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Review Article

Recent Advances in Green Synthesis, Physicochemical Characterization and Pharmacological Applications of Carbon Dots

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ABSTRACT

Carbon dots (CDs) are tiny carbon-based nanoparticles that have gained significant attention because of their unique optical properties, high stability, low toxicity, and good biocompatibility. Green synthesis of carbon dots using natural materials has become an eco-friendly and cost-effective approach that avoids the use of harmful chemicals. This review summarizes recent advances in the green synthesis of carbon dots, their physicochemical characterization, and their pharmacological applications. Various synthesis methods, including hydrothermal, microwave-assisted, and pyrolysis techniques, are discussed along with important characterization methods such as UV–Visible spectroscopy, fluorescence spectroscopy, FTIR, XRD, TEM, SEM, particle size, and zeta potential analysis. The review also highlights the biological activities of carbon dots, including antioxidant, antimicrobial, anti-inflammatory, anticancer, wound healing, and drug delivery applications. Overall, green-synthesized carbon dots represent a promising nanomaterial for future biomedical and pharmaceutical research because of their safety, effectiveness, and environmentally friendly production methods.

INTRODUCTION

Nanotechnology is one of the fastest-growing fields in science and technology because it deals with materials that have dimensions between 1 and 100 nanometers. Materials at the nanoscale show unique physical, chemical, optical, and biological properties that are different from their bulk forms. These special properties make nanomaterials useful in medicine, pharmacy, electronics, agriculture, environmental science, and biotechnology. Among the different types of nanomaterials, carbon-based nanomaterials have attracted significant attention due to their excellent stability, low toxicity, high surface area, and ease of surface modification. Carbon nanomaterials

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include graphene, carbon nanotubes, fullerenes, nanodiamonds, and carbon dots. Among these, carbon dots (CDs) have become one of the most promising nanomaterials because of their outstanding optical properties, biocompatibility, and environmentally friendly synthesis methods.[1–3]

Carbon dots are small carbon nanoparticles with sizes generally below 10 nm. They were first discovered accidentally during the purification of single-walled carbon nanotubes in 2004. Since then, researchers have explored their unique fluorescence, water solubility, chemical stability, and low toxicity, making them attractive for biomedical and pharmaceutical applications. Unlike traditional semiconductor quantum dots that contain toxic heavy metals such as cadmium or lead, carbon dots are considered safer and more environmentally friendly. Their excellent fluorescence characteristics, easy functionalization, and good compatibility with biological systems have encouraged researchers to develop new applications in drug delivery, bioimaging, biosensing, tissue engineering, antimicrobial therapy, antioxidant therapy, cancer treatment, and environmental monitoring.[4–6]

The remarkable properties of carbon dots mainly depend on their small particle size, surface functional groups, crystal structure, and synthesis method. These nanoparticles usually possess oxygen-containing functional groups such as hydroxyl (-OH), carboxyl (-COOH), carbonyl (C=O), and amino ($-NH_2$) groups on their surface. These functional groups improve their water solubility and provide sites for chemical modification with drugs, biomolecules, polymers, or targeting ligands. Surface modification can further enhance their fluorescence intensity, biological activity, and drug-loading capacity. Therefore, carbon dots are considered multifunctional nanomaterials with wide applications in pharmaceutical and biomedical sciences.[7,8]

Carbon dots can be synthesized using two main approaches: top-down and bottom-up methods. Top-down methods involve breaking larger carbon materials into nanosized particles through techniques such as laser ablation, arc discharge, electrochemical oxidation, or chemical oxidation. Although these methods can produce high-quality carbon dots, they usually require expensive equipment, high energy consumption, and harsh reaction conditions. In contrast, bottom-up methods involve carbonization of small organic molecules or natural materials using hydrothermal treatment, solvothermal synthesis, microwave irradiation, pyrolysis, or ultrasonic methods. Bottom-up methods are simple, economical, and suitable for large-scale production of carbon dots.[9–11]

In recent years, green synthesis has become an important area of nanotechnology research. Green synthesis follows the principles of green chemistry by using renewable natural resources, reducing hazardous chemicals, minimizing waste generation, and lowering energy consumption. Instead of using toxic chemical precursors, researchers utilize plant extracts, fruit peels, vegetables, flowers, herbs, agricultural waste, natural sugars, proteins, amino acids, and essential oils as carbon sources for synthesizing carbon dots. These natural materials are inexpensive, biodegradable, renewable, and rich in carbohydrates, phenolic compounds, amino acids, flavonoids, and organic acids that can be easily converted into fluorescent carbon nanoparticles.[12–14] Green synthesis offers several advantages over conventional chemical synthesis. It reduces environmental pollution, lowers production costs, improves safety during manufacturing, and increases the biocompatibility of the final nanomaterials. Moreover, plant-derived carbon dots often contain naturally occurring bioactive compounds on their surface, which may enhance their antioxidant, antimicrobial, anti-inflammatory, and anticancer activities. These advantages have made green synthesis one of the preferred approaches for preparing carbon dots intended for pharmaceutical and biomedical applications.[15,16] Another important advantage of green-synthesized carbon dots is their excellent biocompatibility. Many studies have demonstrated that carbon dots prepared from natural sources exhibit very low cytotoxicity toward normal mammalian cells while maintaining significant biological activity against pathogens and cancer cells. Their small particle size allows easy penetration into biological tissues, whereas their abundant surface functional groups facilitate interaction with proteins, nucleic acids, and cell membranes. These characteristics make carbon dots highly suitable for drug delivery, gene delivery, bioimaging, biosensing, and targeted therapy.[17,18]

In addition to their biological applications, carbon dots possess excellent optical properties. They exhibit strong fluorescence under ultraviolet or visible light, high photostability, broad absorption spectra, and tunable emission wavelengths. These unique optical characteristics have enabled their application as fluorescent probes in disease diagnosis, imaging of living cells, detection of metal ions, monitoring of biological molecules, food safety analysis, and environmental sensing. Their fluorescence can be easily modified by changing the synthesis conditions, precursor materials, reaction temperature, and surface functionalization, providing flexibility for different biomedical applications.[19,20]

Green Synthesis of Carbon Dots

Green synthesis is an environmentally friendly method used to prepare carbon dots (CDs) by following the principles of green chemistry. This approach uses natural and renewable materials instead of toxic chemicals, making the synthesis process safer, economical, and sustainable. In recent years, green synthesis has become one of the most preferred methods for producing carbon dots because it reduces environmental pollution and minimizes the use of hazardous reagents. Natural materials such as fruits, vegetables, flowers, leaves, seeds, agricultural waste, food waste, medicinal herbs, natural sugars, amino acids, proteins, and essential oils are commonly used as carbon sources for the preparation of carbon dots. These materials are rich in carbohydrates, phenolic compounds, flavonoids, proteins, and organic acids, which easily undergo carbonization to produce fluorescent nanoparticles.[21–23]

The synthesis of carbon dots generally involves converting carbon-rich natural materials into nanosized particles through heating or chemical reactions. During this process, dehydration, polymerization, and carbonization occur simultaneously, resulting in the formation of stable carbon nanoparticles. Various green synthesis methods have been developed, including hydrothermal synthesis, solvothermal synthesis, microwave-assisted synthesis, pyrolysis, ultrasonic synthesis, and one-pot synthesis. Among these methods, hydrothermal synthesis is the most widely used because it is simple, cost-effective, and produces highly fluorescent carbon dots with uniform particle size.[24,25]

In the hydrothermal method, the natural precursor is mixed with distilled water and heated in a sealed autoclave at temperatures ranging from 150°C to 250°C for several hours. High temperature and pressure convert the organic compounds into carbon nanoparticles. The obtained solution is then filtered and purified by centrifugation or dialysis to remove larger particles and impurities. The final product contains highly dispersed carbon dots with good water solubility and fluorescence properties.[26] Microwave-assisted synthesis is another rapid and energy-efficient method for producing carbon dots. In this method, microwave radiation provides uniform heating, reducing the reaction time from several hours to only a few minutes. This method consumes less energy and produces carbon dots with excellent optical properties. Similarly, pyrolysis involves direct heating of natural materials at high temperatures in the absence of oxygen, resulting in carbonization and nanoparticle formation. Although pyrolysis is simple, controlling particle size and fluorescence properties may be more difficult than hydrothermal synthesis.[27,28]

Recently, researchers have also explored the use of essential oils as carbon precursors because they contain various bioactive compounds such as terpenoids, alcohols, aldehydes, esters, and phenolic compounds. These compounds not only serve as carbon sources but may also contribute to the biological activity of the synthesized carbon dots. The use of essential oils has opened new opportunities for developing multifunctional carbon dots with antioxidant, antimicrobial, anti-inflammatory, and therapeutic properties. Such naturally derived carbon dots are increasingly being investigated for pharmaceutical and biomedical applications.[29,30]

Advantages of Green Synthesis

Green synthesis offers several advantages over conventional chemical methods used for the preparation of carbon dots. One of the major advantages is environmental safety. Conventional synthesis methods often require strong acids, alkalis, organic solvents, and toxic chemicals that generate hazardous waste and increase environmental pollution. Green synthesis eliminates or significantly reduces the use of these harmful chemicals, making the overall process environmentally friendly.[31] Another important advantage is the use of renewable natural resources. Plant materials, agricultural residues, food waste, and natural biomolecules are inexpensive, easily available, biodegradable, and renewable. Utilizing these materials helps reduce waste while promoting sustainable development and circular bioeconomy practices. The conversion of biological waste into valuable nanomaterials also adds economic value to agricultural by-products.[32]

Green synthesis is also cost-effective because natural raw materials are generally inexpensive and readily available. The synthesis procedures usually require simple laboratory equipment and consume less energy compared to conventional methods. This makes large-scale production more feasible and economically attractive for industrial applications.[33] Carbon dots synthesized through green methods generally show excellent biocompatibility and low toxicity. Since the synthesis process avoids toxic chemicals, the resulting nanoparticles are more suitable for biological applications such as drug delivery, tissue engineering, biosensing, bioimaging, and wound healing. Many studies have demonstrated that green-synthesized carbon dots exhibit minimal toxicity toward normal cells while maintaining desirable therapeutic activities.[34]

Natural precursors often contain biologically active compounds such as flavonoids, polyphenols, vitamins, amino acids, and antioxidants. During synthesis, some of these functional groups remain on the surface of carbon dots, improving their biological properties. As a result, green carbon dots frequently exhibit enhanced antioxidant, antimicrobial, anti-inflammatory, anticancer, and free radical scavenging activities without requiring additional chemical modification.[35]

Surface functionalization is another significant advantage of green-synthesized carbon dots. Their surfaces naturally contain hydroxyl, carboxyl, amino, and carbonyl groups that improve water solubility and facilitate the attachment of drugs, proteins, antibodies, nucleic acids, and other biomolecules. This characteristic greatly expands their applications in targeted drug delivery and diagnostic imaging.[36] Green synthesis also supports sustainable pharmaceutical development by reducing hazardous waste generation and improving manufacturing safety. As environmental regulations become stricter worldwide, green nanotechnology is expected to play an increasingly important role in developing safe and eco-friendly pharmaceutical products. The simplicity, scalability, and sustainability of green synthesis make it an attractive strategy for future industrial production of carbon dots.[37] Despite its many advantages, certain challenges remain. Variability in natural precursor composition may affect particle size, fluorescence intensity, and reproducibility between batches. Therefore, optimization of synthesis parameters such as temperature, reaction time, pH, and precursor concentration is essential to obtain consistent product quality. Continued research is needed to establish standardized synthesis protocols for large-scale commercial production.[38–40]

CONCLUSION

Carbon dots have emerged as one of the most promising carbon-based nanomaterials because of their unique optical properties, excellent biocompatibility, low toxicity, and easy surface modification. Green synthesis has further improved their importance by providing an environmentally friendly, simple, and cost-effective method for producing high-quality carbon dots from natural and renewable resources. Compared with conventional chemical methods, green synthesis minimizes the use of hazardous chemicals, reduces environmental pollution, and supports sustainable nanotechnology. The presence of natural functional groups on green-synthesized carbon dots also enhances their stability and biological activity, making them suitable for various pharmaceutical and biomedical applications. Different physicochemical characterization techniques such as UV–Visible spectroscopy, fluorescence spectroscopy, FTIR, XRD, TEM, SEM, particle size analysis, and zeta potential measurements play an important role in confirming the structural, optical, and surface properties of carbon dots. These characterization methods ensure the quality and reproducibility of the synthesized nanomaterials. In recent years, carbon dots have demonstrated significant potential in drug delivery, bioimaging, biosensing, antimicrobial therapy, antioxidant therapy, anti-inflammatory treatment, wound healing, and cancer therapy. Their multifunctional nature and excellent safety profile make them attractive candidates for future clinical applications.

Future research should focus on improving synthesis methods, understanding biological mechanisms, and conducting extensive preclinical and clinical studies. Overall, green-synthesized carbon dots represent a sustainable and innovative nanomaterial with great potential to advance pharmaceutical research, nanomedicine, diagnostics, and targeted therapeutic applications.

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