothermal/solvothermal, ultrasonic, and microwave processes.

However, particle size alone does not fully explain the broad range and variability of PL emissions observed in CDs. CDs with similar sizes can emit light at vastly different wavelengths, suggesting that additional factors contribute to their optical behavior [20]. These factors include surface passivation, the presence of surface defects, heteroatom doping and the degree of carbonization and conjugation within the core structure. The synthesis conditions such as temperature, time, pH, and precursor type also significantly influence the resulting surface chemistry and core structure of CDs, which in turn affect their PL performance [21]. The most widely accepted explanation for the PL mechanism in CDs is classified into three major categories: surface state, carbon core state, and molecular state.

In the surface state mechanism, the photoluminescence originates from surface defects and functional groups such as hydroxyl, carboxyl, amine, and carbonyl groups that form during synthesis. The increase of acidity mainly affects the amino groups on the surface of CDs. These surface moieties create discrete energy levels within the band gap, leading to radiative recombination of excitons. The nature and density of these surface groups can be deliberately modified to tune the PL emission, often enabling multicolor emission from a single batch of CDs [22]. Moreover, the application of higher synthesis potentials has been reported to increase the degree of surface oxidation in CDs, leading to a red-shift in their PL emission. This red-shift is generally attributed to the formation of a higher density of oxygen-containing functional groups, which introduces more surface defects and deeper trap states. These trap states enhance exciton localization and delay recombination, resulting in longer-wavelength emissions. Thus, as the surface oxidation intensifies, a progression in emission color can be observed, typically shifting from blue to green or even red, depending on the extent of defect state formation. For instance, Bao et al. (2011) observed that CDs with a high degree of surface oxidation exhibit a prominent green photoluminescence, supporting the strong influence of surface state modulation on emission characteristics (**Fig. 2**). This mechanism is particularly important for sensing because analytes can directly interact with surface groups. For example, NH_3, as a Lewis base, can deprotonate –COOH groups or coordinate to –C=O/–COOH sites, thereby shifting surface-state energy levels and often causing blue shifts or PL enhancement/suppression. Meanwhile, H_2S can act as an electron donor or engage in electron-transfer quenching, suppressing the excited-state population; its soft-acid nature also allows interaction with oxidized sulfur- or nitrogen-containing defects. pH influences the protonation state of –COOH, –OH, and $–NH_2$ groups, which modulates trap depth and typically yields reversible PL shifts or intensity changes.

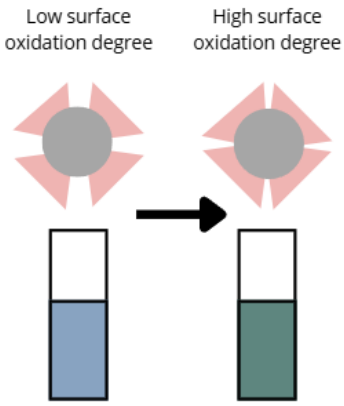

Figure 2. Scheme of changes in CDs emission due to different degrees of surface oxidation.

The carbon core state mechanism relates to the intrinsic electronic transitions within the sp^2-hybridized carbon network. Specifically, the π–π* transitions in the conjugated carbon domains are responsible for light emission. These domains, formed via partial carbonization and graphitization during synthesis, are akin to nanoscale graphite-like structures. Emissions from this mechanism are generally more stable and less sensitive to environmental conditions compared to surface-state emissions [24]. Eventually, the formation of the carbon core contributes to additional emission channels. However, analytes can still influence core-state emission indirectly. For example, strong electron acceptors or donors adsorbing near the core can induce electron/energy transfer, altering the recombination pathways.

On the other hand, the molecular state mechanism involves fluorescent organic molecules or their aggregates that are either incorporated into or attached onto the CD structure during or after synthesis. Molecular states originate from precursor-derived organic intermediates that form through dehydration, condensation, aromatization, and other carbonization-related reactions during CD synthesis. These molecular species may originate from incomplete carbonization of the organic precursors or from additives. They typically exhibit strong and sharp fluorescence with high photoluminescence quantum yields (PLQYs). In the early stages of CD formation, the PL is predominantly governed by these small fluorophores. As the reaction progresses, molecular cross-linking and carbonization occur, leading to crosslink-enhanced emission (CEE) a phenomenon in which the emission intensity increases due to restricted intramolecular motions within the polymerized structure [25]. In the bottom-up synthesis approach, understanding the molecular state is essential, but because CDs are formed in mixtures that are difficult to analyse, it is difficult to determine their specific structure or mechanism. This limits the understanding and application of the molecular state concept in explaining the photoluminescence of CDs.

4 CDs Applications in Intelligent Food Packaging

CDs have shown great potential in smart food packaging applications, especially as visual sensors to detect food freshness or contamination. Through the integration of CDs into the biopolymer matrix, the packaging can respond to changes that occur during food storage [26]. This ability to change the fluorescence of CDs by interacting with specific substances could be exploited to develop fluorescent nanosensors to detect changes in pH in various environments, including food [27]. Intelligent packaging systems can be categorized into three primary categories: indicators, sensors, and data carriers. Indicators are used to identify the presence or absence of a specific analyte or offer semiquantitative data. Sensors, enable the quantification of target analytes within the package by interpreting response signals. Data carriers are primarily utilized for automation, traceability, theft prevention, and counterfeit protection [28].

As illustrated in Figure 3, **Fig. 3a** shows an example of an indicator, where a color change label on a milk carton shifts from dark blue (fresh milk) to light blue (spoiled milk). This visual change indicates the freshness status of the milk, helping consumers identify spoilage without opening the package. **Fig. 3b** also demonstrates an indicator application for seafood, where the label changes color from red to dark blue as shrimp spoil at 30°C over time. These smart indicators visually communicate food quality changes caused by microbial activity or chemical reactions, aligning with the role of indicators in intelligent packaging systems. Such tools are vital in enhancing food safety, reducing waste, and empowering consumer awareness through clear, real-time visual cues.

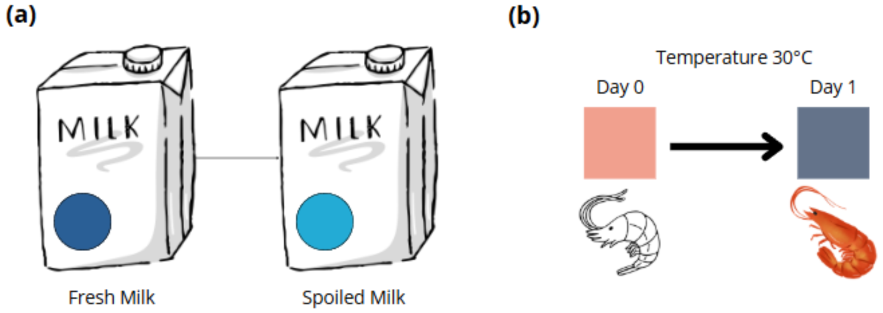

Figure 3. (a) a cartoon showing the application of intelligent packaging to milk packaging, (b) freshness monitoring of prawns using intelligent film.

Changes such as pH or the presence of NH_3, can provide visual signals that are easy to observe, such as colour changes as can be seen in **Table 1**. Variation in colorimetric intensity and contrast arises mainly from the chemical structure and surface functionalities of the CDs, such as amine, carbonyl, hydroxyl, or aromatic groups that influence the PL behavior. For instance, CDs synthesized from nitrogen-rich precursors like urea or m-phenylenediamine tend to exhibit more pronounced visual transitions due to their ability to generate highly responsive surface-state emissions. CDs synthesised from citric acid and urea using a hydrothermal method and integrated into a PVA matrix, showed a light dark colour change when detecting NH_3 in shrimp packaging [29]. Meanwhile, biomass-derived CDs such as those from coffee grounds, sweet potato peels, or purple pistachio often display more gradual color transitions due to the predominance of oxygenated and phenolic surface groups. Coffee waste-based CDs in a chitosan (CS) matrix used to package milk, showed a red-shift in emission in response to pH changes [30]. Other biomass sources such as rose petals, phytic acid, and even the plant Koelreuteria paniculata have also been explored, each producing significant colour changes when used to package meat products such as pork and shrimp, responding to pH changes from storage or microbial degradation. For example, packaging containing CDs from rose petals showed a change from red to dark yellow when used for packaging shrimp and pork [31], while CDs of phytic acid showed a colour change from brownish yellow to purplish red when used for pork [32].

The choice of matrix further modulates sensor performance. Hydrophilic and permeable polymers such as chitosan, carrageenan, and soy protein isolate facilitate rapid diffusion of volatile spoilage compounds toward the CD surface, resulting in faster and more distinct color changes. In contrast, denser matrices like PVA exhibit lower gas permeability, producing subtler visual shifts even when paired with responsive CDs. CMC/alginate or chitosan/locust bean gum offer a balance between permeability and mechanical stability, enabling complex multi-step color evolutions such as transitions from green to blue or lilac to brown that correlate with the degree of spoilage and matrix-specific interactions.

Overall, the application of CDs in smart packaging demonstrates excellent flexibility in assessing the quality of various animal-based food products. These sensors are not only inexpensive and environmentally friendly but also highly customizable through the selection of precursors, synthesis methods, and matrix polymer types. These factors also indicate that the success of CD-based intelligent packaging films is driven by the synergy between precursor chemistry, synthesis mechanisms that shape the optical structure of the CDs, and the permeability and chemical interactions of the film matrix. The interplay of these factors determines the system's sensitivity, response speed, color clarity, and stability under real storage conditions, thereby providing rational design guidelines for the development of next-generation food packaging sensors.

Table 1. CDs Applications in Intelligent Food Packaging

Precursor	Synthesis Method	Matrix	Food Product	Analyte	Observed Change	Ref
Citric acid and urea	Hydro-thermal	PVA	Shrimp	NH_3	A slight darkening of color	[29]
Coffee ground waste	Hydro-thermal	CS	Milk	pH	Emission red-shifted	[30]
Urea and Dodecylbenzen esulfonic acid (DTSA)	Solvo-thermal	Carr	Shirmp	NH_3	Film color changed from orange to blue	[11]
Sweet potato peels	Hydro-thermal	Carr	Shrimp	pH	the pinkish/ reddish colour on the film turns light yellow and dark yellow/brownish	[33]
Purple hull pistachio	Hydro-thermal	CS/ Soy protein isolate	Fish	pH, TVB-N	Film color changed from light lylac to brown	[34]
m-phenylenediam ine and D-penicillamine	Hydro-thermal	CMC/ Sodium alginate	Fish and shrimp	pH	color changed from greenish to light greenish (shrimp), and cyan to light cyan, then to blue gradually (fish)	[35]
Aminated lignin and N, N-dimethyl formamide	Solvo-thermal	Carr	Milk	pH	Emission red-shifted	[36]
Chitosan	Hydro-thermal	Fish Gelatin	Shrimp	pH	a color change to green	[37]
Rose petals	Hydro-thermal	Carr	Shrimp and pork	NH_3, Acetic acid	Color change from red colors to dark yellowish	[31]
Phytic acid	Hydro-thermal	Strach/ PVA	Pork	TVB-N	Color change from brownish yellow to purplish-red	[32]
Koelreuteria paniculata Laxm. and TiO_2	Hydro-thermal	Chitosa n/locust bean gum	Shrimp	TVB-N	Color change from light yellow to dark brown	[38]
1,2,4-triaminobenzen e dihydrochlorid e	Hydro-thermal	CNF	Prawns, grape and strawber ries	TVB-N, pH	Color change from pink to yellowish-pink, light yellow to reddish	[39]

5 Conclusion

CDs represent a highly promising material for intelligent food packaging applications due to their excellent photoluminescent properties, environmental friendliness, and adaptability in synthesis. Their ability to detect spoilage indicators such as pH, ammonia, H_2S, and TVBN through observable optical changes provides an effective tool for real-time food freshness monitoring. The integration of CDs into biopolymer matrices has shown significant potential in developing colorimetric sensors that are not only sensitive and reliable but also cost-effective and compatible with scalable manufacturing. To advance these systems toward commercial deployment, future studies should prioritize the development of ratiometric dual-emission labels to minimize variations caused by illumination or sensor aging, and the standardization of testing protocols, including controlled headspace generation for NH_3/H_2S, relative humidity management, and storage temperatures relevant to meat and dairy products. Additionally, integrating smartphone-based colorimetry with on-label calibration tools (such as color cards or QR-encoded correction profiles) can enhance readout accuracy for end users. Equally important is establishing comprehensive migration, NIAS, and cytotoxicity assessment workflows to ensure regulatory compliance prior to pilot-scale trials. These steps collectively strengthen the pathway toward precise, safe, and commercially viable intelligent packaging solutions based on CDs.

References

[1] Jeddi MZ, Boon PE, Cubadda F, et al. A vision on the 'foodture' role of dietary exposure sciences in the interplay between food safety and nutrition. *Trends in Food Science and Technology* 2022; 120: 288–300. DOI: https://doi.org/10.1016/j.tifs.2022.01.024

[2] Marsh K, Bugusu B. Food packaging - Roles, materials, and environmental issues: Scientific status summary. *Journal of Food Science*; 72. Epub ahead of print 2007. DOI: https://doi.org/10.1111/j.1750-3841.2007.00301.x.

[3] Azeredo HMC, Correa DS. Smart choices: Mechanisms of intelligent food packaging. *Current Research in Food Science* 2021; 4: 932–936. DOI: https://doi.org/10.1016/j.crfs.2021.11.016

[4] Alfei S, Marengo B, Zuccari G. Nanotechnology application in food packaging: A plethora of opportunities versus pending risks assessment and public concerns. *Food Research International* 2020; 137: 109664. DOI: https://doi.org/10.1016/j.foodres.2020.109664

[5] Huang M, Li R, Zhou P, et al. Carbon dots@silica-based dual-emission ratiometric fluorescent sensor for highly selective detection of Cu2+ and thiram. *Journal of Photochemistry and Photobiology A: Chemistry* 2025; 468: 116498. DOI: https://doi.org/10.1016/j.jphotochem.2025.116498

[6] Đorđević L, Arcudi F, Cacioppo M, et al. A multifunctional chemical toolbox to engineer carbon dots for biomedical and energy applications. *Nature nanotechnology* 2022; 17: 112–130. DOI: https://doi.org/10.1038/s41565-021-01051-7

[7] Ampollini L, Katz EF, Bourne S, et al. Observations and Contributions of Real-Time Indoor Ammonia Concentrations during HOMEChem. *Environmental Science and Technology* 2019; 53: 8591–8598. DOI: https://doi.org/10.1021/acs.est.9b02157

[8] Kumar V, Majhi SM, Kim KH, et al. Advances in In2O3-based materials for the development of hydrogen sulfide sensors. *Chemical Engineering Journal* 2021; 404: 126472. DOI: https://doi.org/10.1016/j.cej.2020.126472

[9] Xu J, Sun L, Guo X, et al. pH and solvent induced discoloration behavior of multicolor fluorescent carbon dots. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 2022; 648: 129261. DOI: https://doi.org/10.1016/j.colsurfa.2022.129261

[10] Alam MB, Yadav K, Shukla D, et al. Ammonia vapour detection at room temperature via carbon quantum dots based facile system. *Chemical Physics Impact* 2024; 8: 100633. DOI: https://doi.org/10.1016/j.chphi.2024.100633

[11] Sangeetha UK, De S, Khatun S, et al. Carbon dots embedded carrageenan based compostable functional packaging films with barrier bio-coating for prawns freshness monitoring. *Int J Biol Macromol* 2025; 310: 143533. DOI: https://doi.org/10.1016/j.ijbiomac.2025.143533

[12] El-Shamy AG. New nano-composite based on carbon dots (CDots) decorated magnesium oxide (MgO) nano-particles (CDots@MgO) sensor for high H2S gas sensitivity performance. *Sensors and Actuators, B: Chemical* 2021; 329: 129154. DOI: https://doi.org/10.1016/j.snb.2020.129154

[13] Rather IA, Koh WY, Paek WK, et al. The sources of chemical contaminants in food and their health implications. *Frontiers in*

Pharmacology; 8. Epub ahead of print 2017. DOI: 10.3389/fphar.2017.00830. DOI: https://doi.org/10.3389/fphar.2017.00830

[14] Liu J, Li R, Yang B. Carbon Dots: A New Type of Carbon-Based Nanomaterial with Wide Applications. *ACS Central Science* 2020; 6: 2179–2195. DOI: https://doi.org/10.1021/acscentsci.0c01306

[15] Wang R, Lu K-Q, Tang Z-R, et al. Recent progress in carbon quantum dots: synthesis, properties, and applications in photocatalysis. *J Mater Chem A* 2017; 5: 3717–3734. DOI: https://doi.org/10.1039/C6TA08660H

[16] Pérez-Jiménez J, Saura-Calixto F. Fruit peels as sources of non-extractable polyphenols or macromolecular antioxidants: Analysis and nutritional implications. *Food Research International* 2018; 111: 148–152. DOI: https://doi.org/10.1016/j.foodres.2018.05.023

[17] Ghorbani M, Tajik H, Moradi M, et al. One-pot microbial approach to synthesize carbon dots from baker's yeast-derived compounds for the preparation of antimicrobial membrane. *Journal of Environmental Chemical Engineering* 2022; 10: 107525. DOI: https://doi.org/10.1016/j.jece.2022.107525

[18] Zhang J, Sun Y, Ye S, et al. Heterostructures in Two-Dimensional CdSe Nanoplatelets: Synthesis, Optical Properties, and Applications. *Chemistry of Materials* 2020; 32: 9490–9507. DOI: https://doi.org/10.1021/acs.chemmater.0c02593

[19] Ye R, Xiang C, Lin J, et al. Coal as an abundant source of graphene quantum dots. *Nature communications* 2013; 4: 2943. DOI: https://doi.org/10.1038/ncomms3943

[20] Ding H, Yu S-B, Wei J-S, et al. Full-Color Light-Emitting Carbon Dots with a Surface - State - Controlled Luminescence Mechanism. *ACS nano* 2016; 10: 484–491. DOI: https://doi.org/10.1021/acsnano.5b05406

[21] Alafeef M, Srivastava I, Aditya T, et al. Carbon Dots: From Synthesis to Unraveling the Fluorescence Mechanism. *Small* 2024; 20: 1–13. DOI: https://doi.org/10.1002/smll.202303937

[22] Kundelev E V, Tepliakov N V, Leonov MY, et al. Amino Functionalization of Carbon Dots Leads to Red Emission Enhancement. *The journal of physical chemistry letters* 2019; 10: 5111–5116. DOI: https://doi.org/10.1021/acs.jpclett.9b01724

[23] Bao L, Zhang Z-L, Tian Z-Q, et al. Electrochemical Tuning of Luminescent Carbon Nanodots: From Preparation to Luminescence Mechanism. *Advanced Materials* 2011; 23: 5801–5806. DOI: https://doi.org/10.1002/adma.201102866

[24] Zhu S, Song Y, Zhao X, et al. The photoluminescence mechanism in carbon dots (graphene quantum dots, carbon nanodots, and polymer dots): current state and future perspective. *Nano Research* 2015; 8: 355–381. DOI: https://doi.org/10.1007/s12274-014-0644-3

[25] Kasprzyk W, Bednarz S, Żmudzki P, et al. Novel efficient fluorophores synthesized from citric acid. *RSC Adv* 2015; 5: 34795–34799. DOI: https://doi.org/10.1039/C5RA03226A

[26] Jafarzadeh S, Yildiz Z, Yildiz P, et al. Advanced technologies in biodegradable packaging using intelligent sensing to fight food waste. *International Journal of Biological Macromolecules* 2024; 261: 129647. DOI: https://doi.org/10.1016/j.ijbiomac.2024.129647

[27] Moradi M, Rahim M, Seyedeh Alaleh K, et al. Carbon dots synthesized from microorganisms and food by-products: active and smart food packaging applications. *Critical Reviews in Food Science and Nutrition* 2023; 63: 1943–1959. DOI: https://doi.org/10.1080/10408398.2021.2015283

[28] Wang Y, Liu K, Zhang M, et al. Sustainable polysaccharide-based materials for intelligent packaging. *Carbohydrate Polymers* 2023; 313: 120851. DOI: https://doi.org/10.1016/j.carbpol.2023.120851

[29] Hong SJ, Riahi Z, Shin GH, et al. Poly(vinyl alcohol)-based multifunctional smart packaging films with carbon dots-loaded metal-organic frameworks for freshness indicator and shelf-life extension of shrimp. *Prog Org Coat* 2025; 198: 108899. DOI: https://doi.org/10.1016/j.porgcoat.2024.108899

[30] Ananda B, Radha Krushna BR, Gagana M, et al. Biodegradable chitosan-based carbon dot-infused intelligent films with UV-blocking and shape memory properties for shrimp preservation and milk freshness monitoring. *Journal of Industrial and Engineering Chemistry* 2025; 151: 388–408. DOI: https://doi.org/10.1016/j.jiec.2025.04.005

[31] Wagh R V., Riahi Z, Kim JT, et al. Carrageenan-based functional films hybridized with carbon dots and anthocyanins from rose petals for smart food packaging applications. *Int J Biol Macromol* 2024; 272: 132817. DOI: https://doi.org/10.1016/j.ijbiomac.2024.132817

[32] Ding J, Liao X, Li W, et al. Preparation of pH sensitive P-doped carbon dots-loaded starch/polyvinyl alcohol packaging film for real-time monitoring freshness of pork. *Food Biosci* 2024; 61: 104654. DOI: https://doi.org/10.1016/j.fbio.2024.104654

[33] Riahi Z, Khan A, Rhim JW, et al. 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. DOI: https://doi.org/10.1016/j.ijbiomac.2024.129371

[34] Hadavifar S, Abedi-Firoozjah R, Bahramian B, et al. Multifunctional performance of chitosan/soy protein isolation-based films impregnated carbon dots/anthocyanin derived from purple hull pistachio for tracking and extending the shelf life of fish. *Food Hydrocoll* 2025; 159: 110678. DOI: https://doi.org/10.1016/j.foodhyd.2024.110678

[35] Chen M, Zhou M, Wang Y, et al. Carboxymethyl cellulose and sodium alginate-enhanced hydrogel for carbon dots loading: A novel platform for pH sensing and sensitive detection of Al3+ and Ag+. *Int J Biol Macromol* 2025; 307: 141955. DOI: https://doi.org/10.1016/j.ijbiomac.2025.141955

[36] Sangeetha UK, Sudhakaran N, Parvathy PA, et al. Coconut husk-lignin derived carbon dots incorporated carrageenan based functional film for intelligent food packaging. *Int J Biol Macromol* 2024; 266: 131005. DOI: https://doi.org/10.1016/j.ijbiomac.2024.131005

[37] Ponnusamy A, Khan A, Prodpran T, et al. Multifunctional fish gelatin film incorporated with chitosan carbon dots and butterfly pea flower anthocyanins for active/smart packaging of Pacific white shrimp. *Food Biosci* 2024; 62: 105483. DOI: https://doi.org/10.1016/j.fbio.2024.105483

[38] Li M, Liu Y, Wang Y, et al. Development, characterization and application of chitosan/locust bean gum based multifunctional green food packaging containing Koelreuteria paniculata Laxm. bracts extract and Ti-carbon dots. *Int J Biol Macromol* 2024; 278: 134610. DOI: https://doi.org/10.1016/j.ijbiomac.2024.134610

[39] Zhu H, Li J, Cheng JH. Designing cellulose nanofibrils/carbon dots intelligent label with colorimetric and fluorescent dual responsiveness for real-time monitoring of food freshness. *Int J Biol Macromol* 2024; 271: 132642. DOI: https://doi.org/10.1016/j.ijbiomac.2024.132642