Carbon Quantum Dots (CQDs) In Enhanced Postharvest Preservation of Fruits and Vegetables

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ABSTRACT

Carbon quantum dots (CQDs) have emerged as a sustainable nanotechnology with transformative potential in food preservation. Derived from renewable sources through green synthesis methods, CQDs exhibit unique properties such as strong photoluminescence, antimicrobial activity, UV absorption and surface functionalization. These attributes enable their integration into smart packaging films and edible coatings, enhancing mechanical strength, barrier performance and shelf-life extension of fruits and vegetables. By combining environmental friendliness with functional versatility, CQDs offer a promising solution for safer, longer-lasting produce and contribute to the advancement of intelligent food safety systems.

INTRODUCTION

Ensuring the safety and longevity of fruits and vegetables is a growing concern in modern agriculture and food supply chains. Traditional preservation methods often rely on synthetic chemicals, which can pose environmental and health risks. In response, researchers have turned to carbon quantum dots (CQDs)- a class of nanomaterials known for their biocompatibility, fluorescence, and eco-friendly synthesis- as a sustainable alternative. CQDs, derived from natural carbon sources such as fruit peels, plant waste or biomass, offer a green and efficient solution for monitoring and enhancing produce safety. Their unique properties enable applications in pathogen detection, freshness tracking and antimicrobial coatings, all while minimizing environmental impact. CQDs are a relatively new class of nanomaterials, first discovered in 2004 during the purification of carbon nanotubes. These are tiny particles less than 10 nanometers in size and they are known for their strong fluorescence, water solubility, and low toxicity. CQDs are being explored for both packaging materials and direct coatings on fruits and vegetables (Chaudhary *et al.*, 2025).

Packaging Material

CQDs are incorporated into biopolymer films to create active packaging. These films exhibit antimicrobial and antioxidant properties, helping to extend shelf life and maintain food quality. This improves the mechanical and barrier properties of the packaging.

Coating

CQDs can also be applied directly as edible coatings on the surface of fruits and vegetables. These coatings form a protective layer that reduces microbial contamination and slows down oxidation, without altering the taste or appearance of the produce.

Source for Carbon Quantum Dots

Carbon quantum dots (CQDs) are a class of fluorescent nanomaterials that can be broadly categorized based on their precursor sources into organic and inorganic types. Organic CQDs are synthesized from naturally occurring carbon-rich materials such as fruit peels, plant extract, amino acids and citric acid. These sources are renewable, biodegradable and highly biocompatible, environmentally friendly nanodots suitable for applications in food safety, bioimaging and environmental sensing. In contrast, inorganic

CQDs are derived from mineral-based or synthetic carbon sources such as graphite, carbon nanotubes and activated carbon. These typically require more intensive chemical or physical processing, but offer enhanced structural stability and tunable optical properties, making them ideal for applications in electronics, photocatalysis and energy storage. The choice between organic and inorganic CQDs depends on the intended application, with organic types favored for biological and environmental uses and inorganic types preferred for high-performance industrial technologies.

Techniques Used for Characterization of CQDs

X-ray Diffraction: It is a non-destructive analytical technique used to determine the crystalline structure, phase composition and degree of graphitization in nanomaterials like carbon quantum dots.

UV Barrier: Carbon quantum dots (CQDs) exhibit unique optical properties, including strong UV absorption, photoluminescence and fluorescence, which make them highly effective as UV barrier materials. Their ability to absorb and scatter ultraviolet (UV) radiation is a key feature in evaluating their optical behaviour. CQDs synthesized from organic sources often show broad absorption in the UV region (200–400 nm), indicating their potential to act as natural UV filters. This property is particularly valuable in applications such as Food packaging to protect fruits and vegetables from UV-induced degradation.

Fourier Transform Infrared Spectroscopy (FTIR): Used to analyze the molecular compounds. It is a widely used analytical technique for identifying the functional groups and chemical bonds present on the surface of carbon quantum dots (CQDs). It provides insight into the surface chemistry, which is crucial for understanding the interaction of CQDs with biological systems, other materials or environmental factors.

Transmission Electron Microscopy (TEM): It is a high-resolution imaging technique used to observe the morphology, size and internal structure of carbon quantum dots at the nano-meter scale. It is one of the most powerful tools for visualizing nanomaterials due to its ability to resolve fine structural details (Ezati *et al*., 2022).

Role of Carbon Quantum Dots in Extending Shelf Life of Fruit and Vegetables

- **Antimicrobial Activity:** CQDs can inhibit the growth of bacteria and fungi on produce surfaces, reducing spoilage and contamination
- **UV Protection:** Their strong UV absorption helps shield fruits and vegetables from harmful radiation that accelerates degradation
- **Ethylene Detection and Control**: CQDs can be used in sensors to monitor ethylene gas, a ripening hormone, allowing better control over storage conditions
- **Smart Packaging:** Incorporated into food packaging, CQDs can act as freshness indicators or active barriers against microbial invasion
- **Non-Toxic Coatings:** CQDs can be applied as edible or biodegradable coatings that preserve moisture and prevent oxidation

Effects of CQDs on Physical and Mechanical Properties of Films

The incorporation of carbon quantum dots (CQDs) into polymeric or biopolymer-based films significantly enhances their physical and mechanical properties. CQDs, owing to their nanoscale size and surface functional groups, improve film uniformity, reduce porosity and contribute to better dispersion within the matrix. This leads to increased tensile strength, flexibility and barrier properties, making the films more durable and resistant to environmental stress. Additionally, CQDs can enhance the thermal stability and moisture resistance of the films, which is particularly beneficial for food packaging applications. Their ability to interact with the polymer chains at the molecular level results in improved structural integrity and mechanical performance, while also imparting functional attributes such as UV shielding and antimicrobial activity. Overall CQDs serve as multifunctional nanofillers that elevate the quality and functionality of films used in various industrial and biomedical applications. Thus, the integration of CQDs into films not only enhances their mechanical strength and barrier properties but also imparts active functionality for produce protection. This makes CQD-based films a promising solution for extending the shelf life and safety of fruits and vegetables (Du *et al.,* 2024).

CONCLUSION

Green synthesis of CQDs and their desired functional features have drawn massive attention toward its utility for Coating and active packaging. CQDs as functional materials can maintain the quality and enhance the shelf life of fruit and vegetables. Antimicrobial properties of CQDs help to reduce spoilage throughout distribution and storage of fresh produce. carbon quantum dots (CQDs) represent a sustainable and multifunctional nanomaterial with significant potential in enhancing fruit and vegetable safety. Derived from both organic and inorganic sources, CQDs can be synthesized through eco-friendly methods that utilize renewable biomass. Their unique properties- such as strong photoluminescence, antimicrobial activity, UV absorption and surface functionalization- make them ideal for applications in food preservation. When incorporated into films or coatings, CQDs improve mechanical strength, barrier properties and shelf-life extension. Additionally, their biocompatibility and low toxicity support safe use in food-related environments. As research advances, CQDs are poised to play a vital role in developing smart, sustainable packaging systems that reduce post-harvest losses and promote food security.

"Preserving nature's freshness begins at the nanoscale- where carbon quantum dots shield, strengthen and sustain."

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