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Preparation of Carbon Quantum Dot Composite Powder and Its Application in Latent Fingerprint Development

Zhouzhou Luo[1,2], Shuang Wang[2], Boheng Song[1], Guangliang Qin[1], Zhuo Wang[1], Baohua Tang[1,*]
[1]China People's Police University, Langfang, China
[2]Tianmen Public Security Bureau, Tianmen, China
**Corresponding Author*

Abstract: Carbon dots (CDs) have unique interfacial modification properties and photophysical performance, offering a new approach for studying latent fingerprint development mechanisms. This paper details the preparation of nitrogen-doped blue carbon quantum dots (N-CQDs) from glucose. N-CQDs were loaded onto three typical porous matrices: lamellar silicate (Na-MMT), microporous zeolite (PMT), and fibrous silicate (APT), to form eco - friendly composite systems with stable photoluminescence for fingerprint development. The study also investigated the effectiveness of these systems on long - standing fingerprints. This work provides new technical routes for fingerprint development and extraction on various substrates, holding practical significance for enhancing the standardization of forensic evidence examination.

Keywords: Latent Fingerprint Development Technology; Carbon Quantum Dots

1. Introduction

Fingerprints are among the most commonly encountered trace evidence and one of the most widely used means of individual identification. In the fields of criminal investigation and forensic identification, latent fingerprints, as vital biological evidence for identity determination, play a crucial role in the recognition, comparison, and subsequent judicial examination of crime scene evidence[1]. Given that latent fingerprints are often invisible, the effective extraction and visualization of these prints have long been key topics of research in forensic science. Traditional fingerprint visualization methods, such as powdering, fumigation techniques (e.g., iodine fumigation, 502 glue fumigation), and chemical staining methods (e.g., ninhydrin, DFO), though extensively applied, still face challenges, including low contrast, significant background interference, the use of toxic reagents, and insufficient long-term stability. Therefore, the development of novel, efficient, environmentally friendly fingerprint visualization materials that are suitable for complex substrates is of significant practical importance[2].

In recent years, the rapid development of nanomaterials has provided new technological routes for the development of latent fingerprints[3]. Among these, carbon dots (CDs) have garnered significant attention due to their low toxicity, tunable luminescence, low cost, excellent biocompatibility, and good photostability. These advantages make CDs a prominent focus of current fingerprint visualization research. Compared to traditional fluorescent materials, CDs offer superior photostability, excitation-wavelength-dependent emission characteristics, and a rich array of surface functional groups, enabling them to selectively interact with fingerprint residues (such as amino acids, lipids, proteins, etc.) through physical adsorption or chemical bonding. This selectivity enhances the contrast and resolution of fingerprint visualization. Moreover, the raw materials for synthesizing CDs are widely available (e.g., glucose, citric acid), the preparation process is simple, and the cost is low, aligning with the growing emphasis on green chemistry[3].

However, pure CDs still face challenges in fingerprint development applications, such as aggregation, fluorescence quenching, and weak adhesion to substrates, which limit their practical effectiveness. To address these issues, researchers have sought to load CDs onto porous or lamellar materials (such as silicates, zeolites, polymers, etc.) to create composite systems that enhance their stability and fingerprint adhesion capabilities. Among these, silicate-based materials (e.g., montmorillonite, zeolite, fibrous

silicates) are considered ideal carriers for CDs due to their high surface area, tunable pore structure, and excellent mechanical properties. By optimizing the preparation methods of these composite systems, the dispersion, fluorescence intensity, and interaction between CDs and fingerprint residues can be further improved, achieving high-contrast, high-sensitivity development of latent fingerprints[4].

In this study, nitrogen-doped blue light carbon quantum dots (N-CQDs) were synthesized using glucose as a precursor, and then loaded onto a lamellar silicate matrix (Na-MMT) to create an eco-friendly composite system with stable photoluminescent properties for fingerprint visualization. The fingerprint development performance of this system was thoroughly investigated. This method is simple to operate, cost-effective, and shows promising potential for practical applications, providing a novel and efficient technique for fingerprint visualization in criminal investigations. Moreover, the green and environmentally friendly material design concept proposed in this study also offers valuable insights for the advancement of other forensic examination technologies[5].

2. Experimental Reagents and Instruments

The experimental materials and equipment are listed in Tables 1 and 2.

Table 1. Experimental Reagents

Reagent Name	Specification	Manufacturer
Glucose	Analytical Pure (AR), 500g	Sinopharm Chemical Reagent Co., Ltd.
Urea	Analytical Pure (AR), 500g	Sinopharm Chemical Reagent Co., Ltd.
Ethanol	Analytical Pure (AR), 500mL	Tianjin Tianli Chemical Reagent Co., Ltd.
Ultrapure Water	≥18 MΩ·cm	

Table 2. Experimental Instruments

Instrument Name	Model Specification	Manufacturer
Scanning Electron Microscope (SEM)	SSX-550	Shimadzu (China) Co., Ltd.
Transmission Electron Microscope (TEM)	JEM-2100HR	JEOL Ltd., Japan
UV-Visible Spectrophotometer (UV-Vis)	UV-1900i	Shimadzu (China) Co., Ltd.
Fluorescence Spectrometer	RF-5301PC	Shimadzu (China) Co., Ltd.
Fourier Transform Infrared Spectrometer (FT-IR)	Spectrum One	PerkinElmer
X-ray Photoelectron Spectrometer (XPS)	ESCALAB250Xi	OPTON Group Co., Ltd.

3. Experimental Methods

3.1 Preparation of N-CQDs Solution

Glucose (2g) and urea (1g) were used as precursors and dissolved in 10mL of deionized water to form a uniform mixed solution. This solution was then transferred to a 50mL PTFE (polytetrafluoroethylene) autoclave for hydrothermal reaction. After the reaction system naturally cooled to room temperature, the resulting solution was transferred to a centrifuge tube and centrifuged at 14,000 rpm for 20 minutes at 25°C. The supernatant was subsequently purified through sequential filtration using a 0.22μm micropore filter and dialysis with a 500-1000Da molecular weight cutoff dialysis bag for 24 hours. The final product, a high-purity N-CQDs aqueous solution, was sealed and stored at 4°C in a light-protected environment for future use[6].

3.2 Preparation of N-CQDs@MMT Composite Material

To 3.5 mL of N-CQDs solution, 0.5g of MMT clay was added and stirred for 1 hour using a magnetic stirrer to form a MMT paste. The mixture was allowed to stand for 3 hours to remove any incompletely fused upper-layer turbid liquid. The material was then vacuum dried at 60°C for 5 hours to obtain the N-CQDs@MMT composite material[7].

3.3 Preparation and Visualization of Latent Fingerprints

The subject's hands were thoroughly washed with soap and dried using a blow dryer. Fingerprints were then imprinted on various objects with consistent pressure. Fingerprints were developed using the powder method, and images of the fingerprints were captured using a Canon digital camera either under sunlight or under UV light at 365 nm.

4. Results and Discussion

4.1 Characterization of N-CQDs@MMT Composite Material

In this study, a lamellar silicate matrix was employed as a support, wherein the electrostatic interaction between the positively charged surface of the silicate matrix and the negatively charged carbon quantum dots (CQDs) allowed for the immobilization of CQDs on the surface of the silicate matrix, thereby constructing the N-CQDs@MMT composite material. The magnetic field facilitated the complete mixing of the carbon dots and the silicate matrix in a short time, enhancing the electrostatic interaction between the two materials. The UV-Vis absorption spectra of the N-CQDs aqueous dispersion and its N-CQDs@MMT composite material are shown in Figure 1. The N-CQDs@MMT water dispersion exhibits good UV-visible absorption properties. The N-CQDs exhibit two main absorption peaks at 225 nm and 293 nm; the 225 nm peak arises from the π-π* transition of the C=C double bond on the aromatic ring, while the 293 nm peak is formed via n-π* transitions (C=O, C-S, C-N). At 600 nm, functional groups on the carbon dots lead to lower energy transitions, resulting in long-wavelength absorption. The results indicate that after the N-CQDs are combined with the lamellar silicate matrix, a red shift in the absorption spectrum occurs due to a decrease in the electron spacing[8].

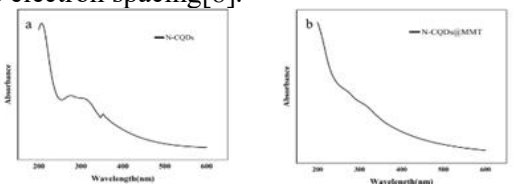

Figure 1. (a) UV Absorption Spectrum of N-CQDs; (b) UV Absorption Spectrum of N-CQDs@MMT

The fluorescence emission spectra of N-CQDs and N-CQDs@MMT at different excitation wavelengths are shown in Figure 2 (a) and (b). Both exhibit emission peaks in the 310-380 nm range, with peak emission at approximately 310-330 nm. The maximum excitation wavelength of N-CQDs@MMT is 330 nm. Both samples have similar emission spectra and peak positions. Under ultraviolet light, N-CQDs appear brownish-yellow, while the N-CQDs@MMT sample emits bright blue fluorescence. When N-CQDs interact electrostatically with the silicate matrix, the matrix selectively adsorbs carbon quantum dots with specific sizes and surface defects, resulting in a more uniform distribution of carbon dots compared to those in the aqueous phase. To confirm the functional groups present, FTIR characterization of N-CQDs, MMT, and N-CQDs@MMT was performed. Compared to the pure silicate matrix, N-CQDs@MMT shows more distinct infrared features and absorption peaks. The absorption peak at 1,533 cm-1 is a characteristic C=N bond, accompanied by O-H/N-H stretching, indicating the presence of carboxyl and hydroxyl groups, which can interact with metal ions in the lamellar silicate matrix. MMT exhibits N—H bending and O—H stretching at 3,345 cm-1 and 3,442 cm-1, respectively. Due to the high content of hydroxyl groups in the silicate matrix (shown in Figure 3), hydrogen bonds can form between the carboxyl-hydroxy radicals of the silicate matrix and its hydroxyl groups. From the comparison of the FTIR spectra of N-CQDs@MMT, it is evident that the spectra of the carbon dots before and after loading remain largely unchanged, primarily because only a small amount of N-CQDs are present during the loading process, and their characteristic peaks are obscured by the characteristic peaks of MMT. The N-CQDs@MMT sample shows four absorption peaks at 2,920 cm-1, corresponding to the hydrogen-bonded stretching vibrations between aromatic carbon molecules, thus enhancing the stability of the N-CQDs.

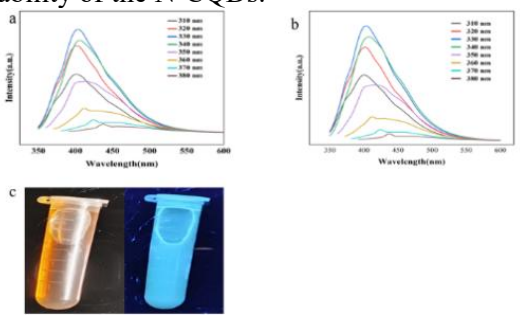

Figure 2. (a) Fluorescence Spectrum of N-CQDs; (b) Fluorescence Spectrum of N-CQDs@MMT; (c) Optical Images of N-CQDs Solution under Sunlight and 365nm UV Light

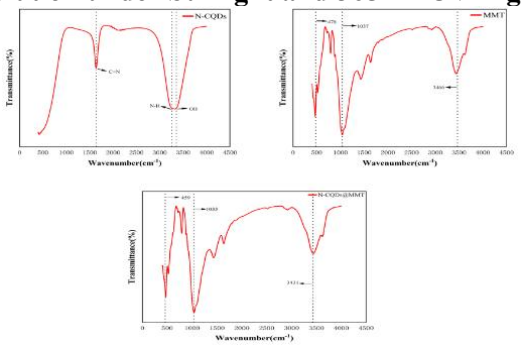

Figure 3. (a) N-CQDs; (b) MMT; (c) FTIR Characterization of N-CQDs@MMT

To elucidate the binding mechanism between the

carbon dots and the lamellar silicate matrix and evaluate their stability, the zeta potential of N-CQDs and N-CQDs@MMT composite material was measured. The zeta potentials of N-CQDs, MMT, and N-CQDs@MMT were 7.8 mV, -31.7 mV, and -2.51 mV, respectively, as shown in Figure 4 (b). The results indicate that the positively charged N-CQDs can be separated from the solution and immobilized on the MMT surface through electrostatic interaction with the negatively charged MMT. The change in zeta potential after loading further confirms this. Additionally, the small-sized carbon dots can penetrate the interlayer gaps of the lamellar silicate matrix, where ion exchange occurs with the sodium ions modifying the interlayers, thus immobilizing the carbon dots between the layers. In practical applications, using small particle suspensions to reveal fingerprints may irreversibly damage permeable objects. Therefore, the solid-state N-CQDs@MMT composite material is more stable and easier to store and use[9].

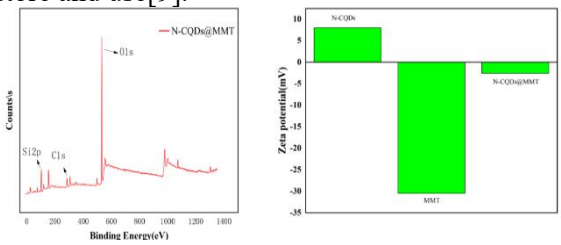

Figure 4. (a) X-ray Photoelectron Spectroscopy of N-CQDs@MMT; (b) Zeta Potential Spectrum

The morphology and structure of N-CQDs and N-CQDs@MMT composite material were investigated using scanning electron microscopy (SEM). As shown in Figure 5, (c) displays the traditional and high-resolution transmission electron microscopy images of N-type quantum dots. The results reveal that the size of the carbon quantum dots is approximately 8 nm, and high-resolution transmission electron microscopy shows that their crystal structure has a lattice spacing of 0.43 nm. During the synthesis of N-CQDs@MMT, the intrinsic crystallinity of the lamellar silicate matrix was not damaged, and no characteristic XRD peaks corresponding to N-CQDs were observed in the N-CQDs@MMT. This is primarily because the larger-sized N-CQDs were masked by the stronger diffraction peaks of MMT. The results indicate that the microscopic morphology of the lamellar silicate matrix provides sufficient space for the immobilization of N-CQDs. However, after incorporating N-CQDs, their particle size, which is significantly smaller than that of the micron-sized lamellar silicate matrix, prevents effective immobilization of the N-CQDs[10].

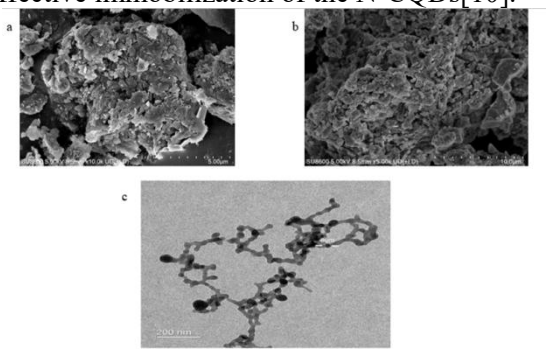

Figure 5. (a) Scanning Electron Microscope Image of MMT; (b) Scanning Electron Microscope Image of N-CQDs@MMT; (c) Transmission Electron Microscope Image of N-CQDs

4.2 Application of N-CQDs@MMT Composite Material in Revealing Latent Fingerprints

N-CQDs@MMT was used as a latent fingerprint developer to simulate a crime scene. Clear and vivid fingerprints were revealed on various surfaces, including metal, packaging boxes, glass bottles, and plastic objects in the trunk. Using the powder method, the samples showed a clear, distinct, and high-brightness green fingerprint pattern under 365 nm wavelength UV light. The fingerprint effect after development is shown in Figure 6. Despite the differences in the underlying materials, the N-CQDs@MMT composite material consistently revealed complete fingerprints with excellent background contrast.

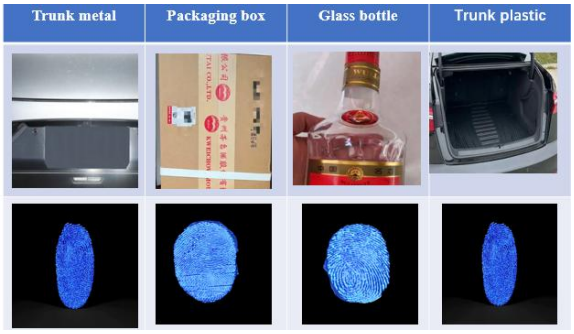

Figure 6. Latent Fingerprint Images on Different Object Surfaces Revealed by N-CQDs@MMT (365 nm, UV)

4.3 Evaluation of Latent Fingerprint Revealing Effect of N-CQDs@MMT Composite Material

The Image J analysis method was employed to measure the grayscale gradient (G) within the yellow line range from top to bottom, in order to determine the selectivity of N-CQDs@MMT for latent fingerprints. By averaging the grayscale variation for each sample, the grayscale differences (d) for each sample were obtained. A larger value of d indicates better selectivity of the material for latent fingerprints, meaning that a greater number of ridges from the fingerprint adhere to the surface, while fewer ridge lines are attached to the surface of smaller grooves, as represented by the object. The latent fingerprints revealed on the metal suitcase using the N-CQDs@MMT composite exhibited high grayscale values of 241.15 and 196.52, demonstrating the material's high recognition ability for latent fingerprints on metal objects (see Figure 7).

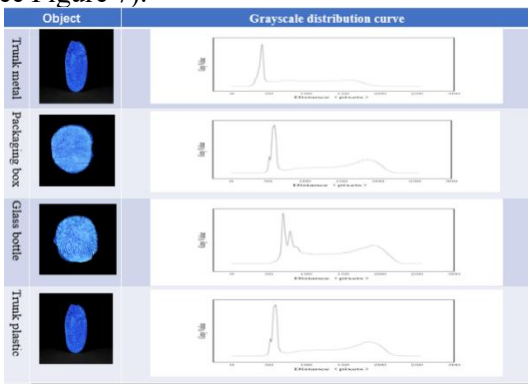

Figure 7. Grayscale Distribution Map of Four Object Surfaces with Latent Fingerprints Revealed by N-CQDs@MMT

5. Conclusion

In this study, the N-CQDs were synthesized using glucose as a precursor, and N-CQDs were loaded onto a lamellar silicate matrix (Na-MMT) to create an environmentally friendly composite system with stable photoluminescent properties for fingerprint detection. The fingerprint revealing effect was systematically studied. This approach provides a novel technical route for fingerprint extraction from various object surfaces, and has practical significance in enhancing the standardization of forensic evidence examination. This research not only offers an innovative solution for latent fingerprint detection but also paves the way for the application of nanomaterials in forensic science. Future studies could further investigate the stability of this composite material in extreme environments (e.g., high temperature, high humidity) and explore its synergistic application with emerging detection technologies such as artificial intelligence-based image recognition. The promotion and application of this technology will contribute to enhancing the efficiency of forensic evidence extraction at crime scenes, providing more reliable technical support for combating crime and ensuring judicial fairness, thus playing a crucial role in advancing the modernization of criminal science and technology in our country.

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