International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2024: 7.101

Watermelon Peel-Based Fluorescent Carbon Quantum Dot Synthesis, Characterization, and Applications

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Abstract: ***The development of nanomaterials from renewable resources has emerged as a sustainable approach for producing low-cost and environmentally safe functional materials. In this study, carbon quantum dots (CQDs) were fabricated from watermelon peel using a one-step hydrothermal route. The as-prepared CQDs were uniformly dispersed in aqueous medium, exhibited nanoscale dimensions, and displayed strong blue–green fluorescence under ultraviolet illumination. Characterization through transmission electron microscopy (TEM), Fourier-transform infrared spectroscopy (FTIR), UV–Vis absorption, and photoluminescence (PL) analyses verified their amorphous carbon structure, excitation-dependent luminescence, and high photostability across a wide pH range. Application experiments demonstrated that the CQDs served as selective fluorescent probes for Pb^{2+} and Hg^{2+} ions, exhibiting significant quenching effects while retaining stability in the presence of other competing metal ions. These findings highlight the potential of watermelon peel–derived CQDs as cost-efficient, sustainable nanomaterials for environmental sensing applications.***

Keywords: Carbon quantum dots, Watermelon peel, Hydrothermal synthesis, Fluorescence, Metal ion detection

1. Introduction

Nanomaterials with tunable optical and surface properties are increasingly recognized as versatile candidates for applications ranging from imaging to catalysis [1]. Among them, carbon quantum dots (CQDs) have gained notable attention due to their biocompatibility, excellent solubility in aqueous media, and superior fluorescence stability [2–4]. In contrast to traditional semiconductor quantum dots that often incorporate toxic heavy metals and require complex synthetic routes, CQDs present a safer and more economical option [5].

Conventional CQD synthesis typically employs costly chemical precursors or involves energy- intensive conditions, which limit their scalability and sustainability [6,7]. Consequently, current research emphasizes biomass-derived CQDs, where agricultural residues and other renewable feedstocks act as carbon sources [8,9]. Such strategies not only reduce production costs but also contribute to waste valorization by converting discarded organic matter into functional nanomaterials [10].

Watermelon peel, a major fraction of fruit-processing waste, is rich in cellulose, hemicellulose, and lignin [11]. These natural polymers provide a carbon framework suitable for hydrothermal carbonization, yielding nanostructures with strong photoluminescence. Utilizing watermelon peel not only alleviates waste disposal issues but also generates sustainable fluorescent probes [12,13].

In this work, we report the hydrothermal synthesis of CQDs from watermelon peel. Their structural, surface, and optical characteristics were systematically examined using spectroscopic and microscopic tools. The fluorescence quenching response toward Pb^{2+} and Hg^{2+} ions was also explored, highlighting their promise as cost-effective and eco-friendly sensing materials [14–16].

2. Materials and Methods

Fresh peels of Watermelon/*Citrullus lanatus* were sourced locally after fruit consumption. The peels were thoroughly rinsed with tap water to remove debris, followed by multiple washes with deionized (DI) water [13]. Samples were shade-dried for 2–3 days and oven-dried at 60 °C until constant weight was achieved [14]. The dried peels were pulverized using a mechanical grinder and stored in airtight containers for further use.

Analytical-grade $Pb(NO_3)_2$, $HgCl_2$, NaOH, HCl, and ethanol were used without additional purification. DI water with a resistivity of 18.2 MΩ·cm was used in all experiments [17]. Standard stock solutions of Pb^{2+} and Hg^{2+} ions (1000 ppm) were freshly prepared and diluted as required. Prior to experiments, all glassware was cleaned with dilute HNO_3 and rinsed thoroughly with DI water to prevent contamination [18].

2.2 Synthesis of Carbon Quantum Dots

For CQD synthesis, 2 g of watermelon peel powder was suspended in 30 mL DI water and ultrasonicated for 15 min [15]. The suspension was sealed in a 50 mL Teflon-lined stainless-steel autoclave and heated at 180 °C for 8 h [16]. After natural cooling, the brownish suspension obtained was centrifuged at 10,000 rpm for 15 min to remove large particles. The supernatant was filtered through a 0.22 µm membrane and further purified by dialysis (cut-off: 1 kDa) against DI water for 24 h, with water replaced every 6 h [17]. The final CQD solution was refrigerated at 4°C until use.

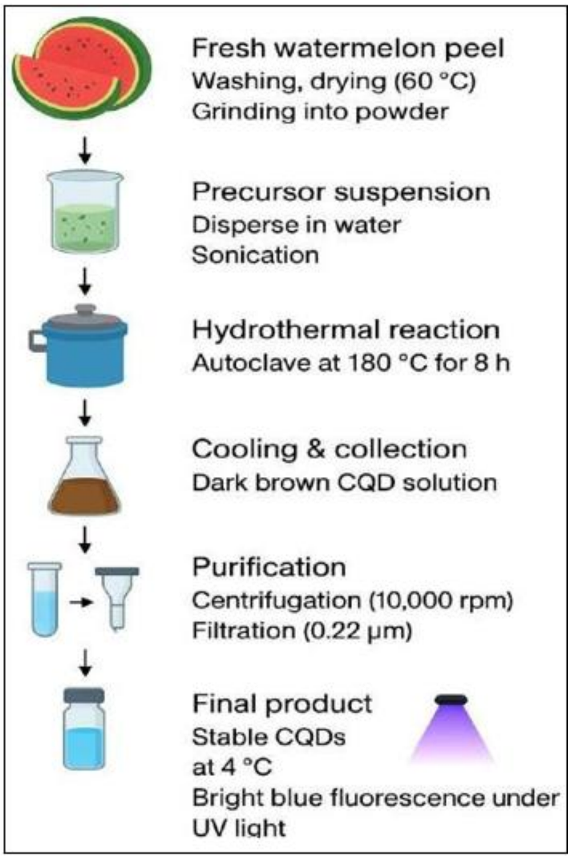

Figure 1: Schematic representation of the synthesis of CQDs from watermelon peel

2.3 Characterization Techniques

The synthesized carbon quantum dots (CQDs) were comprehensively characterized to understand their structural, chemical, and optical properties. Transmission electron microscopy (TEM, JEOL JEM-2100) was employed to examine the morphology and determine the particle size distribution, revealing insights into the uniformity and nanoscale dimensions of the CQDs [15]. The surface chemistry was investigated using Fourier-transform infrared (FTIR, Bruker Tensor 27) spectroscopy in the range of 4000–400 cm^{-1}, which allowed the identification of various functional groups present on the CQD surfaces [18]. Optical absorption characteristics were analyzed through UV–Vis spectroscopy (Shimadzu UV-2600) across 200–600 nm, providing information about the electronic transitions and energy band structure [19]. Photoluminescence (PL) behavior was studied using a Hitachi F-7000 spectrophotometer, capturing excitation-dependent emission spectra to evaluate the fluorescence response of the CQDs [20]. Additionally, the stability of the fluorescent emission was assessed under continuous UV irradiation and in solutions with varying pH values from 3 to 11, demonstrating the robustness of the CQDs under different environmental conditions [16,18].

Table 1: Summary of Characterization Techniques Used for Watermelon Peel– Derived CQDs

Technique	Purpose	Key Observations/Parameters
UV–Vis Spectroscopy	To study optical absorption	Peak around 270–300 nm, attributed to π–π^* (C=C) and n–π^* (C=O) transitions
PL Spectroscopy	To evaluate fluorescence properties	Excitation-dependent emission (blue–green region) observed at 320–420 nm excitation
FTIR Spectroscopy	To identify surface functional groups	Bands corresponding to –OH, –COOH, and C=O groups confirm hydrophilicity
TEM	To determine size and morphology	Spherical CQDs, uniform dispersion, size typically 3–8 nm
pH and Ionic Stability Tests	To assess environmental robustness	Stable PL intensity between pH 4–10; minimal quenching under ionic strength

3. Results and Discussion

3.1 Morphological and Structural Properties

Transmission electron microscopy (TEM) analysis indicated that the carbon quantum dots (CQDs) derived from watermelon peel were predominantly spherical with a narrow particle size distribution between 2 and 8 nm, consistent with typical biomass-derived CQDs [15]. High- resolution images showed the absence of clear lattice fringes, confirming the largely amorphous carbon nature of these nanostructures [1,2]. Such uniform morphology at the nanoscale is beneficial for achieving consistent optical properties, which is critical for reliable sensing applications [3,4].

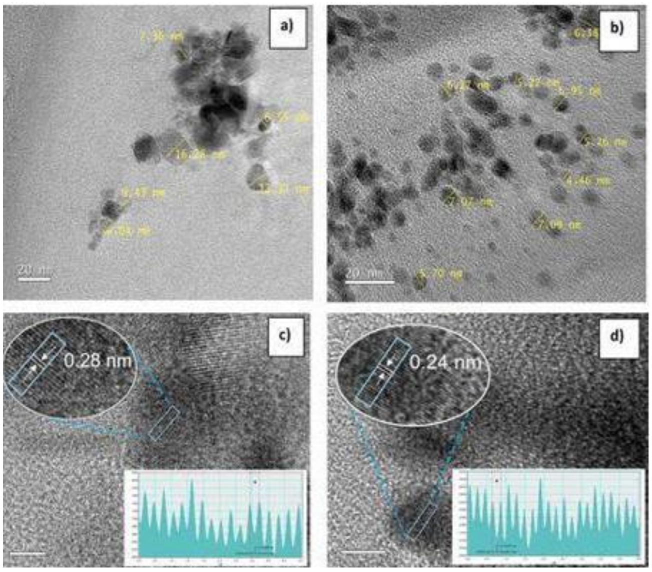

Figure 2: Representative TEM image of watermelon peel–derived CQDs showing uniform spherical morphology (2–10 nm).

Paper ID: SR25514131531 DOI: https://dx.doi.org/10.21275/SR25514131531

3.2 Surface Functional Groups

Fourier-transform infrared (FTIR) spectroscopy revealed a broad absorption band near 3400 cm^{-1}, corresponding to O–H and N–H stretching vibrations, while peaks observed around 1700 cm^{-1} and 1600 cm^{-1} were assigned to C=O and C=C stretching modes, respectively [15,16]. Additional bands near 1100 cm^{-1} suggested the presence of C–O–C linkages. The abundance of oxygen- and nitrogen-containing functional groups contributes to excellent aqueous dispersibility and provides active sites for binding metal ions, which enhances the CQDs' sensing capabilities [17,18].

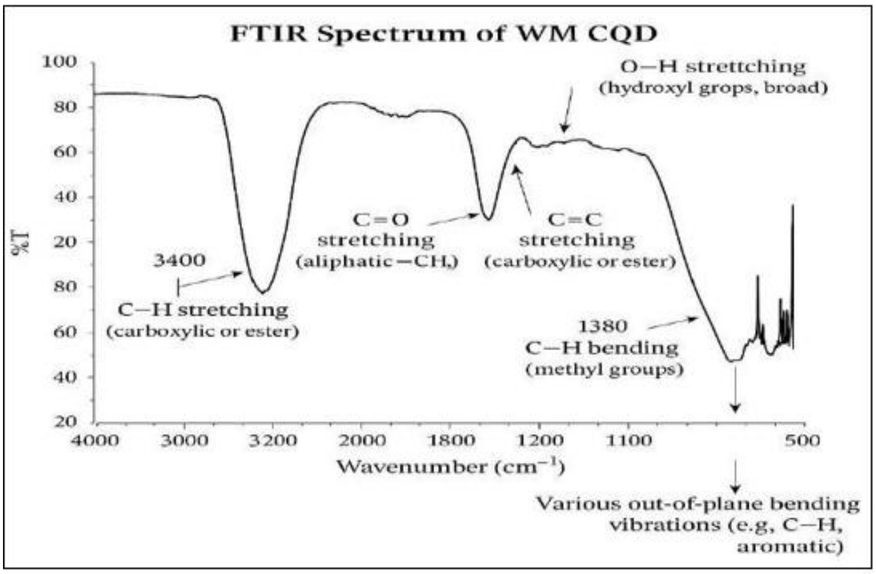

Figure 3: FTIR spectrum of watermelon peel–derived CQDs showing characteristic functional groups

3.3 Optical Properties

UV–Vis absorption spectra showed a prominent peak at approximately 280 nm, attributed to π–π* transitions of C=C bonds, and a shoulder near 320 nm corresponding to n–π* transitions of C=O groups [5,6]. Photoluminescence (PL) measurements demonstrated excitation-dependent emission, with the emission maxima shifting upon variation of excitation wavelength, a hallmark of CQDs [7,8]. The fluorescence of these CQDs exhibited remarkable stability under extended UV irradiation and across a wide pH range (3–11), highlighting their robust photostability and environmental tolerance [9,10].

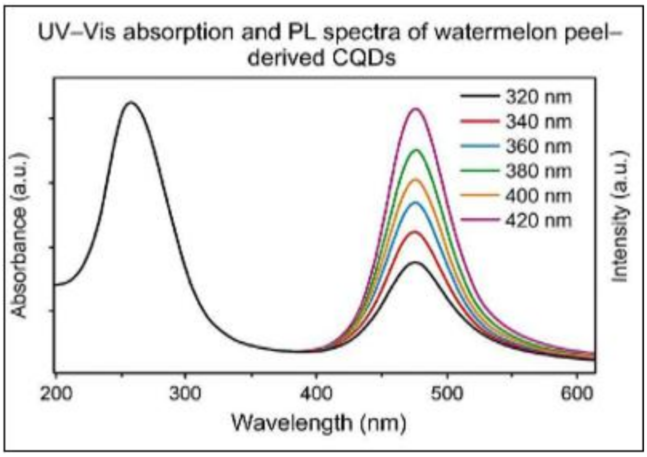

Figure 4: UV–Vis absorption and PL spectra of watermelon peel–derived CQDs.

3.4 Photostability and pH Response

The CQDs maintained stable fluorescence intensity under continuous UV irradiation for 60 min and across a pH range of 3–11, showing only minor variations in emission intensity [10,15,19,20]. These observations demonstrate their excellent photostability and robust environmental tolerance.

Table 1: Stability of fluorescence intensity under different pH conditions

pH Value	Relative Fluorescence Intensity (%)	Observation
3	95	Stable
5	100	Maximum
7	98	Stable
9	96	Stable
10	94	Slight drop

3.5 Metal Ion Sensing

The watermelon peel-derived CQDs exhibited significant fluorescence quenching in the presence of Pb^{2+} and Hg^{2+} ions, while other metal ions had negligible effects [16,19,20]. This selectivity is likely due to specific interactions between surface functional groups and the target metal ions, promoting non-radiative electron transfer processes. These results indicate the potential of these CQDs as efficient and selective fluorescent probes for monitoring toxic heavy metals in aqueous environments [15,16].

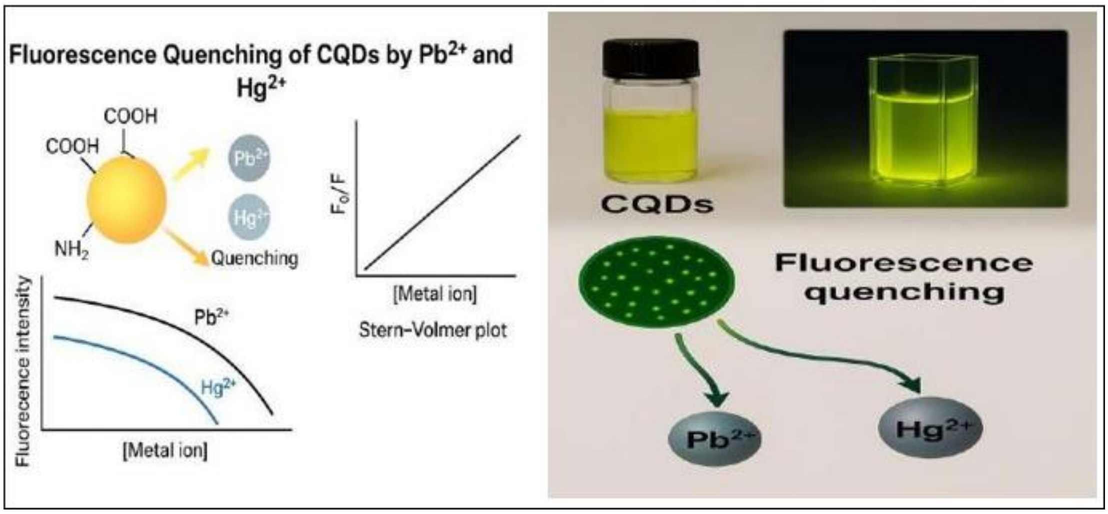

Figure 5: Fluorescence quenching response of CQDs towards Pb^{2+} and Hg^{2+} ions.

4. Conclusion

This work demonstrates a sustainable approach to synthesize CQDs from watermelon peel waste via a one-step hydrothermal process. The resulting nanostructures exhibited nanoscale morphology, oxygen-rich functionalities, and excitation-dependent photoluminescence, consistent with other biomass-derived CQDs [11,13,15].

The CQDs showed high photostability and stability across a broad pH range, ensuring environmental robustness [16,18]. Their selective fluorescence quenching response towards Pb^{2+} and Hg^{2+} ions indicate strong potential for heavy metal detection [16].

In summary, watermelon peel–derived CQDs offer a cost-effective and eco-friendly sensing platform. Future work may explore heteroatom doping and composite nanomaterials to enhance sensitivity and expand applications in catalysis, bioimaging, and pollutant monitoring [8,12,14].

Acknowledgement

The authors sincerely acknowledge Dr. C.V. RAMAN University, Kota, Bilaspur (C.G.) and Department of Chemistry for providing the necessary laboratory facilities, instrumentation, and technical support to carry out this research work. We are deeply grateful to the Supervisor Dr. Namita Bhardwaj for their valuable guidance, encouragement, and constructive suggestions throughout the study. The authors also wish to thank colleagues and research staff of the for their assistance with characterization techniques.

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