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CARBON QUANTUM DOTS: A SMART PRESERVATIVE FOR FRUITS AND VEGETABLES

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ABSTRACT
Fruits and vegetables remain metabolically active even after harvest causes microbial contamination, oxidative degradation and rapid deterioration leads to significant postharvest losses. Conventional preservatives often raise an environmental and health concerns, creating the need for safer, environmentally friendly and cost-effective preservation technology. Carbon Quantum Dots (CQDs) are nano sized carbon materials with unique and antimicrobial properties have recently emerged as a promising preservation technology for fruits and vegetables. Their excellent tunable properties, biocompatibility makes them ideal for integration of CQDs into edible coatings and smart packaging films to enhance the shelf life and prolonging the storage of fruits and vegetables. CQDs inhibit bacterial and fungal growth through reactive oxygen species generation and membrane disruption. CQDs has excellent fluorescent properties which allows for real-time monitoring of freshness indicator. Furthermore, CQDs can be derived from agricultural waste offering a sustainable and cost-effective approach for preservation. This review explores the synthesis, mechanism of action and recent application in preservation of fruits and vegetables, highlighting CQDs potential as next generation preservatives.

KEYWORDS: Carbon Quantum Dots, Nanotechnology, Fruits and vegetables, Postharvest quality, Shelf-life extension.

Abbreviations
CQD – Carbon Quantum Dots
PLQY - Photoluminescence quantum yield
LED - Light Emitting Diode
UV – Ultraviolet
ROS – Reactive Oxygen Species
DPPH - 2,2-Diphenyl-1-picrylhydrazyl
ABTS - 2,2'-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)
CMC - carboxymethyl cellulose
PVA - Polyvinyl Alcohol
PPO – Polyphenol Oxidase
CD – Carbon dots

INTRODUCTION

Fruits and vegetables are very important components of the human diet, as they provide essential nutrients, fibers, as well as bioactive compounds that boost the health status and prevent various diseases. Despite containing higher moisture content and having active metabolic processes, fruits and vegetables are very susceptible to spoilage, leading to significant losses at the postharvest level. It has been estimated that up to 50% of the fruits and vegetables consumed get lost at the entire chain of consumption, from the level of harvest to the consumption of the produce, due to spoilage, damage, contamination with microbes, and improper handling practices (Porat *et al.,* 2018). This impacts the security of food as well as creates various environmental issues in developing countries where there are deficiencies in the cool storage chain infrastructure (Etefa *et al.,* 2022). Perishability in fruits and vegetables is largely caused by high respiration rate, susceptibility to microbial infections, as well as environmental factors. Losses could occur at various points, such as during harvesting, storage, transportation, and retail and factors such as pests, diseases, damage or improper means of storage could be responsible for such losses (Porat *et al.,* 2018). Such losses result in reduced availability for nutritious food, as well as wastage of resources.
In order to reduce postharvest losses, a number of preservation technologies have been designed and widely adopted. Examples include refrigeration, chemical preservatives, and modified atmosphere packaging. Refrigeration has been an effective way to lower postharvest losses because it slows the rate at which products go

to spoil. However, such preservation requires high energy utilization (Chen *et al.,* 2024). Even though chemical preservatives help lower postharvest losses, their toxicity has been a major cause of concern because people have been searching for healthier preservation methods (Lisboa *et al.,* 2024). Modified atmosphere packaging and modern technologies can be beneficial in reducing postharvest losses. However, such technologies typically require more high-quality packaging materials and equipment, which can be costly (Wilson *et al.,* 2019). In return, the inefficiency in many preservation methods calls for the need for new technologies that are effectively safe and environmentally friendly. Consumers and industry stakeholders would be searching for approaches or modes that minimize chemical residues, energy consumption with renewable resources (Awlqadr *et al.,* 2025). Ideally, sustainable preservation methods should be affordable, scalable, maintain the nutritional and sensory qualities of fresh produce and assure food safety. These days, the logics have entailed the use of natural preservatives, biodegradable packaging options, and smart monitoring technologies in a holistic approach to reduction of postharvest loss and improving food security have been considered important *(*Chaudhary *et al.,* 2025).
Carbon quantum dots (CQDs) are emerging as promising nanomaterials (less than 10 nm) in preservation of food because of their unique properties, such as biocompatibility, low toxicity, water solubility, high fluorescence, and ability to be derived from renewable materials such as food waste (Hu *et al.,* 2022). CQDs show high antibacterial and antioxidant activity, making them potential materials in the preparation of active packaging, edible coatings, and intelligent sensors for real-time monitoring of food quality (Chaudhary *et al.,* 2025; Khan, Priyadarshi, *et al.,* 2023). In applications involving the preservation of fruits and vegetables, the utilization of CQDs may increase the storage life of produce, reduce microbes that cause spoilage, and enable the preparation of intelligent preservatives. CQDs can be considered environmentally friendly alternatives because of the rising need for innovative, safe and effective preservation methods in the food industry.

Synthesis of Carbon Quantum Dots

Carbon Quantum Dots (CQDs) signify a new class of fluorescent nanomaterials, characterized by their tiny size (typically below 10 nm), semi-spherical structure, and rich supply of surface functional groups, thereby offering excellent solubility within water as well as the ability for further functionalization (Yang *et al.,* 2023). As shown in fig. 1, these carbon quantum dots can be prepared using a range of top-down approaches like arc discharge, laser ablation, electrochemical oxidation, as well as bottom-up approaches like hydrothermal, microwave, as well as pyrolysis, although recent advances involve using eco-friendly, one step, and solid green chemistry for their synthesis (Kumar *et al.,* 2022). These carbon quantum dots exhibit strong, controllable fluorescence, high photostability, strong excitation dependent emissions, unique characteristics that emanate from quantum confinement effects, as well as controlled photoluminescence via surface states, thereby making them excellent candidates for bio-imaging, sensing as well as food preservation applications (Park *et al.,* 2025). The surface chemistry of CQDs rich in oxygen as well as nitrogen components, not only increases their ability to distribute within aqueous systems, but they can be easily functionalized, thus widening their range of potential applications (Nallayagari *et al.,* 2022). Compared with other nanomaterials that have been used in food preservation, including semiconductor quantum dots that often include toxic heavy metal elements, graphene, or carbon nanotubes, the advantages of CQDs include their lower toxicity, biocompatibility, and sustainability in the environment. In addition, the optical properties of CQDs are outstanding, and they can be synthesized from eco-friendly precursors (Pan *et al.,* 2020). These attributes of CQDs make them highly desirable for applications in the food industry, where sustainability and multifunctionality, including UV protection, antioxidant, and antibacterial properties are more highly valued (Osman *et al.,* 2024).

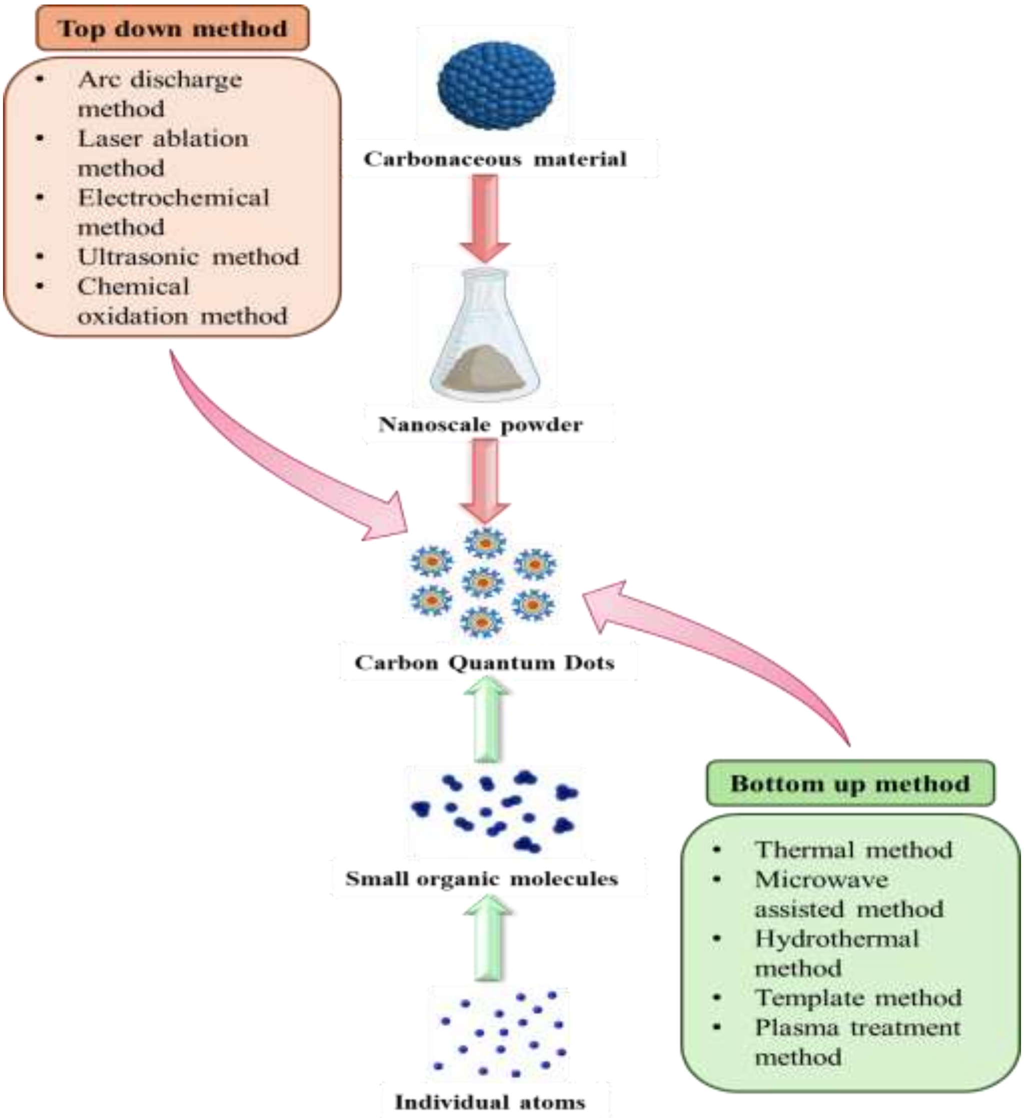

Fig. 1: Synthesis of Carbon Quantum Dots

Top-down synthesis

Top-down methods of producing carbon quantum dots (CQDs) include the reduction of bulk carbon materials to nanometric dots using physical, chemical or other processes such as arc discharge, laser ablation, electrochemical oxidation, and acid-assisted chemical oxidation (Kong *et al.,* 2024). The arc discharge method relies on the use of high energy plasma between electrodes to vaporize carbon, producing CQDs with high oxygen content that are strongly fluorescent, but it requires very high temperatures with quite expensive set up, resulting in varying sizes of the CQDs with low purification efficiency due to the presence of impurities (Rasal *et al.,* 2021). Laser ablation requires high laser pulses to fragment carbon resources such as graphite or carbon nanotubes, which have controllable size and morphology with water solubility, fluorescence, but relatively high costs with complex processes, resulting in low quantum yields and poor size control (Singh *et al.,* 2018). Electrochemical oxidation uses an electrochemical system that oxidizes carbon electrodes in an electrochemical cell, thereby obtaining water soluble CQDs with tunable properties depending on the applied current density. However, this method is complex, requires prolonged processing times, and has low quantum efficiency (Kaur *et al.,* 2022). Acid-mediated chemical oxidation requires the interaction of strong acids that transform carbon compounds into water-soluble CQDs. However, this method requires the utilization of dangerous chemicals that pollutes the environment during processing and requires frequent purification of the sample, leading to the presence of varied sample size (Iravani & Varma, 2020). In conclusion, top-down approaches can be able to produce CQDs of varying properties but experiences limitations including sample size variability, high energy requirements, high-cost processing equipment, extreme conditions of reactions and complex purification steps (Iravani & Varma, 2020; Kong *et al.,* 2024; Rasal *et al.,* 2021).

Bottom-up synthesis

In contrast, bottom-up methods synthesize CQDs through assembling small organic molecules or polymers using different approaches such as hydrothermal, solvothermal, microwave, pyrolysis and ultrasonic methods (Rasal *et al.,* 2021). The hydrothermal method involves the heat treatment of organic precursors in a closed vessel. It produces highly water-dispersible, non-toxic CQDs with relatively comparable sizes, although controlling the size can still be challenging (Singh *et al.,* 2018). The solvothermal method, is similar to hydrothermal, involves the use of organic solvents, which can further offer variations in the characteristics of CQDs (Kong *et al.,* 2024). Microwave synthesis involves the quick heating of the precursors, thus allowing fast, easy, and environmentally friendly production of CQDs, but the control over the size may not be accurate (Singh *et al.,* 2018). Pyrolysis results from the thermal decomposition of precursors at high temperatures, which allows a solvent free, scalable, and cost-effective approach, while the ultrasonic method involves the use of ultrasonic waves for the decomposition of precursors, providing an easy green synthesis method (El-Shabasy *et al.,* 2021). The Bottom-up approaches are usually preferred because they tend produce CQDs of more regular size, the processes are easier and scalable, at lower cost, and eco-friendly conditions, which makes them more suitable for large scale and sustainable production (El-Shabasy *et al.,* 2021; Kong *et al.,* 2024; Rasal *et al.,* 2021).

Doping of CQDs

Traditional Carbon Quantum Dots (CQDs) have encountered some limitations because of their poor quantum yield (limited fluorescence emission), which hinders their usage in the fields of sensing, imaging and antimicrobial applications. The incorporation of foreign atoms such as nitrogen (N), sulphur (S), Phosphorus (P), boron (B) or different metals, into the structure of CQDs makes it feasible to increase the optical and biological properties (Li *et al.,* 2025). Doping represents the intentional incorporation of non-carbon atoms within the core or outer structure of the carbon dots synthesized. These foreign atoms, which include heteroatoms, work by causing alterations in the electronic structure (energy levels, band gap, surface states) as well as outer structure's chemical composition (Charge, functional groups, hydrogen-bonding sites). Both factors significantly affect fluorescence emission, the efficiency of catalysis and cell and microbial interactions (A. Lee et al., 2021). Nitrogen doped Carbon Quantum Dots (N-CQDs) have the highest quantum yields with blue green fluorescence emission ideal for bioimaging and sensing (Li *et al.,* 2025). Doping with non-metal atoms such as nitrogen, sulphur, phosphorus, boron and selenium, as well as metal or metal ion doping with Mn, Fe, Cu, Ag, Ce, Cr has been reported to promote remarkably the photoluminescence quantum yield (PLQY), tune emission wavelength, and specific binding sites of ions and biomolecules (Hareesh, 2024). In regard to nitrogen doping, (Nguyen *et al.,* 2022) reported that N-CQDs prepared by continuous hydrothermal flow synthesis show an improvement by an order of magnitude in PLQY from less than 1% to 9.6% compared with undoped CQDs, attributed to the modification of the electronic structure and surface states brought by the nitrogen doping effect. The role of doping in the preparation of carbon quantum dots by modulating the nitrogen sources to achieve excitation free emission and high quantum yields up to 40% would be reflected in the systematic studies focusing on the effect to different nitrogen sources in carbon quantum dot preparation and their resultant photoluminescence properties. Except for doping with nitrogen alone, simultaneous doping with more than one heteroatom (such as N and S; N and B; N and P; N, P and S) synergistically enhances fluorescence intensity, shifting emission into the visible spectrum, while it improves stability and biocompatibility, thus becoming especially advantageous in bioimaging and LED applications (Kong *et al.,* 2024). Typically, heteroatom-doped CQDs are prepared by mixing carbon precursors (organic or inorganic) with suitable dopant sources and then exposed to hydrothermal, solvothermal or microwave-assisted treatment. Heteroatoms such as N, S, P, and B modify the electronic structure and surface as chemistry of CQDs, shown in fig. 2, which results in enhanced photoluminescence, stability, and multifunctional properties (Fu *et al.,* 2024; Kou *et al.,* 2020; Rani *et al.,* 2025).

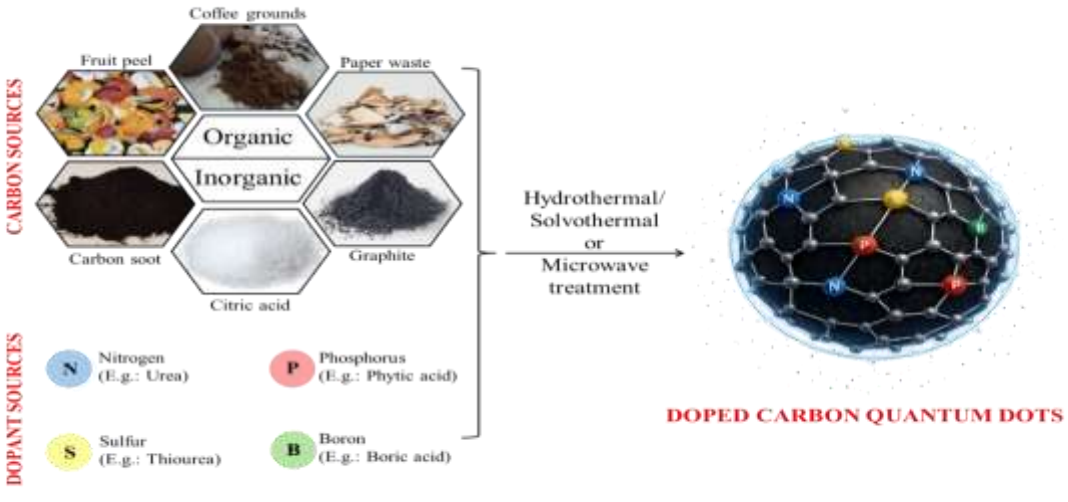

Fig. 2: Doping of CQDs

Heteroatom doping alters the redox and surface coordination properties of CQDs, hence enhancing their photocatalytic performance for hydrogen generation by locating the Fermi level closer to the conduction band of the semiconductor, thereby facilitating interfacial electron transfer(Hareesh, 2024). In sensing, nitrogen- and sulphur-doped CQDs exhibit enhanced absorption and emission intensities, coupled with selectivity of metal ions, thus enabling sensitive detection of hazardous ions such as Cr (VI), Hg2+, Fe3+, Ag+ and Ca2+ via fluorescence quenching or colorimetric changes (Aygun *et al.,* 2024). The doping of carbon quantum dots with metal ions and/or doping with metals has increased their functionality by incorporating coordination sites with high binding affinity and new states in the dots, thereby greatly improving their fluorescence-based detection abilities toward

vitamins and low molecular weight compounds; however, their toxicity to the environment has been noted and demands careful consideration by the scientific community (Lin *et al.,* 2018).
In recent years, multi heteroatom doped carbon quantum dots with high redox activity and radical scavenging abilities have been incorporated within plastic materials, thereby providing an active role in the development of anti-fogging, antioxidant food packing materials and active substrates for food analysis applications in food related industries (Das *et al.,* 2021). In conclusion, by rationally controlling the dopants and precursors in the carbon quantum dots, one could control and modify the dots band structure, charge and reactivity to develop conventional low-yielding carbon quantum dots to highly luminescent and multi-functionalized nano platforms designed for applications in bacteriostatic, antioxidant, and photocatalytic and food safety related applications (John *et al.,* 2021).

Efficacy and advantages of CQD in postharvest quality regulation of fruits and vegetables
Carbon quantum dots (CQDs) have been found to be an emerging class of carbon-based nanomaterials with excellent solubility, tunable surface chemistry, and optical properties, making them very useful for food and agricultural applications. After being harvested, fruits and vegetables remain physiologically active, resulting in metabolic processes such as respiration, water loss, cell membrane breakdown, and oxidative stress, all contributing to faster deterioration, nutrient depletion, browning and microbial spoilage (Meitha *et al.,* 2020). Conventional preservation techniques such as refrigeration, modified atmospheres, or chemical preservatives can prevent these changes, but often fail to maintain nutritional quality or create acceptance concerns for consumers (Khan *et al.,* 2021).
CQDs are nanomaterials that are carbon-based; they are extracted from cheap and abundant materials, have simple preparation mechanisms, as well as being biologically compatible. This makes CQDs very valuable as agents to extend the storage life of fresh fruits and vegetables. Their basic functional properties are UV blocking, antibacterial, as well as antioxidant agents. These can very effectively target the major mechanisms of decay that happen to fresh produce after harvest (Chelladurai *et al.,* 2024). Films that consist of CQDs can either absorb or covert UV rays. This can greatly help to prevent produce from depreciating due to the photooxidation of pigments as well as vitamins (Ezati, Priyadarshi, *et al.,* 2022). On top of that, they can greatly work as antibacterial agents to halt decay because of microorganisms, ultimately raising their potential to ensure fresh produces are consumed (Zhang *et al.,* 2025). The high density of surface functional groups on surface of CQDs makes them exhibit a high capacity of scavenging radicals, thus slowing down the process of degradation due to oxidation as well as inhibiting any loss of produce quality during storage (Sun *et al.,* 2022). Recent research has shown that nanocomposites composed of CQDs can be very useful in the regulation of ethylene as well as other factors that may lead to spoilage, hence improving control over the ripening process of produce (Chaudhary *et al.,* 2025). The sustainable nature and multifunctional protective capabilities make them popular as preservative agents for fruits and vegetables using active as well as intelligent packaging designs (Aksu & Güzdemir, 2025).

Antioxidant properties
Oxidative degradation is one of the most significant factors causing deterioration in the quality of fresh and vegetables during storge. These factors, which accelerate lipid peroxidation, pigment loss, and enzymatic browning, include exposure to oxygen, light, and physical damage, leading to discoloration, development of off-flavours, nutrient losses, and softening of the tissue. Cell membranes and cellular components can be damaged by ROS, including hydroxyl radicals and hydrogen peroxide, which further reduces shelf life and marketability (Gu *et al.,* 2025). Therefore, the management of oxidative processes should take into account methods to preserve freshness, colour, flavour, and nutritional value in both fresh and minimally processed produce.
CQDs possess strong antioxidant properties owing to their high surface area and strong functionality, which makes them ideal for the scavenging of free radicals. CQDs extracted from renewable sources such as citrus fruits peel, crayfish and vegetable waste possess the ability to scavenge radicals 2,2-Diphenyl-1-picrylhydrazyl (DPPH) / 2,2'-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) and other similar methods to the extent of or even better than many plant extracts (Aouadi *et al.,* 2025). (Zhang *et al.,* 2025) reported that Citrus peel extract based CQDs incorporated into guar gum and sodium alginate films showed about 43% antioxidant properties and further demonstrated the ability to delay browning of blanched asparagus. Nitrogen/sulphur doped CQDs extracted from crayfish waste showed enhanced efficiency and the capacity to prevent the formation of mold on strawberries (Kechagias *et al.,* 2023). (Riahi *et al.,* 2022) prepared carboxymethyl cellulose (CMC) films incorporating chitosan based CQDs, which produced highly transparent yet UV blocking protective films. These films showed oxidation properties and DPPH and radical scavenging capacity and strong antimicrobial properties. These films significantly prevented mold growth and preserved the appearance of citrus fruits when coated for up to 21 days.

Antimicrobial properties
Microbial contamination is considered as one of the prime factors in the spoilage and deterioration of fruits and vegetables, as microorganisms drain all the nutrients, cause discoloration, mildew, tissue damage and could also produce toxic metabolites that might be harmful to consumers. It is necessary to kill or inhibit the growth of microorganisms on food surfaces and packaging materials with the aim of preserving freshness and safety and prolonging its shelf life.

Carbon quantum dots have shown strong antibacterial activity over a wide range and are expected to enhance the antimicrobial properties of foods and biopolymer films. CQDs adhere to bacterial surfaces, alters the cell wall and membrane structure and permeability. The antimicrobial mechanisms involve inducing free radicals, disrupting the cell wall and membrane and arresting the gene expression. As shown in fig. 3, upon photoexcitation by visible or natural light, CQDs efficiently generate Reactive Oxygen Species (ROS) such as hydroxyl radicals and oxygen by activating oxygen in air or water. ROS cause irreversible protein inactivation, lipid peroxidation, mitochondrial impairment and gradual deterioration of cell membrane, leading to cell death.

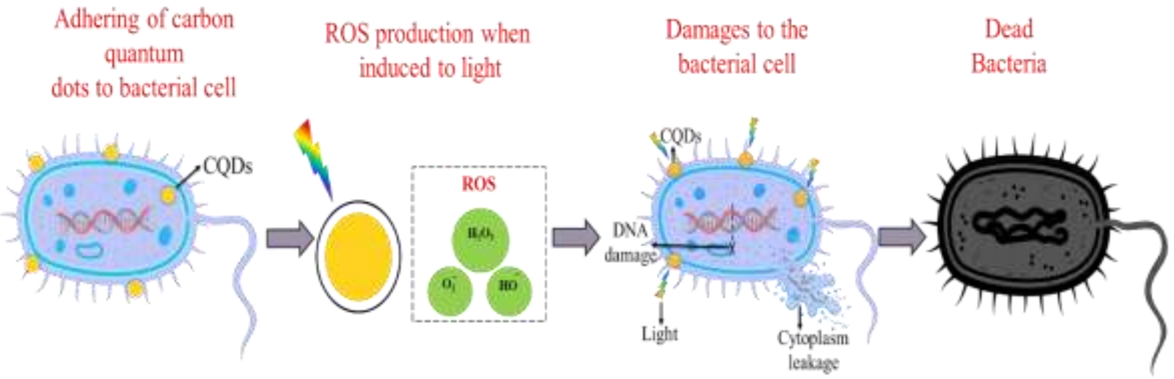

Fig. 3: Antimicrobial mechanism of CQDs

According to (Mohammad Nejad Khiavi *et al.,* 2025), CQDs synthesized from the biomass sources of butternut squash peel inhibit the growth of both Gram-positive and Gram-negative food contaminants, which often results in a reduction in bacterial populations. (Zhang *et al.,* 2025) reported that asparagus, which received minimal processing and was coated with lemon extracted carbon quantum dots (CQDs) incorporated in guar gum/sodium alginate films, delayed browning and microbial spoilage, thus extending the shelf life of blanched asparagus during storage. (Riahi *et al.,* 2022) reported that fresh citrus fruits covered with CQD films containing chitosan delayed mold growth by at least 21 days, implying that CQDs can be effective inhibitions of surface colonization by spoilage fungi under storage conditions. Reports have shown that edible coatings made from CQDs emphasize the blending of antimicrobial properties and the barrier properties of CQD to suppress the flow of oxygen and moisture, thus decelerating the growth and degradation of fresh fruits and vegetables.

UV blocking properties

The ultraviolet radiation from the processing, packaging, storage and retail display stages accelerates the photo-oxidation process of pigments, lipids, vitamins and phenolic compounds in fruits and vegetables, resulting in accelerating discoloration, loss of firmness, development of off-flavours and loss of nutrients (Rezvan & Shekarchizadeh, 2024). Although the use of transparent polymer films ensures the transmission of UV-A and UV-B with good visibility, they can also act as accelerators for the above photochemical reactions unless they contain UV blockers as additives. Thus, the development of UV-blocker based systems with high visible light transmittance becomes an essential consideration for packaging fresh fruits and vegetables (Tripathi *et al.,* 2024). (Silva *et al.,* 2024) found that films made from CQD filled PVA or cellulosic materials have the potential to block 85-99% of ultraviolet radiation with high visible light transmittance, thereby allowing the fresh fruits and vegetables packed inside to maintain their natural appearance and be easily inspected by consumers for their freshness.

Apart from providing passive UV protection, films containing many CQD offer combined UV blocking, antioxidant and antimicrobial functions that contribute significantly to extending the eventual oxidation of pigments, enzymatic browning and microbial decomposition of fruits on their surface (Bijoy & Sangeetha, 2024). Studies involving UV protective composites developed from CQD and lignin show that this material keeps fruits longer by maintaining colour properties, lowering weight loss, and decreasing microbial counts in grapes, strawberries, melons and other fruits when treated with UV radiation compared to unprotected samples or those packaged in conventional packaging materials (Chen *et al.,* 2022). The inhibition of UV driven ROS formation coupled with active protection against decomposition provides a powerful strategy in maintaining fruit quality despite exposure to UV radiation during storage and marketing.

Role of CQDs in preservation of fruits and vegetables

Postharvest storage of fruits and vegetables is primarily influenced by their biological processes such as respiration, production of ethylene, transpiration, and the development of microbes, which contribute to a decrease in storage quality as well as shelf life. Fruits and vegetables can be categorized as climacteric and non-climacteric based on their rates of respiration and production of ethylene during ripening processes. In the case of climacteric fruits such as apples, bananas and tomatoes, a significant increase in their rates of respiration as well as a rapid production of ethylene is observed during ripening processes (Giovannoni, 2004). However, non-climacteric produce such as grapes, strawberries, and cucumbers exhibit a steady flow of respiration rates with little production of ethylene (Saltveit, 1999). Studies have confirmed that carbon quantum dots (CQDs) possess properties which can significantly decrease the development of microbes, remove reactive oxygen species, and regulate processes related to production of ethylene in fresh produce. CQDs have been found to be considerably useful edible coatings and packaging for maintaining the firmness, colour, and nutritional quality of fresh vegetables and fruits during storage. Therefore, CQDs were acknowledged to act as versatile agents, applicable on climacteric or non-climacteric fruits and vegetables as a novel method for extending shelf life and enhancing post-harvest quality.

Application of CQDs in Fruits

Fruits are highly susceptible to postharvest losses due to rapid respiration rate, building up of acids and sugars, fruit tissue softening and hastened ripening (Chen *et al.,* 2018). In addition to that, microbial contamination, oxidative damage are key factors that cause short span of fruits. CQDs have excellent antioxidative and antibacterial property that can reduce and degrade the ethylene production leads to prolonged preservation of fruits (Wang *et al.,* 2023; Zuo *et al.,* 2019).

Table 1: Role of CQDs in preservation of fruits

Fruits	Source material	Production method	Method of application	Outcomes	References
Banana	Coffee bean hulls	Hydrothermal carbonization method	CQDs/PVA composite coating applied as an edible film on banana peel	Coating reduced enzymatic browning and delayed peel colour change during 3 days compared with uncoated and PVA only coated bananas.	(Zhang *et al.,* 2018)
Lemon	Chitosan + Ascorbic acid	Hydrothermal synthesis of N-doped CQDs	CQDs incorporated into carboxymethylcellulose (CMC) to form CQD/CMC edible coating on lemons	No mold growth or decay for 21 days at 25°C and 50% RH; shelf life increased more than threefold vs uncoated lemons.	(Riahi *et al.,* 2022)
Avocado	Glucose	Hydrothermal synthesis of CQDs	CQDs incorporated into chitosan/gelatin edible coating on avocado surface	Coating inhibited mold growth and extended the shelf life by more than 21 days.	(Ezati, Rhim, *et al.,* 2022)
Fresh cut apple	Coffee husks	Hydrothermal synthesis	CQDs incorporated into carboxymethyl cellulose (CMC) active composite film in contact with apple pieces	Strong antioxidant and antibacterial activity; slowed decay and extended freshness of fresh cut apples by 7 days at 4°C.	(Yang *et al.,* 2024)
Banana	Rosemary leaves	Hydrothermal synthesis	Combination of CQDs and PVA as edible coating on banana surface	Reduced peel browning and blackening, maintained peel colour and improved storage quality and shelf life of bananas up to 19 days compared with uncoated and PVA only coated bananas.	(Eskalen *et al.,* 2021)
Strawberry	Papaya peel	Hydrothermal method	Papaya peel CQDs incorporated into carboxymethyl cellulose and pectin nanohydrogel	Reduced weight loss, enhanced microbial stability and exhibits improved shelf life compared to uncoated strawberries in refrigerated conditions up to 10 days.	(Thakur *et al.,* 2024)
Strawberry	Biomass derived multicolour CQDs	Hydrothermal carbonization method	CQDs incorporated into a polymer based edible coating/film	Reduced weight loss, inhibited microbial growth and spoilage over 6 days at room temperature and 12 days at 4°C.	(Alaş *et al.,* 2022)

Application of CQDs in Vegetables

Fresh-cut vegetables are preserved mainly by CQDs application since they face severe challenges due to more risk of microbial spoilage (Koukounaras *et al.,* 2020) . Application of CQDs reduces the risk of photooxidative damage, microbial spoilage and enzymatic browning. The combination of CQDs and coatings with ultrasound treatment improves antioxidant and antibacterial properties thereby maintains better appearance and food quality (J. Y. Lee *et al.,* 2021).

Table 2: Role of CQDs in preservation of vegetables

Vegetables	Source material	Production method	Method of application	Outcomes	References
Blanched asparagus	Lemon juice	Hydrothermal synthesis, then film casting into Guar gum/Sodium alginate matrix	CQDs incorporated into guar gum/sodium alginate active film used as packaging around blanched asparagus	Reduced weight loss and browning, maintained firmness and color, improved the storage quality of blanched asparagus up to 8 days at 4°C.	(Zhang *et al.,* 2025)
Fresh cut spinach	Banana peel	Hydrothermal method	CQDs/sericin nanocomposite edible coating on fresh cut spinach	Exhibits strong antioxidant and antibacterial activity, delayed microbial growth and preserved sensory quality at 4°C for 8 days.	(Zhu *et al.,* 2025)
Chinese flowering cabbage	Biomass derived CQD	Hydrothermal carbonization method	CQDs incorporated into chitosan quaternary ammonium salt and sericin as nanocomposite coating	Maintained higher ascorbic acid and chlorophyll levels, inhibits microbial growth and overall postharvest quality of Chinese flowering cabbage than uncoated samples at 10°C for 8 days.	(Ban *et al.,* 2025)
Fresh cut potatoes	Ca-doped CQDs	Heteroatom-doping via green synthesis	Immersion of potato slices in Ca-CQDs solution	Inhibited browning, reduce PPO, peroxidase and tyrosinase activities, improved visual quality and extended the shelf life of potatoes	(Gu *et al.,* 2025)
Tomatoes	Onion peel waste	S, N-doped CQDs in amylopectin xerogel	Edible smart film on tomatoes	Provide strong antimicrobial barrier against E. *coli*, S. *aureus*, C. *albicans*; enabled real time monitoring of tomato freshness while inhibiting microbial spoilage.	(Tohamy, 2025)
Fresh cut lettuce	Chitosan with CQDs	Hydrothermal method	Lettuce subjected to ultrasound treatment and dipped in chitosan CQD coating solution	Reduced microbial growth, decreased respiratory rate, better retention of ascorbic acid and chlorophyll at 4°C for 15 days.	(Yao *et al.,* 2024)
Fresh cut cucumber	Chitosan with CQDs	Hydrothermal method	Cucumber subjected to combination of ultrasound treatment and CQDs	Inhibits bacterial counts, reduced respiration rate, maintained cucumber quality at 4°C for 15 days.	(Fan *et al.,* 2020)
Potato	Spent Gromwell roots	Hydrothermal method	Potato slices were subjected to g-CDs and g-SCDs coatings	Significantly reduced browning of potato slices during 3 days of storage.	(Bhattacharya *et al.,* 2023)

CQDs based smart labels for real time freshness detection of fresh produce

The rapid spoilage of fruits and vegetables during storage and transportation is a significant challenge in food safety, quality and waste management. The lack of real-time monitoring of freshness in conventional packaging methods has led to the development of intelligent packaging systems based on advanced sensors. In addition to the conventional packaging methods, Carbon Quantum Dots (CQDs) are emerging as core sensing elements in smart labels for real-time monitoring of fruit and vegetable freshness, due to their strong, tunable fluorescence, high sensitivity to pH and gases and excellent biocompatibility (Khan, Ezati, *et al.,* 2023). To translate the biochemical processes of ripening or spoilage into visible colour or fluorescence signals that can be detected by the human eye or simple electronics, smart packaging uses CQDs optical sensors embedded in films, coatings or labels (Alam *et al.,* 2021). CQDs enable non-destructive, real-time monitoring during storage and distribution by responding to key freshness markers in fresh produce, such as pH shifts, CO_2 and volatile organic acids and other metabolic byproducts of respiration and microbial growth (Kumar & Rhim, 2024). Due to their photostability, non-toxicity and ease of surface modification, CQDs can be embedded in biopolymer matrices, nanocellulose or paper to make flexible labels that maintain food contact safety. CQD labels have the potential to replace static "best before" dates with dynamic freshness displays in fruit and vegetable products by acting as colorimetric and fluorescent pH indicators to visually indicate quality degradation (Alam *et al.,* 2021).

Besides the ability to endow antibacterial, antioxidant and UV barrier properties that extend the shelf life of fruits and vegetables, CQDs derived biomass or food waste like peels and bagasse can be used to make smart labels. While the lack of standardization, approval and migration/toxicity studies remains a significant challenge, it is clear from the literature that the inclusion of such labels in intelligent packaging systems could help in waste reduction and digital monitoring of the supply chain (Thakur *et al.,* 2024). (Zhu *et al.,* 2024) designed a pH responsive smart label with CQDs embedded in sustainable pineapple peel cellulose nanofibrils (CNF), which enables simultaneous colorimetric and fluorescent tracking of freshness. The labels were packed with strawberries and grapes in airtight containers at 25°C for a period of 4 days. On the 3rd day, the labels changed colour from yellow to red, accompanied by a reduction in fluorescence intensity and an enhanced orange-red colour under normal lighting conditions, indicating a reduction in freshness. Concurrently, a substantial amount of mold development was observed on the fruits, with a further reduction in fluorescence intensity under UV light. These results demonstrate the effectiveness of dual-functional indicators for real-time assessment of fruit freshness. The study highlights the need for evaluation of fruit freshness by considering various factors such as appearance, aroma, and the presence of microbial contamination. It is recommended that the initial color and fluorescence properties of various fruits be optimized for improved accuracy.

Future perspectives

Future researches should expand the role of Carbon Quantum Dots (CQDs) in food preservation by clarifying their interactions with fruit physiology and advanced packaging systems. CQDs based edible films can reduce ethylene production and delay ripening, the exact mechanisms remain unclear. Optimization of pore structure, surface chemistry of CQDs their toxicity studies should be further explored for setting safe usage standards and regulatory frameworks for CQDs usage as smart preservatives in fruits and vegetables.

CONCLUSION

The spoilage of fruits and vegetables are mainly caused by microbial contamination, oxidative damage. CQDs are emerging preservation technology that possess antimicrobial, antioxidative and UV blocking properties and for safety uses. Moreover, CQDs are used as smart labels for real time freshness detection of fruits and vegetables. This review comprehensive insight into the potential use of CQDs for preservation and shelf-life extension of fruits and vegetables.

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