A review of the preparation and application research of carbon quantum dot materials

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Abstract: Carbon quantum dots (CQDs), as a zero dimensional fluorescent carbon nanomaterial, have unique optical stability, biocompatibility, and fluorescence properties, and are widely used in fields such as chemical and biological sensing, optical catalysis, and TNP detection. This article not only discusses the research review on the preparation of carbon quantum dot materials, but also provides a comprehensive analysis of their application fields, hoping to provide some references for relevant personnel.

Keywords: Carbon quantum dots; Material preparation; Application

1. Preparation method of carbon quantum dots

1.1 Top-down preparation method

The top-down preparation method of carbon quantum dots mainly refers to the use of physical or chemical methods to cut and decompose large-sized carbon materials into nano-sized (below 10nm) carbon quantum dots. This method is suitable for large-scale preparation of carbon quantum dot materials, but impurities may occur during the preparation process, which can be affected by performance and purity. Generally speaking, there are several top-down preparation methods, including:

1.1.1 Arc discharge method

In the field of carbon quantum dot preparation, arc discharge method is one of the earliest applied methods. It mainly applies high voltage to the graphite electrode in an inert gas or high vacuum environment, which enables it to generate an arc, thereby promoting the evaporation and condensation of graphite material, and forming carbon quantum dots. Researchers used this method to treat cigarette ash and isolated fluorescent carbon particles derived from SWNTs, which exhibited yellow, green, blue, and orange fluorescence under 365nm ultraviolet light irradiation. Afterwards, Sun et al. named these particles "carbon quantum dots". Although the arc discharge method can ensure that carbon quantum dots have small size and strong fluorescence and water solubility, it cannot guarantee uniform particle size, and the particle fluorescence efficiency is low and difficult to purify, which also limits its use in the large-scale preparation of carbon quantum dots.

1.1.2 Laser erosion method

This method mainly uses laser as a heat source to rapidly increase the temperature of the target material to above its boiling point, and then evaporates to form nanoparticles. The carbon quantum dots prepared by this method have the characteristics of high purity, good fluorescence performance, and small particle size. Yang et al. used this method to prepare carbon quantum dots, and the resulting nanodots exhibited ultraviolet emission at 305nm, 325nm, and 335nm particle sizes. Calabro et al. used this method to prepare carbon quantum dots in liquid phase using carbon nano onions, obtaining smaller sized carbon quantum dots than chemical methods, which also confirms the cleanliness and convenience of this method. However, it should be noted that this method has high requirements for experimental procedures and instruments, and the particle size of the prepared carbon quantum dots also varies to some extent, which is not conducive to its promotion and use in large-scale production.

1.1.3 Ultrasonic treatment

This method mainly utilizes the cavitation effect and high-frequency vibration of ultrasound to generate huge energy in a short period of time, thereby crushing and peeling off carbon materials and preparing carbon quantum dots. Preethi et al. used this method to prepare melon and potato raw materials, and the obtained carbon quantum dots exhibited uniform distribution, spherical morphology, and quantum yield close to 50%, with an average particle size of around 3nm. Zhang et al. used ultrasound to treat porous nanosheets and prepared single-layer carbon quantum dots with an average particle size between 2-6nm. The ultrasonic treatment method is relatively simple to operate, but it has a relatively long reaction time and is difficult to separate and purify. The production efficiency of carbon quantum dots is also not high, so it is limited in practical applications.

1.1.4 Electrochemical oxidation method

This method mainly relies on the potential of a strong electric field, using carbon material as the working electrode, allowing the electrolyte to be oxidized at the anode, and then preparing carbon quantum dots through stripping and passivation treatment. Ran Qingqiang combined his research and pointed out that single peak carbon dots (U-CDs) were prepared using graphite as a representative carbon source and electrochemical oxidation method under typical working conditions. The average size of U-CDs was about 3.7 ± 0.7nm, with rich functional groups and blue-green fluorescence emission. However, when the temperature rises to indoor temperature, its color will change to yellow, and its dispersed non displacement fluorescence emission and color change are mainly caused by surface oxidation induction.

1.2 Bottom up preparation method

The bottom-up preparation method of carbon quantum dots involves using small molecules as precursors and then utilizing methods such as pyrolysis and chemical reactions to prepare carbon quantum dots. This method can accurately control the surface properties, structure, and size of carbon quantum dots, effectively ensuring their performance and purity. Generally speaking, there are several bottom-up preparation methods, including:

1.2.1 Hydrothermal method/solvent pyrolysis method

This method mainly involves mixing carbon source materials and related solvents, and then preparing carbon quantum dots through high temperature and high pressure. The solvent used in hydrothermal method is water, and the solvent used in solvent pyrolysis method is organic solvent. The raw materials for this method are readily available and easy to operate, and the prepared carbon quantum dots can also be better controlled in size. Zhu Lingli and others used hydrothermal method to produce carbon quantum dots, with a very short synthesis time of only about 2 hours, which also reflects the convenience of this method. Zhu Xiaomeng et al. conducted a study on the performance improvement of perovskite cells prepared by carbon quantum dot doped green anti solvent method using solvent pyrolysis method.

1.2.2 Template method

This method mainly relies on specific supporting materials to prepare carbon quantum dots, while emphasizing the use of template spatial confinement to control the morphology and size of carbon quantum dots, thereby ensuring their good water solubility, uniformity, and low toxicity. Khasevani et al., prepared heterogeneous ternary carbon dots through MIL-88B (Fe) metal organic frameworks (MOFs) template, which has good adhesion on the board and good photocatalytic activity.

1.2.3 Solid phase method

This method refers to the preparation of carbon quantum dots through chemical reactions in a solid-state state. Typically, a solid carbon source and reactants are mixed and then subjected to high resolution solid-phase treatment to generate carbon quantum dots. Zhang Haijuan has conducted some research on the solid-state synthesis and application of doped carbon quantum dots. This method is relatively easy to operate and control, and the prepared carbon quantum dots have excellent crystallinity and high purity. However, it is difficult to effectively control the reaction rate and particle size uniformity, which limits its practical application.

2. Application of Carbon Quantum Dots

2.1 Biosensing

In the new era, due to the high quality, low toxicity, biocompatibility, and fluorescence of carbon quantum dots, as well as their small particle size of less than 10nm, they have a wide range of applications and enormous potential in biosensing. And its specific application in this field is mainly reflected in two aspects. Firstly, it is biological imaging. The low toxicity and biocompatibility of carbon quantum dots make them valuable for biological imaging applications. It can label the tissues and cells of animals both inside and outside the body, enabling us to better detect physiological and behavioral processes of organisms. For example, by surface modifying specific antibodies or ligands, carbon quantum dots can recognize and bind to cellular tissues of organisms for precise imaging. In addition, its fluorescence characteristics also make it have a high contrast under a microscope, which is more conducive to observation and analysis by relevant personnel. Secondly, there are biosensors. Carbon quantum dots have a wide range of applications in biosensors due to their excellent fluorescence properties. When it binds to the target organism, its wavelength and fluorescence intensity will undergo certain changes, thereby helping relevant personnel to better detect the target organism. Carbon quantum dot based biosensors have high response efficiency and sensitivity, and have been applied in various fields such as metal ions (such as Fe^{3+}, Cu^{2+}, Hg^{2+}, etc.), viruses and bacteria, as well as biomolecules (such as glucose, amino acids, etc.), and have demonstrated excellent performance, effectively improving detection efficiency.

2.2 Optical catalysis

Firstly, it is the application of photocatalysis in the degradation of pollution. Under the irradiation of ultraviolet and visible light, carbon quantum dots can generate photo generated holes and electrons, and undergo redox reactions, thereby degrading pollutants in air or water. For example, it can be combined with semiconductor materials such as TiO_2 to promote the comprehensive improvement of photocatalytic degradation of organic dyes. At the same time, it can also promote the separation of photo generated holes and electrons, enhance carrier lifetime, and improve photocatalytic activity. Secondly, it is photocatalytic hydrogen production. Under illumination, carbon quantum dots can absorb the broad electrons generated by photons and transfer them to metal catalysts, causing them to react with water molecules and generate hydrogen gas.

2.3 TNP (Trace Nuclide) Detection

With the development of environmental science and nuclear energy technology, the demand for detecting trace nuclides (TNPs) is increasing day by day. Carbon quantum dots exhibit unique advantages in TNP detection due to their high specific surface area, excellent adsorption performance, and fluorescence properties. Jiang Xiaolan et al. conducted INP experiments using glucose as a carbon source and cysteine hydrochloride as a nitrogen sulfur dopant, using hydrothermal and pyrolysis methods. The results showed that the carbon quantum dots prepared by pyrolysis method had higher fluorescence quantum yield and relatively longer emission wavelength, making them valuable for TNP detection.

2.4 Virtual simulation

Based on the actual situation, although carbon quantum dots themselves are not directly related to virtual simulation, their applications in materials science and nanotechnology have also opened the door to virtual simulation applications. By constructing a virtual model based on carbon quantum dots, relevant personnel can have a more intuitive and accurate understanding of their properties, mechanisms, and structural characteristics, which also lays a solid foundation for the advancement and development of related experiments. For example, computer simulation technology can be used to construct molecular models of carbon quantum dots, and then simulate their reaction under different scenario conditions. This can help experimenters better predict their optimized synthesis conditions and related performance changes, comprehensively improving the success rate and effectiveness of experiments. For example, in the research of carbon quantum dot applications, virtual space can be constructed to simulate its application in multiple fields such as biosensing and optical catalysis, providing scientific data and information references for relevant personnel, and thus bringing effective assistance to scientific progress and innovative development in related fields.

Overall, carbon quantum dots, as an emerging nanomaterial, have unique characteristics such as optical stability, biocompatibility, and fluorescence properties. With the development of related technologies, it has shown broad application prospects in fields such as biosensing, optical catalysis, TNP detection, and virtual simulation. Looking towards the future, we have reason to believe that it will play an important role in more fields and make greater contributions to the development of human society.

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