Carbon Nanostructures As Antibacterials and Active Food-Packaging Materials: A Review

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ABSTRACT: In this article, we discuss carbon nanoparticles for application as antibacterials and food-packaging materials. The use of petroleum-derived products, synthetic materials, ceramics, wax, etc. in the food-packaging industry emits polluted gas and wastewater, which leads to environmental pollution. To overcome the problems faced by the industry to preserve and package food, carbon nanomaterials may be good alternatives to enhance the shelf life of food without affecting the nutrients. Carbon atoms bond with each other in diverse ways to form many allotropes, resulting in a variety of carbon nanomaterials (CNMs). CNMs include zero-dimensional carbon dots, graphene quantum dots, 1-dimensional carbon nanotubes, 2-dimensional pristine graphene, graphene oxide, reduced graphene oxide, and other derivatives of graphene. Most of the carbon-based nanomaterials are synthesized through a green process that is widely used in the field of food science and technology, and they are used mostly as antibacterial agents and as a biofiller in the development of active food-packaging materials. Carbon nanomaterials (CNMs), viz., carbon dots, graphene, activated carbon-based nanocomposites, carbon nanotubes, etc., are found to be environmentally benign and better materials for food packaging. With antibacterial efficiency, they support food preservation and other applications as well. Thus, carbon nanostructures are found to be applicable as superior materials for food preservation and packaging in modern industry.

1. INTRODUCTION

Most of our daily purchases are packaged. Whatever the source of food, from grocery store to restaurant to online delivery to farmers market, all are artificially packaged. Today’s industry uses synthetic materials, ceramics, petroleum products, paper, glass, paperboard, wax, cardboard, etc. as food-packaging materials.1a Unfortunately, most of the available packaging materials are made for single use and thrown away without recycling or reusing. As per the United States Environmental Protection Agency (USEPA), half of the municipal waste comes from food waste and food-packaging materials.1b The trouble we face for food packaging comes from its manufacturing. There is heavy consumption of water, chemicals, minerals, petroleum, etc. during the manufacturing of food-packaging materials. Heavy metals, wastewater, and sludge, including air emissions produced during packaging, are responsible for environmental problems.1c In addition, bacterial growth in food for prolonged preservation is also a problem. Conventional food preservation and packaging increases environmental pollution with degradation of food nutrients and taste. Carbon nanoparticles have multifaceted applications in modern industry.1d,e They also find an important application in the smart packaging of food.1f

Due to the onset of multidrug-resistant bacteria, it is of prime importance to research and develop newer antibacterial agents. Metallic nanoparticles, like gold, silver, and copper and, more recently, zinc, titanium, and magnesium, as well as carbon-based nanomaterials have shown remarkable antibacterial potential and antifungal properties. Carbon and metal nanostructures can be easily synthesized through a green and synthetic approach and have versatile applications.2a,e They are, therefore, applied as antimicrobial agents in food-packaging materials, textiles, etc. In this article, we discuss their antimicrobial efficacy against a diverse set of bacterial species, as well as their newfound application in food packaging.

2. CARBON NANOMATERIALS AND THEIR APPLICATION AS FOOD PACKAGING AND ANTIBACTERIALS

2.1. Carbon Dots. Carbon dots (CDs) are also known as fluorescent carbon. They have exceptional qualities, for example, high chemical stability, solubility in water, and easy synthesis methods. CDs have a carbon center and different functional groups like −COOH, −OH, and −NH on the
surface. Over the years, many researchers have studied their antibacterial properties. For instance, Raina et al.3 reported the use of Ag@CD against Staphylococcus aureus and Escherichia coli. Carbon dots were synthesized using the leaves of Cannabis sativa. The statistical analysis showed 42 μg/mL as the minimum inhibitory concentration (MIC) of Ag@CD against test strains. Other researchers also determined the antibacterial potential of N-doped CDs via the hydrothermal method.4 Osmanthus leaves were utilized as the precursor to synthesize CDs. Only 13.09% of Escherichia coli and 3.37% of Staphylococcus aureus thrived at a concentration of 1000 μg/mL. Several experiments were also conducted to check the feasibility of utilizing CDs in active packaging. An ecofriendly antimicrobial bacterial nanocellulose (BNC) sheet was fabricated using CDs.5 Carbon dots derived from white mulberry were found to have a size in the range of 4–5 nm, and they were incorporated into the BNC. The fabricated nanopaper showed a good UV-blocking property as well as antimicrobial activity against L. monocytogenes. Carbon dots (530 g/L) were used for the fabrication process with an impregnation time of 14 h at 30 °C. Kousheh et al.6 prepared an antimicrobial and UV-protective bacterial nanocomposite (BNC) film using CDs synthesized from lactic acid bacteria. Scanning electron microscopy (SEM) micrographs indicated high porous networks with homogeneous distribution of bacterial nanocomposite fibers that were prepared using CDs (Figure 1). The film was prepared using CDs of 2.8 nm size and 500 mg/mL concentration. The study revealed that the fabricated film showed good mechanical properties as well as antimicrobial activity against L. monocytogenes and E. coli.

### 2.2. Carbon Nanotubes

Carbon nanotubes (CNTs) are one-dimensional carbon materials, classified as single-walled carbon nanotubes (SWCNTs) and multiwalled carbon nanotubes (MWCNTs). There are two types of carbon that have an aspect ratio >1000. In 1991, Iijima and Ichihashi reported microtubules of graphitic carbon with concentrically arranged cylinders, and they are known as multiwalled carbon nanotubes today.7 SWCNTs have a single layer of graphene rolled up into a cylinder, but MWCNTs have more than one concentric cylindrical shells arranged coaxially around a central hollow core with van der Waals forces between adjacent layers.8 Over the past year, research has been conducted to study the antibacterial effect of these CNTs. Ag-doped TiO₂ nanoparticles (NPs) coated with SWCNTs and MWCNTs were synthesized10 and studied for their antibacterial potential against E. coli and S. aureus. The study revealed that SWCNTs-TiO₂/Ag possessed higher toxicity than its counterpart, MWCNTs-TiO₂/Ag. In addition to that, these classes of nanomaterials were also utilized in food-packaging materials. Yu et al. prepared bionanocomposites of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) reinforced with functionalized CNTs.11 They reported that the addition of CNTs in the polymeric matrix improved the thermal and mechanical properties of the film. The tensile strength also was improved by 88%, and the Young’s modulus was enhanced by 172%. The prepared materials could be well-utilized as food preservative and packaging materials. Furthering the study to utilize CNTs, Dias et al.12 fabricated a film to pack shredded and cooked chicken meat using carbon nanotubes and allyl isothiocyanate. The study concluded that allyl isothiocyanate at a concentration of >28% with CNTs at concentrations >0.02% resulted in microbial reduction. The developed film was effective for 40 days. Pattanshetti et al.13 prepared garlic-microparticle-coated gelatin/MWCNT nanocomposite films for prospective use as a food-packaging material. The CNTs were synthesized using the T-chemical vapor deposition (T-CVD) method. The CNTs were of sizes ranging from 30 to 45 nm. The fabricated film showed antibacterial activity as well as improved resistance toward both oil and water.

### 2.3. Graphene-Based Nanomaterials

Graphene, synthesized from graphite, is a 2-D single-atom-thick structure. It is produced by mechanical or chemical exfoliation of graphite via a CVD process.14 Graphene oxide (GO) is synthesized by Hummer’s method. Reduced graphene oxide (rGO) is produced from the thermal or chemical reduction of GO.15 It is considered as an intermediate structure between an ideal graphene sheet and highly oxidized graphene oxide. Graphene-based nanomaterials have also been widely studied for their antibacterial properties. In a recent study, Aunkor et al.16 studied the antibacterial activity of graphene oxide nanosheets against many Gram-positive and Gram-negative bacteria and compared the results with commercially available antibiotics. They reported the different zones of inhibition by GO, e.g., E. coli, 39 mm; K. pneumoniae, 41 mm; S. aureus, 38 mm; P. aeruginosa, 38 mm; P. mirabilis, 27 mm; and S. marcescens, 39 mm. GO synthesized using the modified Hummers method showed better antibacterial activity than all of the commercial antibiotics tested. In another study, Rago et al.17 revealed the antibacterial activity of graphene nanoplatelets against Streptococcus mutans. It was found that the killing effect of the synthesized nanomaterial on S. mutans was inversely proportional to both its lateral size and thickness. Vi et al.18 studied the antibacterial activity of Ag-GO against S. aureus and E. coli. They reported that, compared with pristine GO and silver nanoparticles, the synthesized Ag-GO displayed 73% inhibition against E. coli and 98.5% inhibition against S. aureus. Various zones of inhibition are seen in Figure 2. Gupta et al.19 studied the antibacterial activity of graphene oxide nanoparticles against B. subtilis, S. epidermis, P. aeruginosa, and E. aerogenes. SEM studies revealed that the NPs were present in the range of 50–60 nm. The zones of inhibition (Zoli) at 100 μg/mL concentration were found to be as follows: B. subtilis, 9 mm; S. epidermis, 12 mm; P. aeruginosa, 7 mm; E. aerogenes, 12 mm.

These graphene-based nanomaterials are also now being widely used as biofiller materials For instance, Arfat et al.20 fabricated antimicrobial films for prospective use as a food-

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**Figure 1.** SEM micrographs of bacterial nanocomposite fibers. Reprinted with permission from ref 6. Copyright 2020 Elsevier.
3. CONCLUSION AND FUTURE SCOPE

In view of providing access to better health, good nutrition, and safe food for the world, new and advanced technologies are inevitable in the food/food-packaging industries. Over the years, several research studies have been conducted to utilize the unique properties of carbon-based nanomaterials, and newer breakthroughs are emerging in the developments of novel technologies for food analysis, food safety, and food packaging. Carbon nanoparticles, viz., carbon dots, graphene, carbon nanotubes, etc., are found to be superior food-packaging materials compared to the conventional one. The CNMs are easy to synthesize and environmentally benign. Being antibacterial in nature, CNMs may be used as a food preservative and food-packaging materials. An antibacterial nanosheet was produced to replace conventional plastic for active food packaging. The nanomaterials were found to be less toxic and have versatile activeness. These studies will open new scopes for industries to fabricate CNM-based biofilm/packaging materials in order to keep food safe and healthy. The development of cheaper and biodegradable food-packaging materials will enhance both the environmental and economic wellness of society.

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Notes
The authors declare no competing financial interest.

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Dr. Dev Vrat Kamboj joined DRDO as a Scientist and is currently serving as Director, Defence Research Laboratory, Tezpur. His field of expertise is biodegradation and biodafence. He is the recipient of several DRDO awards that include DRDO Scientist of the Year Award, Defence Technology Spin-off Award, Technology group award, and Laboratory Scientist of the Year Award for his contributions in Biodigester Technology and Biodafence. Dr. Kamboj has 25 patents, 70 research publications, and 3 books to his credit.

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