Carbon Quantum Dots for Food Analysis: Advancements and Application

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Abstract

Carbon Quantum Dots (CQDs) are tiny nano scale particles made of carbon which are arranged in a crystalline or amorphous structure, typically less than 10 nm in size. CQDs have gained significant attention due to exhibit the unique Optical, Electrical, Chemical, Sensitivity, fluorescence and biocompatible properties, which finds various potential applications span across various fields including but not limited to food analysis. Different kinds of food analysis like detection of Contaminants and Adulteration, Food Quality Monitoring, Foodborne Pathogens, Food packing, Nutrient Analysis, Food preservation, Food Additives and fortification. CQDs have emerged as a revolutionary tool in food Analysis, offering precision, speed, and sustainability. With continuous advancements, their role in ensuring global food safety and quality is set to expand significantly. However, public concern about the nanomaterials for food analysis still remains a hot topic for further research. This article provides a brief overview of the applications and advancements of CQDs for food analysis.

Keywords: CQDs, Fluorescence, Nanomaterials

Introduction

Researchers discovered the carbon nanoparticles with unique optical properties in 2000s. CQDs early synthesis methods involved arc discharge, laser ablation, chemical vapour deposition. Development of various top-down and bottom-up methods involved hydrothermal synthesis, solvothermal, microwave assisted synthesis using precursors. Carbon Quantum Dots are tiny sized carbon based nanomaterials that ranges from 2-10 nm in diameter, which are arranged in a crystalline or amorphous structure. At this scale, CQDs exhibit unique Optical, Electrical, Chemical, Sensitivity, fluorescence and biocompatible properties that differ from their other bulk counterparts. Globally, CQDs has gradually but firmly taken over a variety of industries. In the developed technological world,

Researchers developed methods to functionalize and modify CQDs surfaces, which are focused on bioimaging, biosensing, optoelectronics, energy storage, conversion, biomedical, food analysis, safety and environmental applications [2]. CQDs can be classified based on their composition, synthesis methods, and structural or functional characteristics. This classification reflects the diversity and multifunctionality of CQDs, making them adaptable for numerous scientific and industrial applications. CQDs are classified based on their structural characteristics, composition and synthesis methods.

Table 2: Classification and Types of CQDs

S.No	Classification Basis	Types
1	Structure	CQDs, GQDs, CNDs
2	Composition	Pure, Doped, Functionalized
3	Synthesis Methods	Top-Down, Bottom-Up
4	Optical Properties	Fluorescent, Non-Fluorescent
5	Size	Ultra-Small, Regular-Sized
6	Surface Chemistry	Hydrophilic, Hydrophobic

The above classification helps in tailoring CQDs for precise application such as bioimaging, food safety, energy devices and environmental sensing. The following characteristics of CQDs that make them ideal for various applications include their small size, unique optical properties, Chemical stability and biocompatibility [5-6].

Table 2: Characteristics and Application of CQDs

S.No	Characteristics	Application
1.	Photoluminescence	Bioimaging, LEDs, Sensors
2.	Biocompatibility	Drug Delivery, Bioimaging
3.	Water Solubility	Water Purification, Biosensing
4.	Chemical Stability	Sensors, Catalysis
5.	High Surface Area	Drug Delivery, Catalysis
6.	Conductivity	Energy Devices, Electrochemistry
7.	Tunable Bandgap	Optoelectronics, Photocatalysis
8.	Eco-friendliness	Agriculture, Sustainability

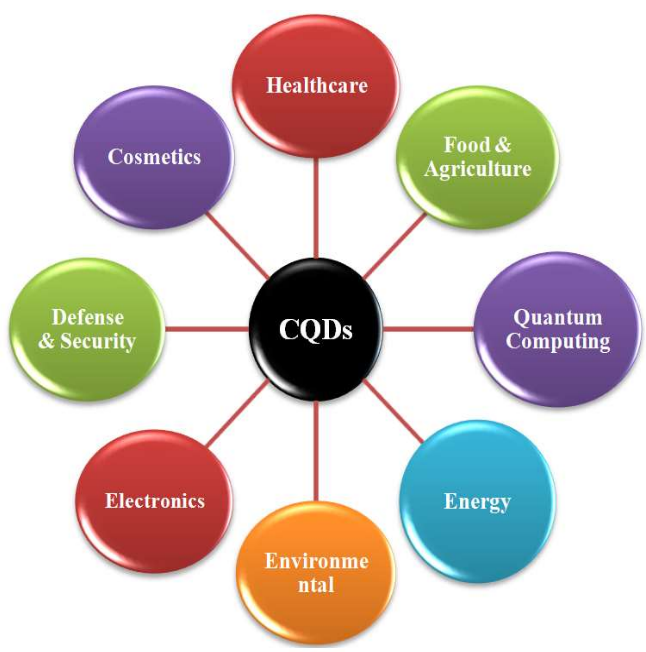

Figure 1: Application of CQDs in Various Industries.

One of the important applications is food analysis among these. CQDs have huge potential to transform food analysis by providing safer, more efficient and eco friendly solutions for ensuring food quality and safety. CQDS are being utilized in various aspects of food analysis like Detection of contaminants, Food Quality Monitoring, Detection of Foodborne Pathogens, Antioxidant Activity Evaluation, Food packing, Adulteration detection, Nutrient Analysis, Food preservation, Food Additives and fortification [1][3=4].

CQDs application in Detection of contaminants

CQDs have shown significant promise in detecting various contaminants due to their properties of fluorescence, biocompatibility and ease of surface functionalization. These are utilized to detect Pesticide residues in fruits, vegetable and grains, Identifying toxic heavy metals (Pb^{2+}, Hg^{2+}, Cd^{2+}) in water, food and soil, Detect toxins produced by fungi in agriculture products like grains, nuts, and dairy [10-12], Identifying bacterial and Chemical adulterants in food, Detect residue antibiotics in meat, fish, Monitor pollutants like polycyclic aromatic hydrocarbons or endocrine-distributing chemicals in food [7-8].

Detecting contaminants is an important for monitoring food quality and assessing public health risks. Traditional food analysis methods such as chromatography, spectroscopy and microbiological techniques have long been used to meet laboratories' routine food analysis needs, but critical role in routine food analysis due to their activity and reliability. [11] Nowadays food safety situations require rapid, time-saving, and low-cost analytical technologies, including on-site, portable, and convenient test kits. Advanced food analysis methods have evolved to meet the routine needs of laboratories, offering a combination of precision, speed and adaptability. Advantages of CQDs over traditional methods are sensitivity, rapid and portable and cost effectiveness. It is offering innovative solution for ensuring food quality and safety.[9]

CQDs application in Food Quality Monitoring

CQDs have emerged as powerful tools in food quality monitoring due to their unique optical, chemical and biocompatible properties. Their fluorescence sensitivity, tunable surface chemistry and ease of functionalization make them ideal for detecting changes in food composition and contamination. Food quality monitoring is a dynamic process of ensuring that food is safe to eat by identifying and eliminating potential hazards [15-16]. CQDs play multifaceted roles to monitor the freshness nutritional content of food in fish, meat and diary products [14].

Traditional methods like physical methods (visual inspection, sensor analysis), Chemical methods (Titration, chromatography), Microbiological methods (Culture based techniques, Plate counts) are reliable and cost-effective. But are often time consuming and require expertise. Modern methods like Near-Infrared Spectroscopy (measure moisture, fat, protein content), Raman Spectroscopy

(Quality analysis), Bio sensors (Detect Specific compounds like glucose or ethanol), Hyperspectral imaging (analysis food composition), X-Ray imaging (detect foreign objects or internal defects), Electronic nose (monitor aroma and spoilage), Electronic Tongues (Analyze taste using sensor), Internet of Things (monitor temperature, humidity and freshness), Blockchain Technology (Ensure traceability and transparency in the supply chain). CQDs are transforming modern food quality monitoring through their integration with advanced technologies like biosensors, small packaging and IOT. These applications of CQDs ensure rapid, sensitive and reliable food quality assessments, enhancing safety and consumer confidence [13].

CQDs application in Detection of Foodborne Pathogens

Carbon Quantum Dots (CQDs), due to their excellent fluorescence properties, biocompatibility, and functionalizability, have become valuable tools for detecting foodborne pathogens such as Salmonella, Escherichia coli(E. Coli), and Listeria monocytogense. Foodborne pathogens are microorganisms that contaminate food, causing illnesses ranging from mild gastroenteritis to severe systemic infections. It is critical to detecting these pathogens for ensuring food safety and preventing outbreaks [17].

Traditional methods like Culture-Based Methods (biochemical identification), Microscopy (Parasites and fungal contaminants), Biochemical Assays (Detects bacterial toxins or viral antigens), Molecular Techniques (Detects pathogen), Immunological Methods (rapid detection of pathogens like *E. coli* and *Salmonella*. Emerging Technologies like Next-Generation Sequencing (Identification of pathogens), Microfluidics (rapid and automated detection of pathogens), Artificial Intelligence (AI) Integration (Identify pathogens by AI algorithms) are modern methods. Carbon Quantum Dots (CQDs) play multifaceted roles for detecting foodborne pathogens by two primary mechanisms such as Fluorescence-Based Detection, Electrochemical Detection. CQDs are revolutionizing the detection of foodborne pathogens by providing rapid, sensitive, and environmentally friendly solutions. Their versatility and cost-effectiveness make them a promising alternative to traditional methods, particularly in applications requiring on-site and real-time analysis [18].

CQDs application in Food packing

Charge-coupled devices (CCDs), known for their role in imaging and sensing technologies, have various potential applications in food packaging such as Quality Inspection, Barcode and Label Scanning, Seal Integrity Testing, Automated Sorting, Printing Verification, UV and Infrared Imaging, Sustainability and Recycling [20-21]. Food packaging has evolved significantly over the years, transitioning from traditional methods to modern techniques driven by advancements in technology, materials, and sustainability [25].

Traditional Methods like Natural Materials, Textiles, Metal Containers, Wax Coating, Glass Jars and Bottles, Smoking and Wrapping. Modern Methods like Plastic Packaging, Vacuum Packaging, Modified Atmosphere Packaging (MAP), Aseptic Packaging, Active Packaging, Edible Packaging, Biodegradable and Compostable Packaging, Intelligent Packaging, Canning and Retort Packaging, Cryovac and Shrink Wrap [19].CQDs represent a promising advancement in food packaging, offering multifunctional solutions for preserving food safety, extending shelf life, and enhancing sustainability. Further research and commercialization efforts are likely to expand their role in next-generation packaging technologies [22] [24].

CQDs application in Adulteration detection

Carbon Quantum Dots (CQDs) have significant potential in detecting food adulteration due to their exceptional optical, chemical, and biosensing properties [27]. CQDs are paving the way for innovative and efficient adulteration detection methods are Fluorescence-Based Sensing, Colorimetric Detection, pH Sensing for Spoilage Indicators, Gas Detection, Electrochemical Sensors, Paper-Based Detection Systems, Detection of Food Additives and Preservatives, Nanocomposite Integration. These are offering a promising solution for enhancing food safety and consumer trust [26].

Detecting food adulteration is essential for ensuring food safety and quality. Over time, traditional methods have evolved into more sophisticated modern techniques that offer higher sensitivity, speed, and accuracy. Physical Inspection, Simple Chemical Tests, Heat-Based Tests, Solubility and Sedimentation are traditional methods. [2] Modern Methods are Chromatographic Techniques, Spectroscopic Techniques, Mass Spectrometry (MS), Electrochemical Sensors, Biosensors, DNA-Based Methods, Nanotechnology-Based Detection, Portable Detection Kits, Artificial Intelligence (AI) and Machine Learning (ML), Smart Packaging with Sensors. Modern methods provide high sensitivity, speed, and reliability, making them indispensable for large-scale and critical applications. However, traditional methods remain valuable for quick, low-cost, and on-the-spot detection in resource-limited settings. Combining both approaches can provide comprehensive food safety solutions. CQDs are paving the way for more reliable, user-friendly, and environmentally sustainable detection methods, ensuring food safety and consumer trust [28].

CQDs application in Nutrient Analysis

Carbon Quantum Dots (CQDs) have significant applications in nutrient analysis due to their exceptional properties, such as high fluorescence, biocompatibility, chemical stability, and tunable surface functionalization. These properties enable CQDs to detect (Vitamins, Mineral and Ion, Micronutrients), Analysis (Protein, Carbohydrate, Antioxidant), functionalized with hydrophobic groups (Lipid Profiling), quantify, pH Monitoring, Food Fortification Quality Assurance, Integration with Smart Devices and monitor various nutrients in food and biological systems with high sensitivity and precision.[30-31]

Nutrient analysis involves determining the composition and concentration of nutrients in food and other biological samples. Over time, methods have evolved from basic chemical techniques to sophisticated instrumental and sensor-based approaches. Traditional methods are often manual and rely on classical chemical and physical techniques such as Gravimetric Analysis, Titration Methods, Kjeldahl Method, Soxhlet Extraction, Spectrophotometric Techniques, Microbiological Assays[32], Traditional methods are reliable but often limited by time, sensitivity, and the need for skilled labor. Modern methods, leveraging advanced technologies like chromatography, spectrometry, and nanotechnology, offer precise, rapid and automated solutions for nutrient analysis, catering to both industrial and field applications [29]. CQDs have revolutionized nutrient analysis by offering highly sensitive, rapid, and versatile detection methods. Their application spans from routine food quality control to advanced nutritional profiling, ensuring food safety and enhancing consumer confidence. These innovative tools pave the way for more efficient and accurate assessment of nutritional content in food systems. Their eco-friendly nature and potential for integration into portable devices make CQDs a promising technology for real-time nutrient analysis [33-34].

CQDs application in Food preservation

CQDs have gained attention in food preservation for their potential to improve safety, extend shelf life, and monitor food quality [35]. Traditional methods such as Drying/Dehydration, Salting, Smoking, Fermentation, Canning, Sugaring, Freezing have been used for centuries to preserve food and prevent spoilage. These methods often rely on natural processes and are widely practiced even today. Modern methods are Vacuum Packaging, Modified Atmosphere Packaging (MAP), Pasteurization, Irradiation, Freeze-Drying (Lyophilization), High-Pressure Processing (HPP), Ultrasound Preservation, Smart Packaging, Edible Coatings, Nanotechnology. These have been incorporate advanced technologies and scientific principles to improve food safety, quality, and convenience [36]. Each method has its advantages, and the choice depends on the type of food, desired shelf life, and resource availability.

CQDs with unique properties like high surface area, photoluminescence, chemical stability, and biocompatibility. These features make them valuable in various applications, including food preservation. It represents a promising innovation in food preservation due to their multifunctional properties. They have the potential to revolutionize food safety and storage by combining antimicrobial, antioxidant, and sensing capabilities in sustainable and efficient ways [37-39].

CQDs application in Food Additives and fortification

In the context of food additives and fortification, CQDs offer innovative solutions for enhancing nutritional value, monitoring food quality, and improving consumer safety. Traditional methods focus on enhancing the flavor, shelf life, and nutritional value of foods using natural or minimally processed substances. Dependable for their simplicity, natural origins, and cultural acceptance but may not meet the nutritional demands of large populations or address complex deficiencies. Modern methods leverage advancements in technology and science to create more efficient, targeted, and scalable solutions. Offer precision, scalability, and innovative solutions for combating malnutrition and improving food quality but face challenges related to public trust and regulatory hurdles. Both approaches can complement each other, with traditional methods maintaining cultural heritage and modern methods addressing global food security challenges [42].

CQDs hold immense potential in food additives and fortification due to their multifunctional properties [40]. By enhancing flavor, color, preservation, and nutrient delivery, they can revolutionize the food industry. However, further research, regulatory approvals, and public education are necessary to fully integrate CQDs into mainstream food products [41] [43].

Conclusion

CQDs research for commercial food applications has rapidly progressed, but the development of nanostructures has been slower. Public concern over the safety of nanotechnology based goods for human consumption and use has increased, necessitating through evaluation of potential risks to human health. Toxicological perspective of nanotechnology in the food sector needs to be explored thoroughly. However, there are still challenges in building a healthy and sustainable food sectors, including regulation of health, safety and environmental effects. Public education is also crucial for the long term success of Nanotechnology in the food industry. CQDs exemplify the potential of nanomaterials to address contemporary challenges in various fields. Their multifunctionality, combined with ongoing research and development, positions them as pivotal tools in the advancement of sustainable technologies and next-generation applications. Future progress will hinge on overcoming production and regulatory hurdles while exploring novel interdisciplinary integrations.

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