Carbon Dots: Nanomaterial for Food Safety and Quality Applications

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Food safety and quality has been a major remained as major, resulting in increased attention from both the public and scientific community. Therefore, ensuring the safety and quality of food is critical to protecting public health and preventing foodborne illness. A new technology with promising potential in addressing these challenges is the use of carbon dots (CDs). Carbon dots, or carbon quantum dots, are nanoscale carbon-based nanoscale materials that have unique properties such as strong fluorescence, high stability and excellent water solubility.

Carbon dots (CDs), also known as carbon quantum dots or C-dots, are a novel class of carbon-based nanomaterials that have attracted great interest in recent years. These nanoparticles, typically ranging between 1 nm and 20 nm in size, exhibit a variety of unique properties that make them extremely versatile and valuable for a variety of applications. Since their accidental discovery in 2004 during the purification of single-walled carbon nanotubes, CDs have become a focus of research due to their remarkable fluorescence, excellent stability, high optical absorptivity, and exceptional aqueous solubility. Recently, carbon dots (CDs) have emerged as promising nanomaterials for food safety applications due to their excellent fluorescence properties, ease of synthesis, and good biocompatibility.

Carbon dots (CDs) are a new category of fluorescent carbon nanoparticles renowned for their tunable fluorescence, which can be adjusted by modifying their size, surface chemistry, or doping with different elements. Their ability to emit tunable fluorescence, along with high photostability and ease of surface functionalization, makes them highly valuable for numerous applications. The ease of surface functionalization further enhances their versatility, allowing the attachment of various functional groups or molecules to tailor their properties for specific uses. This versatility has led to the application of C-dots in various fields, including bioimaging, drug delivery, sensing, photocatalysis, and energy conversion. In addition, they have been studied for applications in food nutrient composition analysis, food quality detection, and monitoring of harmful organic pollutants.

Synthesis of carbon dots

Carbon dots are synthesized using two main approaches: top-down and bottom-up. The main difference between these two approaches is the starting materials and the mechanisms involved in the formation of the carbon dots. In the top-down method, graphene, grapheme carbon nanotubes, graphite, carbon fibres, oxide sheets, and other much larger components are broken into small pieces as the sp2 fluorescence structure of carbon through arc discharge, ultrasonic, acidic, hydrothermal, laser ablation, chemical, and solvothermal exfoliations. In the bottom-up methodology, CDs are created as bulk carbon materials convert to particles by physical and chemical processes such as solvo-thermal, microwave-assisted, hydrothermal, and thermal pyrolysis (An et al., 2020). CDs are produced by breaking down larger carbon structures such as graphite powder, graphite oxide, carbon soot and other carbon source materials into nano-size fragments. Recently, there has been a focus on green synthesis using biomass waste as a sustainable and cost-effective raw material (Fauziyah, 2022) and is shown in figure 1. The hydrothermal method is particularly popular for biomass-derived CDs.

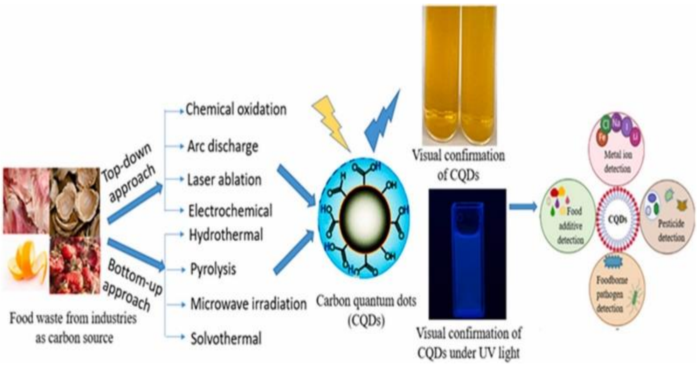

Fig. 1: Carbon quantum dots from food waste (Thakur et al., 2024)

Application of carbon dots in Food Safety and Quality

Carbon dots (CDs) have emerged as promising tools for food safety, quality monitoring and packaging, enhancing both the safety and shelf life of food products. The CDs have been studied in detecting various food contaminants, including metal ions, pesticides, veterinary drugs, and pathogenic bacteria and in food packaging (Shi et al., 2019).

Contaminant residues in food products is a serious problem and effective detection is of utmost importance for their control in the food chain (Lacivita et al., 2023). Several researchers have explored CDs for fabricating sensitive and reliable methods for detection of contaminant residues and food borne pathogens. For example, Xu et al. (2015) created a CDs-based sensor that can detect tartrazine in steamed buns, honey, and candy at concentrations ranging from 0.25 to 32.50 mM. Similarly, Dai et al. (2014) developed a FRET system for detecting melamine using CDs and AuNPs, with a detection limit of 36 nM. This method was successfully applied to milk samples and produced satisfactory results. Aslam et al. (2024) fabricated a non-enzymatic electrochemical sensor using CDs-Ag@Cu2O-GA composite to detect metronidazole, an antibiotic, in milk. This sensor demonstrated high stability and sensitivity with detection limit of 7.1×10^{-7} mol/L. In another study Mansour et al. (2024) developed nitrogen and sulfur co-doped CDs as fluorescent probes for quantifying monosodium glutamate (MSG) in food and probes exhibited high selectivity and a low detection limit. Highlighting a sustainable approach Kumari et al. (2023) developed paper-based probe using carbon dots (CQDs) synthesized from waste rice straw for detection of monosodium glutamate (MSG) as low as 1.33 nM, which is suitable for food safety applications. Furthermore, Liu et al., (2020) developed portable fluorescent strips using CDs-based molecularly imprinted photonic crystal hydrogels for detecting tetracycline residues and methods is generalized as simple method for monitoring antibiotic residues in animal-derived foods.

Food borne pathogen detection in food products accurately and rapidly is another concern of food industry. The utilization of nanoparticles has led to the development of sensitive fluorescent probes with detection limits comparable to PCR techniques, enabling the identification of pathogens like *E. coli* O157:H7 in milk (Zhao et al., 2021). Moreover, CDs have demonstrated potential for photodynamic inactivation of pathogens such as *Listeria monocytogenes* and *Salmonella* by inducing the generation of reactive oxygen species that inflict damage on bacterial cells (Dong et al., 2021). The combination of CDs with microfluidic technology opens up new possibilities for point-of-care testing (Ma et al., 2024).

Carbon dots have been used to develop the sensors for detection of food constituents and monitoring freshness of food. (Liu et al., 2016) developed a CQD-MnO2 sensing platform using fluorescent recovery to detect ascorbic acid in fresh fruits, vegetables, and juices. Recently, (L. Liu et al., 2020) used green fluorescent nitrogen and sulphur co-doped CDs (G-CDs) to detect curcumin in food samples and was sensitive with detection limit of 46.4 nmol/L, and was generalized for application in a variety of food samples. To create biocompatible food freshness indicators, resazurin-derived carbon dots (Tan/Res CDs) and tangerine peel were synthesized by Ezati et al. (2023) was able to use as portable sensor to monitor ammonia with satisfactory monitoring of freshness of shrimp.

Recent advancements in carbon quantum dots (CQDs) have transformed food safety and quality assurance through innovative packaging solutions. Chen et al. (2023) developed N-CDs with chitosan composite film was able to reduce the total bacterial count and had greatly increased the shelf life of pork and blue berries. In the study by Lacivita et al. (2023) coating of fiordilatte cheese with CDs derived from whey was able to increase the shelf life of cheese as compared to the control cheese. These nanocomposite films exhibit enhanced physicochemical properties and act as freshness indicators, thereby extending shelf-life and maintaining food quality (Wen et al., 2023). Recently Wagh et al. (2024) developed color-changeable nanocomposite indicator smart film using carrageenan (CAR) doped with rose petal-derived carbon dots (RP-CDs) that was able to indicate the freshness of minced pork and shrimp by changing color from red to yellow as food quality declines. Similarly Parveen et al. (2024) created chitosan/gelatin nanocomposite films integrated with *Vachellia nilotica* gum-derived carbon dots (VNG-CDs) for smart food packaging and the developed packaging was effective on preservation of bananas with satisfactory results. Likewise Sangeetha et al. (2024) was able to demonstrate the CDs derived from food waste coconut husk composite film had excellent pH responsive fluorescent property along with significant reduction in oxygen permeability and the film was detect to monitor the milk spoilage through pH dependent fluorescent emission.

Conclusion and future perspectives

Carbon Dots (CDs) have emerged as versatile tools in the food industry. Their applications range from detecting contaminants and residues to improving functionality of packaging materials and extending shelf life. Despite their favorable characteristics, challenges remain in development of specific sensor probes for complex food samples. CDs can be produced from a variety of sources, including food waste, providing economic and sustainability benefits. Nevertheless, the concern in the use of CDs from food applications lies in their inherent toxicity, as their small size and unique properties could cause negative biological effects therefore comprehensive safety assessments find their commercial application.

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