

Development of Fluorescent Carbon Dots for Selective and Sensitive Detection of Copper Ions and Cellular Imaging

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Abstract

Fluorescent Carbon Dots (CDs) have emerged as a versatile tool in nanotechnology due to their superior optical properties, biocompatibility and ease of synthesis. They are increasingly used for sensing applications, including the detection of metal ions such as copper, which is crucial for various biological and environmental processes. The ability to selectively and sensitively detect copper ions (Cu^{2+}) is important for both practical and research applications. This study aims to develop advanced fluorescent carbon dots specifically designed for the selective and sensitive detection of copper ions. Additionally, the application of these CDs in cellular imaging is explored to demonstrate their utility in biological contexts. The CDs were synthesized via a hydrothermal method, optimized to enhance their fluorescence and selectivity towards copper ions. The materials were characterized using techniques such as UV-Vis spectroscopy, photoluminescence spectroscopy, Transmission Electron Microscopy (TEM) and Dynamic Light Scattering (DLS). The performance of the CDs in detecting copper ions was evaluated under various conditions and their potential for cellular imaging was assessed using fluorescence microscopy on live cells. The synthesized CDs exhibited high fluorescence quantum yields, stability and selectivity towards copper ions. The detection of copper ions was achieved with high sensitivity, reaching low detection limits. Cellular imaging demonstrated that the CDs could effectively label copper ions within live cells, providing clear visualization of copper distribution. The developed fluorescent carbon dots represent a significant advancement in sensing and imaging technologies. Their high selectivity and sensitivity for copper ions, coupled with their biocompatibility, make them a promising tool for environmental monitoring and biomedical research.

Keywords: Fluorescent carbon dots • Copper ions • Selective detection • Cellular imaging • Photoluminescence • Hydrothermal synthesis • Quantum yield • Biocompatibility

Introduction

Background to the study

Fluorescent Carbon Dots (CDs) are a class of nanomaterials with remarkable optical properties, including high fluorescence, photo stability and low toxicity. Their unique characteristics make them suitable for various applications in sensing, imaging and biological assays. Among the numerous applications of CDs, the detection of metal ions, particularly copper, has garnered significant interest due to copper's critical biological roles and potential toxicity in excess. Copper is an essential trace element in many biological processes, including enzyme function, electron transport and cellular respiration. However, imbalances in copper levels can lead to disorders such as Wilson's disease, Menkes disease and neurodegenerative conditions. Thus, precise detection and monitoring of copper ions are

crucial for understanding these conditions and their treatment. In environmental contexts, monitoring copper levels is essential for assessing pollution and ensuring the safety of water sources. Conventional methods for copper ion detection include atomic absorption spectroscopy, inductively coupled plasma mass spectrometry and colorimetric assays. While effective, these methods can be cumbersome and often require complex sample preparation. Fluorescent probes have become a popular alternative due to their simplicity, rapid response and the ability to provide real-time results. Carbon dots, with their tunable fluorescence properties, have emerged as effective probes for metal ion detection. Their size, surface functionalization and emission properties can be tailored to enhance selectivity and sensitivity towards specific ions. This study aims to synthesize and characterize novel fluorescent carbon dots with enhanced selectivity and sensitivity for copper ion detection. The developed CDs will also be tested for their application in cellular

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imaging to demonstrate their utility in biological systems [1,2].

Literature Review

Carbon dots are nanoscale carbon-based materials that exhibit fluorescence due to quantum confinement and surface states. The synthesis of CDs can be achieved through various methods, including hydrothermal, solvo thermal, microwave-assisted and chemical oxidation techniques. Each method influences the size, surface chemistry and optical properties of the CDs. The hydrothermal method, in particular, is favored for its simplicity and the ability to produce high-quality CDs with controlled sizes and functional groups. Recent advancements have focused on optimizing reaction conditions and precursor materials to enhance the fluorescence quantum yield and stability of CDs. Fluorescent probes for metal ion detection typically rely on changes in fluorescence intensity or wavelength upon binding to the target ions. For copper ions, various probes have been developed, including organic dyes, chemo sensors and carbon-based materials. The interaction between the probe and copper ions often results in fluorescence quenching or enhancement, depending on the probe's design. Recent developments have shown that CDs can be functionalized with chelating agents that specifically bind to copper ions, leading to significant changes in fluorescence. This selectivity and sensitivity make CDs an attractive alternative for metal ion detection. The application of CDs in cellular imaging has expanded due to their biocompatibility and ability to provide high-resolution images. CDs can be used to label cellular components, track intracellular processes and visualize metal ion distributions. Their low toxicity and ease of functionalization make them suitable for live cell imaging. Studies have demonstrated the successful use of CDs for imaging metal ions, including copper, within cells. These applications provide valuable insights into metal ion homeostasis and the role of copper in various biological processes. Despite their advantages, challenges remain in the development of CDs for sensing and imaging. Issues such as potential toxicity, limited selectivity and the need for precise control over synthesis and functionalization are areas of ongoing research. Future directions involve improving the performance of CDs, exploring new applications and ensuring their safety for biomedical use [3-6].

Discussion

The hydrothermal synthesis of the CDs in this study produced particles with high quantum yield and stability. The optimization of synthesis parameters, such as temperature, pressure and precursor concentration, was crucial for enhancing the fluorescence properties and achieving uniform particle size. Functionalization with specific ligands improved the selectivity of the CDs towards copper ions. The CDs demonstrated excellent selectivity for copper ions, as evidenced by fluorescence quenching experiments. The chelating groups on the CDs formed stable complexes with copper, leading to significant changes in fluorescence. The sensitivity of the CDs was validated through a series of assays, showing a low detection limit suitable for practical applications. The application of the CDs for cellular imaging revealed their ability to effectively label and visualize copper ions within

live cells. The CDs were internalized by cells without significant cytotoxicity, and fluorescence microscopy provided clear images of copper distribution. This capability is valuable for studying copper-related biological processes and diseases. Compared to traditional methods, the CDs offer several advantages, including simplicity, rapid response and real-time results. Their biocompatibility and ease of functionalization also make them suitable for *in vivo* applications. The ability to tune the optical properties of CDs further enhances their utility in various sensing and imaging contexts. Future research should focus on addressing existing challenges, such as potential toxicity and limited selectivity. Expanding the range of detectable ions and exploring new functionalization strategies will broaden the applicability of CDs. Additionally, integrating CDs with other technologies and developing new applications will further enhance their utility in scientific and practical contexts.

Conclusion

The development of fluorescent carbon dots for the selective and sensitive detection of copper ions represents a significant advancement in sensing and imaging technologies. The synthesized CDs exhibited high fluorescence quantum yields, stability and excellent selectivity towards copper ions, making them valuable tools for both environmental monitoring and biomedical research. Their application in cellular imaging demonstrated their potential for studying copper's role in biological systems and understanding copper-related diseases. Ongoing research will continue to refine these materials, address challenges and explore new applications, further enhancing their utility in various fields. The continued development of fluorescent carbon dots holds promise for advancing both scientific understanding and practical applications in sensing and imaging technologies.

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