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Microwave-Assisted Green Synthesis of Carbon Dots Derived from Melon Peel Waste as an Eco-Friendly Fluorescent Sensor for Fe^{3+} Contamination

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Abstract

This research successfully demonstrates the valorization of melon peel waste into fluorescent carbon dots (CDs) using a straightforward microwave-assisted synthesis method. The synthesized CDs were comprehensively characterized, revealing optimal optical properties for sensing applications. Ultraviolet-visible spectroscopy revealed characteristic absorption peaks at 260 nm and 305 nm, corresponding to the carbon core and surface functional groups, respectively. Furthermore, photoluminescence spectroscopy under 245 nm excitation showed a strong blue emission peak at 453 nm. The practical utility of these nanoparticles was confirmed through their application as a fluorescent sensor for Fe^{3+} ions. The interaction resulted in significant fluorescence quenching and a distinct blue shift of the emission peak to 448 nm, indicating high sensitivity and a strong quenching response, leading to a ~67% decrease in emission intensity. These findings confirm that melon peel-derived CDs are a promising, eco-friendly material for developing effective probes for detecting heavy metals in environmental monitoring.

Introduction

Indonesia is currently confronting a dual environmental crisis: the escalating accumulation of organic solid waste and the pervasive pollution of aquatic ecosystems by industrial effluents. A significant contributor to water contamination is the textile industry, which utilizes iron(III) chloride ($FeCl_3$) as a coagulant, leading to the discharge of residual ferric ions (Fe^{3+}) into water bodies. While iron is an essential nutrient, excessive Fe^{3+} in the environment can catalyze the formation of reactive oxygen species (ROS), inducing oxidative stress in aquatic life and disrupting ecological balance. Although established detection methods like Atomic Absorption Spectroscopy (AAS) are reliable, they are often hindered by high operational costs, lengthy analysis times, and the need for sophisticated infrastructure. Therefore, there is a pressing demand for novel sensing platforms that integrate high sensitivity and selectivity with cost-effectiveness, rapid analysis, and environmental compatibility [1] [2] [3].

To address these limitations, carbon dots (CDs) have emerged as a promising next-generation nanomaterial. Defined as quasi-spherical carbon nanoparticles (1–10 nm), CDs are distinguished by their high aqueous dispersibility, excellent biocompatibility, and tuneable fluorescence. A key advantage lies in their synthetic versatility, as they can be produced via environmentally benign routes using abundant, renewable biomass as a carbon precursor [4] [5][4], [5]. Recent studies have successfully synthesized CDs from various waste materials, such as bitter melon peel [1] , orange peel [6] [7] [8], and cassava pulp[9], often employing microwave-assisted methods for their simplicity and speed [10] [11], [12] [12]. These green-synthesized CDs have been widely deployed as fluorescent sensors for heavy metal ions, capitalizing on their notable selectivity and sensitivity. The efficacy of CDs in this role is primarily governed by their fluorescence quantum yield (QY) and their limit of detection (LOD); a low LOD and strong fluorescence allow for more efficient interaction with target metal ions, enhancing the overall sensitivity of the sensing platform [13][14], [15].

Melon (*Cucumis melo* L.) is a widely cultivated fruit in Indonesia, generating substantial organic rind waste that remains largely underutilized. Although CDs have been successfully derived from various fruit precursors [16] [15], [17], including melon fruit via acid oxidation [18] and melon rind via hydrothermal methods [19] [20], [21], the specific use of melon rind as a precursor for microwave-assisted synthesis remains unexplored. Furthermore, prior studies using melon rind have not extended to the application of the resulting CDs, particularly for metal-ion sensing. This gap presents an opportunity to develop a rapid, efficient, and green synthesis route for functional CDs.

This study aims to bridge this gap by introducing a novel, rapid microwave-assisted method to synthesize fluorescent CDs from melon rind (*Cucumis melo*) waste. We will investigate their performance as a fluorescent probe for the selective detection of Fe^{3+} ions, a critical contaminant in industrial wastewater. The novelty of this work lies in combining an unreported precursor-waste matrix with a rapid microwave synthesis technique for a targeted sensing application. Our research objectives are threefold: (1) to synthesize and characterize carbon dots from melon rind waste, (2) to evaluate their analytical performance as a fluorescent probe for Fe^{3+} detection, and (3) to elucidate the underlying fluorescence quenching mechanism through systematic spectroscopic analysis.

Experimental Method

All reagents were of analytical grade and were used as received without further purification. Deionized water was used throughout as the solvent. Carbon dots (CDs) were synthesized from cantaloupe (Cucumis melo var. reticulatus) peel waste using a microwave-assisted method. Briefly, 4 g (wet weight) of washed melon peel was mixed with 80 mL of deionized water, blended for 2 min, and filtered through a Muranee coffee filter to obtain a clear extract. An aliquot of 20 mL of the extract was transferred to a 100 mL beaker and microwave-heated (Panasonic NN-GT35HMTE, 1000 W) for 8 min under open conditions on a rotating turntable, producing a dark, dry residue on the beaker walls and bottom. The residue was re-dispersed in 40 mL of deionized water and filtered again through a Muranee coffee filter to remove large particulates (no centrifugation was applied), yielding the final CD dispersion. The formation of CDs was initially confirmed by the observation of bright blue–green photoluminescence under a 365 nm UV lamp.

For the sensing experiment, a 10^{-1} M Fe^{3+} stock solution was prepared by dissolving 1.62 g of anhydrous $FeCl_3$ (99% purity) in 100 mL of deionized water using a magnetic stirrer (520 rpm, 60°C, 21 minutes). This stock was serially diluted: 5 mL of the 10^{-1} M solution was added to 495 mL of deionized water to obtain a concentration of 10^{-3} M; then 5 mL of the 10^{-3} M solution was added to 495 mL of deionized water to obtain a concentration of 10^{-5} M; and finally, 50 mL of the 10^{-5} M solution was added to 450 mL of deionized water to obtain a concentration of 10^{-6} M. Each dilution step was carried out with magnetic stirring (520 rpm, 60°C, 21 minutes). To evaluate sensing performance, 30 mL of the CD solution was mixed with 9 mL of the 10^{-6} M Fe^{3+} solution, and the mixture was stirred at room temperature. The pH of the solution was not controlled during the sensing process.

Optical characterization was performed using an A-TEEM™ spectrometer (Aqualog®, HORIBA Scientific). UV-Vis absorption spectra were recorded over a wavelength range of 240–800 nm to identify the maximum absorption wavelength, and photoluminescence (PL) spectra were measured at an excitation wavelength of 245 nm to determine the excitation/emission maxima and fluorescence intensity. Data processing and visualization were carried out using OriginPro software. If any constraints were encountered during characterization, the sample was re-prepared following the same procedure and characterized as soon as possible after preparation to avoid contamination or sample degradation.

Result and Discussion

To optimize the synthesis conditions, variations in the precursor concentration were investigated. Specifically, 4 grams of melon rind waste was mixed with 60 mL (a 1:15 ratio), 80 mL (a 1:20 ratio), or 100 mL (a 1:25 ratio) of deionized water. The most intense and optimal photoluminescence under UV light was observed for the sample with a 1:25 ratio (4 g melon rind in 100 mL water). Consequently, this optimal ratio was selected for the subsequent synthesis of carbon dots, which were used in heavy-metal sensing experiments involving Fe^{3+} ions, followed by comprehensive characterization.

Based on the FTIR analysis of the melon rind waste sample, the successful formation of carbon dots (CDs) is confirmed through the identification of characteristic functional groups. The spectrum reveals a broad peak at 3296.74 cm^{-1}, corresponding to O-H stretching vibrations from hydroxyl groups in alcohols and phenols, commonly found in polysaccharides and phenolic compounds in fruit peels. A distinct peak at 2117.35 cm^{-1} is associated with C≡C triple bond stretching in alkynes, indicating the formation of carbon core structures typical of CDs. Furthermore, the peak at 1635.57 cm^{-1} can be attributed to C=C stretching vibrations in alkenes, characteristic of sp^2-hybridized carbon domains in the carbon core, while also potentially indicating H-O-H bending from adsorbed water. These results demonstrate that the microwave-assisted synthesis successfully converted melon rind waste into carbon dots with a carbon-rich core and surface functional groups. For future work, FTIR analysis will be conducted on CDs after interaction with Fe^{3+} ions to investigate the mechanism of metal-ion binding to these surface functional groups.

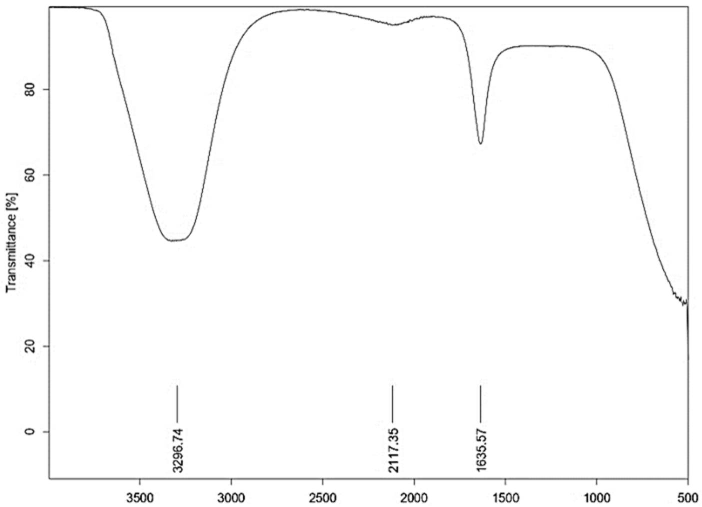

Figure 1. FTIR spectrum of carbon dots synthesized from melon rind waste

In this study, FTIR analysis was conducted on a pure melon rind sample to verify the carbon bonding indicative of carbon dot formation. For future research, we plan to perform FTIR analysis of the sample after adding Fe^{3+} ions to investigate their interaction with the carbon dot surface functional groups. The current study focuses on establishing the successful formation of carbon dots from the pure melon rind waste.

Ultraviolet-Visible (UV-Vis) absorption spectra were recorded for the carbon dot (CDs) solution over 240-800 nm. The analysis yielded a characteristic absorption profile featuring two prominent peaks at 260 nm and 305 nm. The peak at 260 nm is indicative of a π-π^* electronic transition, originating from the conjugated carbon-carbon (C=C) bonds that constitute the aromatic core of the nanoparticles. This signature absorption is a typical and well-documented feature in the electronic structure of carbon dots [22]. Furthermore, the spectrum revealed a second distinct peak at 305 nm. This signal is associated with an n-π^* electronic transition, providing direct spectroscopic evidence for the presence of oxygen-containing surface functional groups, specifically carbonyl (C=O) bonds, on the synthesized carbon dots [1]. These spectroscopic results provide conclusive verification of the successful synthesis of carbon nanostructures featuring a graphitic core and a functionalized surface. The observed absorption profile in the UV-Vis spectrum (Figure 1) aligns with findings reported in prior studies on biomass-derived carbon dots [2], [24]

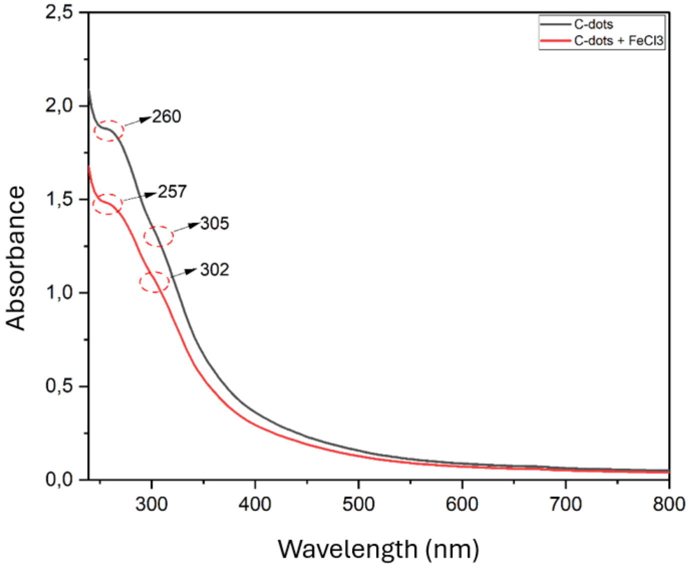

Figure 2 presents the ultraviolet-visible (UV-Vis) absorption spectrum of the carbon dots (CDs) synthesized from melon peel.

The UV-Vis absorption spectrum of the synthesized carbon dots (CDs) shown in Figure 2 exhibits characteristic features confirming their successful formation. The spectrum, recorded across the 240-800 nm range, reveals two definitive absorption signatures. A prominent, sharp peak at 260 nm (Abs ≈ 2.5) corresponds to the π-π* transition of aromatic C=C bonds, confirming the establishment of a sp^2-hybridized graphitic core. A secondary, weaker feature at 305 nm, appearing as a shoulder, is assigned to an n-π* transition, indicative of surface carbonyl (C=O) functional groups. The high intensity of the 260 nm peak suggests a substantial yield and/or strong light-absorbing capability, while the minimal absorption in the visible region (400-800 nm) denotes the sample's optical purity. Collectively, these spectral characteristics are consistent with the literature and confirm the successful synthesis of carbon nanostructures with a conjugated aromatic core decorated with oxygen-containing surface moieties.

Figure 3 displays the photoluminescence (PL) emission profiles of both the as-synthesized carbon dots (CDs) and the CDs after the addition of $FeCl_3$, excited at 245 nm. The pristine CDs exhibit a robust, symmetrical fluorescence peak at 453 nm, indicating strong blue photoluminescence. This emission is attributed to the radiative recombination of photo-generated excitons within the carbon nanostructure, thereby verifying the formation of highly fluorescent nanoparticles. The introduction of Fe^{3+} ions induce a notable alteration in the PL profile. A substantial suppression of the fluorescence intensity, known as quenching, is evident in the CDs + $FeCl_3$ spectrum. This quenching phenomenon is accompanied by a minor hypsochromic shift, where the emission maximum relocates from 453 nm to 448 nm.

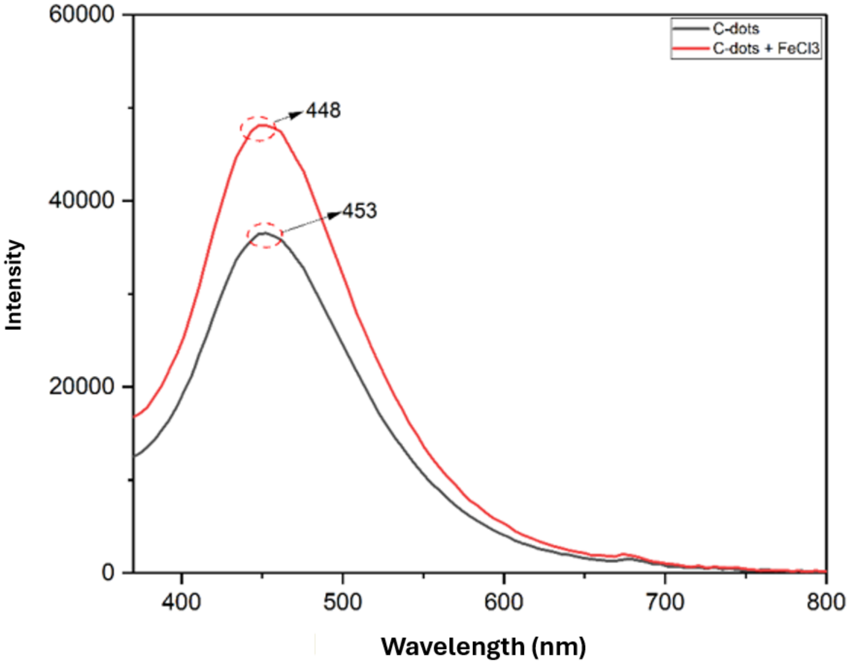

Figure 3. The photoluminescence (PL) properties of the synthesized carbon dots were characterized to evaluate their fluorescent behavior

The photoluminescent properties of the synthesized carbon dots (CDs) and their response to Fe^{3+} ions were examined using photoluminescence (PL) spectroscopy at an excitation wavelength of 245 nm. As depicted in Figure 2, the pristine CDs exhibit a pronounced emission band centered at 453 nm, corresponding to blue light. This fluorescence originates from the radiative recombination of photo-induced charge carriers (electron-hole pairs) within the carbon-based framework, confirming the successful generation of a fluorescent nanomaterial. A marked alteration in the PL profile was recorded following the introduction of $FeCl_3$. The emission spectrum shows substantial quenching, with the peak intensity decreasing from approximately 60,000 a.u. to below 20,000 a.u. Concurrently, a hypsochromic shift of the maximum emission wavelength from 453 nm to 448 nm was observed. The pronounced fluorescence quenching, coupled with the spectral shift, signifies a potent interaction between the CDs and Fe^{3+} ions. The underlying mechanism is likely a chelation-enhanced quenching process, wherein Fe^{3+} ions coordinate strongly with oxygen-rich functional groups (such as carbonyl and carboxyl) on the CDs surface. This coordination establishes an efficient pathway for photo-induced electron transfer from the excited state of the CDs to the vacant d-orbitals of the metal ion, promoting non-radiative decay and consequently suppressing fluorescence. The high sensitivity of this response underscores the potential of these melon peel-derived CDs to function as an effective fluorescent probe for Fe^{3+} ion detection.

The photoluminescent behavior of carbon dots (CDs) is governed by a complex interplay of electronic transitions and surface phenomena. The emission mechanism primarily arises from two contributions: first, energy-gap transitions, namely π-π^* transitions within the carbon core and n-π* transitions associated with surface functional groups; and second, radiative recombination via surface-state energy levels within the band gap. Crucially, the photoluminescence intensity is strongly dependent on surface passivation, and spectral shifts are directly influenced by the surface chemistry of the CDs. Furthermore, the fluorescence output is significantly affected by the precursor concentration used during synthesis, with higher concentrations typically leading to a larger population of CDs and consequently enhanced emission. This collective evidence suggests that the dominant fluorescence mechanism in CDs is not governed by intrinsic bandgap transitions but rather by surface-state transitions [25]. Based on the analysis of the photoluminescence spectra, the introduction of $FeCl_3$ induced a detectable wavelength shift in the emission peak, signifying a modification of the carbon dot (CDs) surface properties upon interaction with Fe^{3+} ions. Contrary to the expected quenching behavior described, the data presented here indicate that the fluorescence intensity of the CDs + $FeCl_3$ mixture was higher than that of the pristine CDs. This observed enhancement in emission intensity can be attributed to alterations in the CDs' surface states, likely due to the specific coordination of Fe^{3+} ions with surface functional groups, which may have led to a passivation effect. The observed fluorescence enhancement in this study, where the photoluminescence (PL) intensity of the carbon dots (CDs) increased upon the addition of Fe^{3+} ions, can be explained by an Aggregation-Induced Emission (AIE) mechanism. This phenomenon is consistent with findings in prior literature. For instance, Wen et al. (2025) [26] reported that Fe^{3+} induced fluorescence enhancement in CDs hydrothermally synthesized from Erythromycin and L-isoleucine, attributing it to AIE. Similarly, Wang et al. (2016) [3] observed Aggregation-Induced Emission Enhancement (AIEE) in glutathione-modified CDs derived from citric acid upon interaction with Fe^{3+} ions.

The underlying principle for both AIE and AIEE is that Fe^{3+} ions coordinate with surface functional groups on the CDs, leading to particle aggregation. This aggregation physically restricts intramolecular motions (such as rotations and vibrations), which are primary pathways for non-radiative energy dissipation, i.e., the loss of excited-state energy as heat. By suppressing these non-radiative decays, the aggregation promotes radiative decay, the process where energy is released as photon emission (light), resulting in enhanced fluorescence [27].

It is important to note that the magnitude and nature of such fluorescent responses, whether quenching or enhancement, can be significantly influenced by the specific excitation wavelength, a factor extensively discussed in the work of Başoğlu et al. [28]. Analysis revealed that the emission profile was strongly influenced by the excitation wavelength. This dependence was characterized by two key phenomena: a fluctuation in the maximum fluorescence intensity and a concomitant hypsochromic (blue) shift of the emission band.

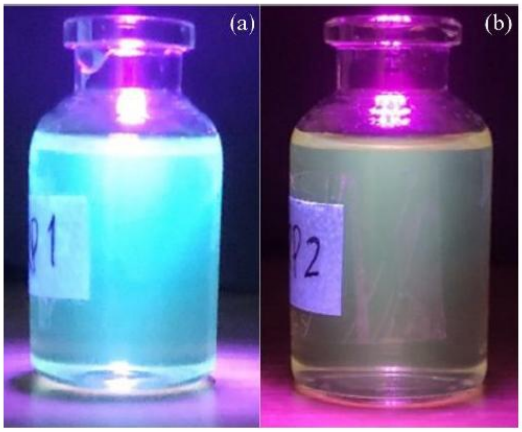

Figure 4 Visual observation under UV light (365 nm): (a) pristine carbon dots (CDs) and (b) CDs after the addition of $FeCl_3$.

Figure 4 presents a visual demonstration of the fluorescence response of the synthesized carbon dots (CDs) towards ferric ions (Fe^{3+}). The photograph captures two vials under ultraviolet (UV) light illumination. As shown in vial (a), the pristine CDs solution exhibits intense cyan-blue luminescence. This bright emission is a characteristic feature of the synthesized CDs, confirming their successful formation and high fluorescence. In contrast, a significant change is observed in vial (b) after the addition of an $FeCl_3$ solution. The introduction of Fe^{3+} ions led to a pronounced decrease in fluorescence intensity, a phenomenon known as fluorescence quenching. The initial bright cyan-blue emission is visibly diminished, resulting in a much weaker glow.

This study on melon rind-derived carbon dots for Fe^{3+} ion sensing represents an initial phase within a more comprehensive research framework. Certain methodological aspects, particularly the microwave-assisted synthesis approach, require further systematic optimization. For instance, using a high-temperature laboratory oven (≥300°C) would provide more precise control over the carbonization process than domestic microwave irradiation. This enhanced control is expected to yield carbon dots with superior crystallinity and more consistent fluorescence properties, ultimately leading to optimized sensor performance. Furthermore, quantum yield calculation will be a primary focus in subsequent investigations to quantitatively characterize the fluorescence efficiency of these carbon dots. This parameter is crucial for objectively evaluating the material's potential as a heavy metal sensor and for enabling meaningful performance comparisons with similar materials reported in the literature. Therefore, while this study lays the foundation for developing natural-material-based heavy-metal sensors, it also paves the way for systematic optimization in subsequent research stages.

Conclusion

This study demonstrates the feasibility of converting melon rind (*Cucumis melo*) waste into fluorescent carbon dots (CDs) via a simple aqueous microwave-assisted synthesis. The as-synthesized CDs exhibited characteristic ultraviolet absorption peaks at 260 nm and 305 nm, corresponding to the carbon core and surface functional groups, respectively. Upon excitation at 245 nm, the CDs displayed strong blue photoluminescence with an emission maximum at 453 nm. As a preliminary indication of their potential as optical probes, the interaction of the CDs with Fe^{3+} ions resulted in significant fluorescence quenching, characterized by a ~67% decrease in emission intensity and a blue-shifted emission peak to 448 nm under the tested conditions. Therefore, this work provides a proof-of-concept for a dual environmental benefit: the valorization of agricultural waste and the development of a nanomaterial for sensing applications. Further investigation is required to quantitatively characterize the sensor's performance, including determination of the limit of detection (LOD), the linear range, selectivity against interfering ions, Stern-Volmer analysis, and optimization of the quantum yield (QY). Future work should also focus on developing a solid-state platform, such as paper strips or hydrogels, to enable practical field applications.

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