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CHAPTER 1

Multifunctionality of Carbon Dots Additives in Food Packaging Materials

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Abstract

Carbon-based nanoparticles or CDs, with their unique structure and fascinating properties, have emerged as a standout in the field of carbon-based nanomaterials. Carbon Dots are noted for their exceptional emission of light at a shorter wavelength than the excitation light, minimal harmful effects on living organisms, compatibility with living tissues, ability to withstand prolonged exposure to light, wavelength of fluorescence emitted by a material can be adjusted or controlled according to specific needs or conditions, also ability to facilitate electrons to move from one molecule or material to another through light energy. Therefore, carbon dots benefit industry of food. They are utilized as packaging materials to prolong shelf life and maintain food safety. Carbon dots possess desirable physical and chemical properties due to their small size, diverse surface chemical groups, non-toxicity, excellent compatibility with biological systems, and notable antibacterial and antioxidant properties. They are also cost-effective and easy to synthesize. Their applications in advanced, the focus will be on exploring active, smart, and biodegradable packaging. Given their lightweight construction and high-efficiency nanostructures, carbon dots offer a viable alternative to non-biodegradable plastic packaging materials. The carbon dots enhance the, chemical, and several otherpackaging characteristics being active element, without introducing any adverse effects. Consequently, CDs are effectively utilized across by various industries to extend the shelf life of food, including the application of coating agents, the use of smart packaging technologies, the implementation of active packaging solutions, and the incorporation of additives at the nano level.

Keywords : Carbon Dots, Non biodegradable, smart packaging technology, carbon based nano particles.

1. Introduction

Nanotechnology has made food packaging a viable commercial option. Incorporating nanoparticles into material packaging helps shelf life improvement and safety of food is assured. Carbon dots (CDs) offer a range of beneficial physical and chemical properties. Effective packaging is crucial for protecting food, presenting it, and preventing deterioration caused by physical, chemical, or biological contamination. Packaging is crucial in both food processing and the food industry [1–3]. The selection of packaging materials significantly affects food quality [4], and several critical factors must be considered when choosing these materials.

When selecting suitable materials for food packaging, designers and manufacturers should consider recommendations [5] that include packaging manufacturing methods, display requirements, cost considerations, marketing needs, specific product attributes, and the properties of packaging materials. Carbon dots (CDs) offer effective barriers to gases, vapors, and odors, along with strong optical qualities, antimicrobial properties, and commendable mechanical and thermal characteristics. They are also environmentally friendly [6]. They have recently garnered attention across various fields such as therapy including light-sensitive compounds, process where light activates a substance known as a photocatalyst, method of detecting and measuring biological substances or processes using various sensors and

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technologies, drug transporting, and devices that convert sunlight directly into electrical energy. These carbon based nanoparticles used a range of materials in their formation including animal-based, human-derived, plant-based, and microbial sources, and are used in applications for active food packaging. Their photoluminescent properties can be utilized to detect counterfeit products. Carbon dots are utilized in food packaging as additive components and coating agents, antioxidants, and antibacterial substances because of their unique properties, such as high stability, excellent biocompatibility, and photoluminescence.

2. Carbon dots (CDs)

Xu and his teamfirst discovered the photoluminescent nanoparticles known as CDs [7]. The use of carbon dots (CDs) and their derivatives, which can be produced from various carbon-based starting materials, has facilitated the repurposing of food waste for various applications that are both eco-friendly and compatible with biological systems [8, 9]. CDs have various applications [10], such as in safety of food using probes. If employed in analysis of etables, a range of contaminants such as pesticides, veterinary drugs, microorganisms, and unauthorized additives can be detected by these probes.

Fluorescent carbon dots (CDs) are derived from surface defects in single- and multi-walled nanotubes. Depending on their structure, CDs can be either amorphous or graphitic. The size of CDs can be customized using various nanocomposites. CDs have been explored for a broad range of applications. Analytical techniques such as X-ray diffraction (XRD) and transmission electron microscopy (TEM) are employed to evaluate these novel materials [11, 12].

Another key feature of CDs is their UV-Vis absorption, which helps determine the excitation band for fluorescence spectra and assess changes in surface properties due to interactions with other substances or modifications. The fluorescence emission of CDs allows them to act as label-free probes, making them useful for detecting targets under a microscope [13, 14].

3. Carbon-based nanomaterials-

Carbon-based nanomaterials, specifically carbon dots (CDs), represent a recent advancement in nanotechnology with applications across various industries. Carbon dots were identified through the purification of single-layer carbon nanotubes. CDs are distinct nanoparticles that are extremely small, spherical, and notable for their exceptional physical and chemical properties. They are not only cost-effective but also offer high ability of a material to withstand stretching or pulling forces without breaking, shield against ultraviolet (UV) radiation and prevent damage from sun exposure, least harmful effects, remarkable compatible with living tissues or organisms without causing adverse reactions, ability of a material to maintain its properties and resist degradation when exposed to light over extended periods, possess antioxidantfeatures. Functional groups such as hydroxyl, carboxyl, and amino groups are present on the surface of CDs, which facilitate elongation of chain, enhance linkages in the reactions. Carbon quantum dots, graphene oxide quantum dots, carbon nanodots and carbon nanoparticles are the subclasses of CDs. The synthesis of CD is based on procedure and internal composition of CDs. CDs derived from non-biomass sources, such as battery discharge, liquid fuels, and polymer waste, can be cytotoxic and may impact the overall characteristics of the material, especially when metal doping is involved. These CDs are therefore unsuitable for applications that involve ocontact with food. They can be categorized into four types based on the use of nanoparticles: improved, packaging systems that interact with the contents or environment to extend shelf life or maintain product quality, packaging equipped with advanced technology to monitor and provide information about the product's condition or environment, and packaging made from renewable and plant-derived materials. These types of properties help reduce spoilage also residue of material.

4. CDs for use in packaging applications

Carbon dots (CDs) can contribute to the development of advanced food packaging films that are biocompatible, antibacterial, antioxidant, and UV-resistant, thereby extending the food's shelf life. In the food packaging industry, CDs need to adhere to stringent standards to enhance both product safety and longevity. Incorporating as an active component, CDs improve the mechanical, chemical, and physical properties of the packaging without affecting other properties of the film or the food. The objective is to design a new form of biodegradable packaging material, utilizing CDs for their antibacterial and antioxidant properties.

Table 1: Applications of CDs in the development of dynamic and intelligent food packaging systems.

Biodegradable polymer	Source of carbon
Cellulose	Glucose
Starch	Soy protein isolate
Collagen	Cotton cellulose
Polyvinyl alcohol	Banana paste
Pectin / gelatin	Turmeric
Chitosan	Silk sericin

Incorporating CDs into food container solutionsenhances the the integrity and freshness of food items [15]. Study shows that carbon dots improve the light blocking ability of the film without altering its mechanical properties, moisture permeability, or water contact angle. The composite film containing CDs produces reactive oxygen species (ROS), which have potent antibacterial and fungal-resistant features. Additionally, this enhances the the film's tensile durability and elasticity.

CDs can also be utilized in anti-counterfeit packaging to ensure product security and prevent imitation. Their photoluminescent properties enable the detection of fakes. For example, packaging could include CDs that emit a specific fluorescence detectable under fluorescent light. CDs can be incorporated within the polymer matrix, either embedded within or added to its surfaces.

Owing to their distinctive features, such as high stability, superior biocompatibility, and photoluminescence, carbon dots pose a significant challenge for counterfeiters. Consequently, CDs are increasingly employed in various food packaging applications, such as coating agents, smart packaging, active packaging, and nanoscale additives, thanks to their exceptional functional properties [16].

4.1. The impact of carbon dots on the characteristics of the polymeric film

Physical properties, barrier performance, and the effectiveness of polymer films are essential attributes of packaging materials [17].
Physical properties
@articlepmdbmto14, Mechanical properties influence the behavior of the film throughout the stages of processing, preservation, shipping, and distribution, up until the food product is consumed. During the food supply chain, packaging protects the food from various external mechanical stresses [18]. Incorporating CDs into biodegradable polymers enhances the film's tensile deformation, elastic modulus, and breaking strength making it more suitable for use in food packaging through the creation of composite films [19]. By enhancing mechanical performance, thinner film packaging can be employed, leading to reduced costs and less waste.

Protective properties

Protective properties are crucial for maintaining the quality, healthy value, also freshness of food. To protect food from atmospheric factors, barriers include gas resistance, water contact angle, water vapor permeability, and UV protection [20].

- **Ultraviolet (UV) Light Barrier**

Carbon dots offer robust barrier properties that effectively shield food products from harmful ultraviolet light. UV radiation can significantly deplete the nutritional value of dairy products containing vitamin B2 and promote food oxidation, resulting in off-flavors, deterioration, and the formation of harmful compounds. UV light can also cause food oxidation, color changes, and loss of vitamins C and D due to its impact on food oils. [21] Carbon dots, with their excellent scattering and absorption capabilities, will be utilized to protect protect food from UV light by quickly transforming UV photons into heat.

- **Moisture barrier**

The passage of water vapor through a film entails multiple physical mechanisms, including the absorption of water vapor on the film's surface, the movement of water molecules through the film, and the evaporation of water from the other side. Reducing water activity in food packaging helps prevent mold and bacterial growth, thus extending the food's shelf life. Water solubility is a key feature of food packaging that aids in preserving foods requiring moisture. For instance, a film made from pure cellulose nanofibers exhibits 18% water solubility, which increases to 24% with the addition of nitrogen-doped and graphene carbon dots. Graphene carbon dots, due to their excellent hydrophilic properties, enhance water solubility. the movement of moisture from the environment to the food can alter food quality, and the interaction between the filler and polymer matrix significantly influences water vapor permeability [22].

- **Oxygen barrier**

Oxygen gas can oxidize various food components, leading to a shorter shelf life. To maximize storage duration, food should be kept in packaging that limits oxygen exposure. A pure cellulose nanofiber-based film exhibits an oxygen permeability rate of approximately 5 cc per square meter per day. Nevertheless, incorporating carbon dots (CDs), including graphene CDs and nitrogen-doped CDs, reduces the oxygen transfer rate of the film made of cellulose nanofiber. The use of CDs to a biopolymer-based film effectively blocks oxygen, thereby minimizing gas exchange between the food and its environment and inhibiting microorganism growth [23].

4.2. Active material-CDs

There is a chemically or biologically interaction of active material with productenclosed in a container or wrapped product, offering benefits such as preventing microbial growth, preserving food quality, and enhancing communication about the product's status. Antimicrobial and antioxidant properties are crucial features of active packaging. Specifically, antioxidant-releasing packaging methods help slow down food oxidation. Various types of carbon dots (CDs), including those doped with selenium, nitrogen, or chlorine, are widely used for their antioxidant properties to reduce reactive oxygen species. These antioxidant CDs are primarily derived from plant sources, with autoclaves commonly used in their production.

CDs also play a role in combating food-borne pathogens and spoilage bacteria. Factors like, size, surface charge, shape and chemical moeities influence the antibacterial efficacy of CDs. They can be incorporated into the packaging material, applied as a coating, or embedded within the product itself. The antibacterial action of CDs involves mechanisms like cytoplasmic leakage and damage to cell structure. While composite films with CDs did not completely halt the growth of Listeria monocytogenes, increasing the concentration of carbon dots enhanced the inhibitory effect [24].

5. Concluding remarks

CDs are a valuable source of inexpensive, photoelectrochemically active materials that boast excellent stability, strong photoluminescence, UV blocking capabilities, and photoelectrochemical properties. They provide several benefits for cutting-edge food packaging, such as enhanced characteristics, resistance to water, stability for heat , and enhanced resistivefunctions, and antibacterial and antioxidant activities. When combined with biological-chemical indicators, CDs enable efficient and precise packaging of food, maintaining its uniqueness and quality. Additionally, compared to other nanoparticles, CDs provide greater safety.

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