RESEARCH PAPER

BIOIMAGING POTENTIAL OF NICKEL-DOPED CARBON QUANTUM DOTS

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ABSTRACT

Carbon quantum dots (CQDs) have emerged as a promising class of nanomaterials due to their exceptional optical properties, biocompatibility, and potential applications in bioimaging and therapeutic interventions. In this study, CQDs were synthesized via hydrothermal process. The synthesized CQDs were characterized using UV-visible spectroscopy, Transmission electron microscopy (TEM), Fourier-transform infrared spectroscopy (FTIR). Bioimaging potential of the CQDs was assessed in lung cancer cells. The results indicated that the CQDs exhibited excellent fluorescence properties for bio-imaging suggesting their potential for theranostic applications.

Keywords: Carbon quantum dots, bioimaging, nickel-doped CQDs, theranostics.

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1.INTRODUCTION

Carbon quantum dots (CQDs) have emerged as a novel class of nanomaterials with exceptional physicochemical properties, including fluorescence, high water solubility, and biocompatibility, making them ideal candidates for various biomedical applications, such as bioimaging, drug delivery, and antimicrobial therapies [1]. CQDs synthesized from different precursors exhibit unique functional characteristics depending on their composition and surface modifications.

Doping with heteroatoms and transition metals has gained significant attention in enhancing the optical and biological properties of CQDs. CQDs, first reported by Sun et al., (2006) are characterized by their small size (<10 nm), high fluorescence quantum yield and low cytotoxicity. The quantum confinement and edge effects contribute to their superior photoluminescent properties, making them suitable for bioimaging and optoelectronic applications [2]. Furthermore, the high surface area and functional groups of CQDs allow for effective interaction with biological molecules, enhancing their antimicrobial potential.

Among the diverse synthesis routes ,the bottom-up synthesis approach enables the controlled fabrication of CQDs with specific structural and optical characteristics. Hydrothermal and microwave-assisted synthesis methods have been widely employed to achieve high-yield and cost-effective production of CQDs. Doping enhances the electronic properties, while metal incorporation influences the catalytic behavior and potential enzyme inhibition effects [3].

Fluorescence-based bioimaging has revolutionized biomedical diagnostics, enabling high-resolution visualization of biological structures. CQDs have gained prominence in bioimaging due to their excellent photostability, tunable emission spectra, and non-toxic nature. The surface functionalization of CQDs allows for targeted imaging of cellular components, improving contrast and resolution in fluorescence microscopy. Furthermore, doped CQDs exhibit enhanced near-

infrared (NIR) fluorescence, which is advantageous for deep tissue imaging [4].
The integration of nickel doping significantly influences the physicochemical properties of CQDs, making them suitable for biomedical applications. Further investigations into in vivo efficacy, toxicity, and large-scale production are essential to translate these findings into clinical settings.

2.MATERIALS AND METHODS

All chemicals used in this study were of analytical grade and utilized without further purification. The A549 (human lung cancer) cell line was obtained from the National Centre for Cell Sciences (NCCS), Pune, India, and maintained under standard cell culture conditions for experimental studies.

2.1 Synthesis of Carbon Quantum Dots (CQDs)

Carbon quantum dots (CQDs) were synthesized using hydrothermal method. The precursors were dissolved in deionized water under continuous stirring to obtain a homogeneous solution. The prepared solution was then transferred into a Teflon-lined stainless-steel autoclave and heated at 180 °C for 12 h. After completion of the reaction, the autoclave was allowed to cool to room temperature, and the resulting solution was filtered and further purified. Finally, the purified CQDs were used for further characterization and applications. [5].

2.2 Analytical Methods

2.2.1 UV–Visible Spectroscopy Analysis

The optical properties of the synthesized carbon quantum dots (CQDs) were analyzed using a double beam UV- 2400 PC series spectrophotometer. The CQDs were dispersed in deionized water to obtain a clear solution and sonicated to ensure uniform dispersion. The absorbance spectrum was recorded over a wavelength range of 200–800 nm using deionized water as a blank. The characteristic absorption peaks corresponding to π–π* transitions of C=C bonds and n–π* transitions of C=O bonds were identified and analyzed.

2.2.2 FT-IR

FTIR analysis was performed to identify the functional groups present in the sample. The spectra were recorded using an FTIR spectrophotometer (IR Affinity-1, SHIMADZU). The instrument was operated in the range of 400–4000 cm^{-1} with a resolution of 4 cm^{-1} in % transmittance mode. Peak assignments were made by comparing the observed wavenumbers with standard reference data.

2.2.3 High-Resolution Transmission Electron Microscopy (HRTEM) Analysis

The morphology and size distribution of the synthesized CQDs were examined using high-resolution transmission electron microscopy (HRTEM). A dilute solution of CQDs was prepared in deionized water and ultrasonicated for uniform dispersion. A drop of the sample was placed onto a carbon-coated copper grid and allowed to dry at room temperature.

2.2.4 Fluorescence Bioimaging Assay

The bioimaging potential of CQDs was assessed using lung cancer cell line (A549) cells. Cells were seeded in 24-well plates at a density of 1 × 10^4 cells/well and incubated at 37°C in a 5% CO_2 atmosphere for 24 hours. The cells were treated with CQDs (50 µg/mL) for 4 hours, washed with phosphate-buffered saline (PBS), and imaged using a fluorescence microscope (Nikon Eclipse Ti) [6].

3.RESULTS AND DISCUSSION

3.1 Optical Properties of CQDs

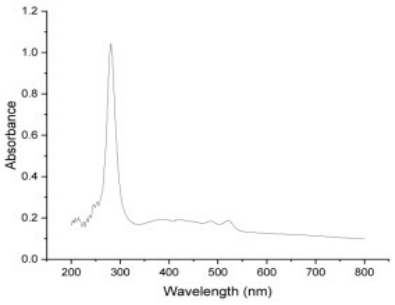


Figure-1. UV Spectrum of Carbon Quantum Dots

The absorption peak around 300 nm is likely due to n→π* transitions of the C=O or C=N groups present on the surface of the CQDs. These groups arise from the functionalization introduced during the synthesis process This peak can also be related to the quantum confinement effect of the CQDs, which influences their electronic structure and optical properties. 300 nm peak suggests the CQDs are relatively small and have distinct energy band gaps. Surface functional groups play a crucial role in determining the optical properties of CQDs. The 350 nm peak may also indicate the presence of electronic states associated with the surface passivation or functional groups. Peaks in the range of 320–400 nm are typical for CQDs and are attributed to various surface and core transitions[7].

3.2Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectra indicated the presence of hydroxyl, amino, and nitro functional groups [8]

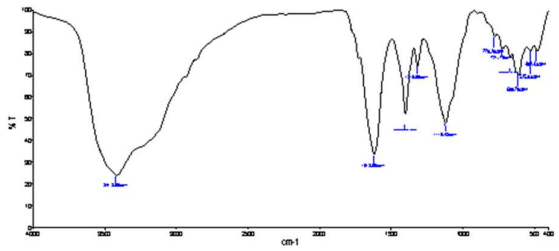


Figure-2. IR spectrum of carbon quantum dots

A broad absorption band observed in the range of 3200–3500 cm^{-1} corresponds to O–H and/or N–H stretching vibrations. The absorption band appearing in the region of 1600–1750 cm^{-1} is assigned to C=O stretching vibrations**.** This band indicates the presence of residual carboxyl or carbonyl groups derived from carboxylic acid precursors. Bands observed in the range of 1300–1600 cm^{-1} are attributed to C=S and/or C=N stretching vibrations introduced by thiourea.The peaks in the 1000–1300 cm^{-1} region correspond to C–O stretching vibrations of hydroxyl or ester linkages, weak absorption bands observed between 500 and 700 cm^{-1} are assigned to Ni–O or Ni–Cl vibrations. The FTIR results confirm that the synthesized CQDs contain abundant oxygen-containing functional groups (–OH, –COOH, C=O, C–O) along with graphitic carbon structures (C=C).

3.3 High-Resolution Transmission Electron Microscopy (HRTEM) Analysis

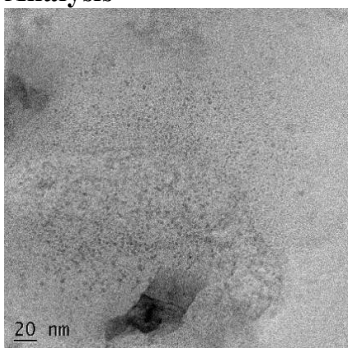


Figure-3. TEM images of carbon quantum dots

The morphology and structural characteristics of the synthesized CQDs were examined using high-resolution transmission electron microscopy (HRTEM).The HRTEM images reveal that the CQDs are predominantly spherical in shape with a uniform and well-dispersed distribution.At lower

magnification (20 nm scale), a large number of ultrafine nanoparticles are visible, indicating successful formation of quantum-sized carbon dots. The particle size is estimated to be in the range of ~2–8 nm, confirming their nanoscale dimensions.The HRTEM results confirm the successful synthesis of monodispersed, spherical, and crystalline CQDs with nanoscale size and graphitic structure. These features are highly favorable for optical properties, fluorescence behavior, and bioimaging applications.

3.4. Fluorescence Bioimaging Assay

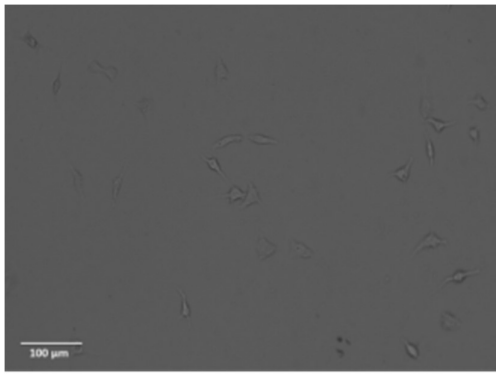
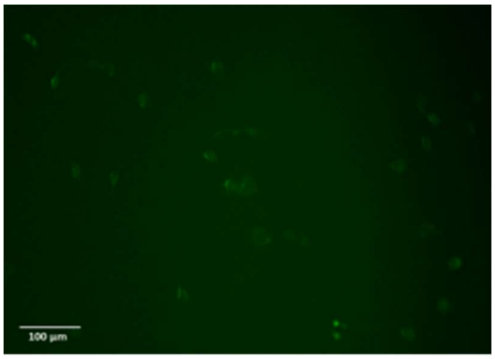


Figure.4 Bio imaging potential of CQDs

The bioimaging potential of CQDs was evaluated using A549 (Human Lung cancer cell line). Fluorescence property was observed in sample subjected to study. Fluorescence emission was observed with tested concentration. CQDs exhibited excellent cellular uptake and emitted strong green fluorescence under confocal laser scanning microscopy, highlighting their suitability as fluorescent probes for bioimaging. Cells were then subjected to fluorescence detection at 40X magnification using an inverted phase contrast fluorescence microscope (Labomed TCM 400, USA). The cells were observed under blue and green filters of the microscope. Green fluorescence was emitted by the sample while observed under the blue filter of the inverted phase contrast fluorescence microscope. From the above it is understood that CQDs exhibited excellent biocompatibility and cellular uptake in the lung cancer cell lines[10]. It has high potential in differentiating cancer cells from normal cells. The fluorescence microscopy images showed strong green fluorescence, indicating the potential of CQDs as fluorescent probes for cellular imaging.

4.Conclusion

Carbon quantum dots (CQDs) were successfully synthesized using hydrothermal method and characterized by UV–Visible, FTIR, and HRTEM analyses. The UV–Vis results confirmed characteristic absorption due to π–π* and n–π* transitions, while FTIR revealed the presence of oxygen-containing functional groups such as –OH, C=O, and C–O, indicating good surface functionality. HRTEM images showed spherical, well-dispersed nanoparticles with sizes in the range of ~2–8 nm. Fluorescence bioimaging studies in A549 cells demonstrated efficient cellular uptake and strong fluorescence emission. Overall, the synthesized CQDs exhibit excellent optical, structural, and biological properties, making them suitable for bioimaging and biomedical applications.



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