Fluorescence Based Detection of Iron Using Carbon Quantum Dots Derived from Camellia Sinensis (Tea) Extract

Mr. Rohan Rathee

Student, Birla Vidya Niketan, Delhi, India

Abstract

This study presents the green synthesis, characterization, and application of carbon quantum dots (CQDs) derived from Camellia sinensis (tea) extract for the selective detection of Fe^{3+} ions. Employing a microwave-assisted carbonization method in a mildly acidic medium, the synthesized CQDs exhibited bright green fluorescence under UV light and demonstrated high sensitivity to Fe^{3+} ions via a fluorescence quenching mechanism. Quenching efficiency was found to be dependent to Fe^{3+} ion concentration, allowing quantitative analysis with minimal interference from other metal ions such as those of Mg^{2+}, Zn^{2+}, and Cu^{2+}. The developed detection method is simple, cost-effective, eco-friendly, and suitable for applications in environmental monitoring, agricultural soil analysis, and biomedical diagnostics. The project highlights the potential of tea-derived CQDs as a sustainable alternative to traditional, resource-intensive iron detection techniques, aligning with the principles of green chemistry and addressing practical needs in real-world scenarios.

Keywords: Carbon Quantum Dots, Fluorescence Quenching, Iron Detection, Tea Extract, Green Synthesis, Environmental Sensing, Fe^{3+} ion Sensors

1. INTRODUCTION

Iron (Fe^{3+}) is a vital micronutrient essential for key biological processes in plants, humans, and animals, including photosynthesis, oxygen transport, and enzymatic functions. Its concentration must be carefully regulated, as both deficiency and excess can harm crop productivity and human health. Additionally, iron contamination in water due to industrial discharge or natural leaching poses significant environmental concerns, underscoring the need for sensitive and efficient detection methods. Conventional techniques like atomic absorption spectroscopy and ICP-MS, though accurate, are often expensive, time-intensive, and require specialized expertise.

This study presents a sustainable, cost-effective approach using carbon quantum dots (CQDs) synthesized via microwave-assisted extraction from Camellia sinensis (tea) leaves. These CQDs display strong fluorescence selectively quenched by Fe^{3+} ions, enabling sensitive detection of iron. The biocompatibility, portability, and scalability of CQDs make them promising tools not only for precision agriculture and environmental water monitoring but also for biomedical applications such as early diagnosis of iron -related disorders.

Methodology

Figure 1 (left to right)

Preliminary extract acidified with acetic acid; after microwave assisted carbonization, sonication and filtration; final QD solution under visible light; luminesent QD solution under UV (365 nm) Carbon quantum dots (CQDs) were synthesized using a microwave-assisted carbonization technique employing Camellia sinensis (tea) leaves as the natural precursor. Approximately 2 g of tea leaves were thoroughly washed with distilled water to remove any surface contaminants then mixed with 100 mL of distilled water and heated to 90°C for 10 mins to extract the bioactive compounds. This extract was then filtered to remove residual solids, followed by adding 2 ml acetic acid to enhance carbonization during synthesis. This mixture was subjected to microwave irradiation at 700 W for five 1 minutes intervals for a total microwave time of 5 minutes in a domestic microwave oven, which facilitated rapid extraction and induced carbonization resulting in an orange- brown solution indicative of CQD formation.

After microwave treatment, the solution was allowed to cool to room temperature (27 ± 4 °C) and then subjected to ultra sonification for 15-20 minutes using a bath sonicator, breaking down larger particles into smaller, uniform carbon quantum dots. Next, the suspension was centrifuged at 10,000 rpm for 15 minutes to separate large particulate matter and impurities. The supernatant was filtered to obtain a clear and homogeneous CQD solution. The synthesized CQDs exhibited strong fluorescence emission when excited at 365 nm under UV light, confirming their successful formation.

Observations

Following the successful synthesis of carbon quantum dots (CQDs) from Camellia sinensis (tea) extract, their fluorescence response was investigated against various metal salts commonly found in environmental and industrial samples. The synthesized CQDs were exposed to aqueous solutions (50 mM) of magnesium chloride ($MgCl_2$), zinc chloride ($ZnCl_2$), copper(II) chloride ($CuCl_2$), and iron(III) chloride ($FeCl_3$). Under UV illumination (365 nm), only the $FeCl_3$ solution induced a marked quenching in fluorescence intensity, while the other metal salts showed negligible or no quenching effect (Figure 1). This confirmed the high selectivity of tea-derived CQDs for Fe^{3+} ions.

Figure 2 (Left to right)

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Fig 4 MgCl2, $ZnCl_2$, $CuCl_2$ and $FeCl_3$ 50 mM solutions with Tea-CQDs under UV light with only the iron salt showing meaningful quenching; QD solution being treated in sonicator; 1:1, 1:10, 1:50, 1:100, tea-QD solution to water ratios tested under 2) daylight, 3) UV light, with 1:10 used due to maximum fluorescence without considerable opacity in solution which would have otherwise induced error due to uneven UV reach.

Concentration-Dependent Fluorescence Quenching

To evaluate the fluorescence response of the synthesized CQDs to varying concentrations of Fe^{3+} ions, a set of test solutions was prepared using a stock $FeCl_3$ solution. A 25 mM $FeCl_3$ stock solution was prepared by dissolving 0.41 g of $FeCl_3$ in 100 mL of distilled water. A 5 mM $FeCl_3$ solution was then obtained by diluting 10 mL of the stock solution to 50 mL with distilled water.

Four test tubes were prepared as follows:

- **Test Tube A (Control)**: 0.5 mL of CQD solution was added with no $FeCl_3$.
- **Test Tube B**: 0.5 mL of CQD solution was mixed with 1.0 mL of 5 mM $FeCl_3$.
- **Test Tube C**: 0.5 mL of CQD solution was mixed with 2.5 mL of 5 mM $FeCl_3$.
- **Test Tube D**: 0.5 mL of CQD solution was mixed with 1.0 mL of 25 mM $FeCl_3$.

Each test tube was then diluted to a final volume of 5.0 mL using distilled water, resulting in final Fe^{3+} concentrations of 0 mM, 1.0 mM, 2.5 mM, and 5.0 mM for Test Tubes A, B, C, and D respectively.

These samples were examined under a UV chamber, and fluorescence intensity was documented photographically. Average fluorescence intensities were calculated using digital analysis of the green channel via Adobe Color tools. The following data was recorded:

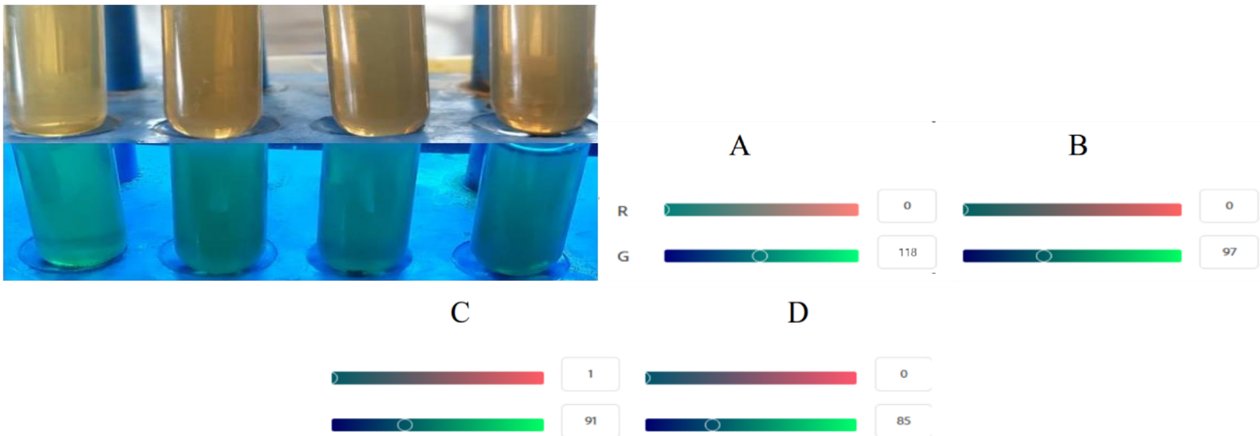

Figure 3 Solutions A,B,C and D under a) daylight b) UV light in the UV chamber respectively ; Red and Green values of each solution (out of max 256) via adobe color tools

Table 1: Fluorescence intensity for different Fe^{3+} ion concentration

Test Tube	**Fe^{3+} ion Concentration (mM)**	**Fluorescence Intensity (Green Channel, max = 256)**
A	0.0	118
B	1.0	97
C	2.5	91

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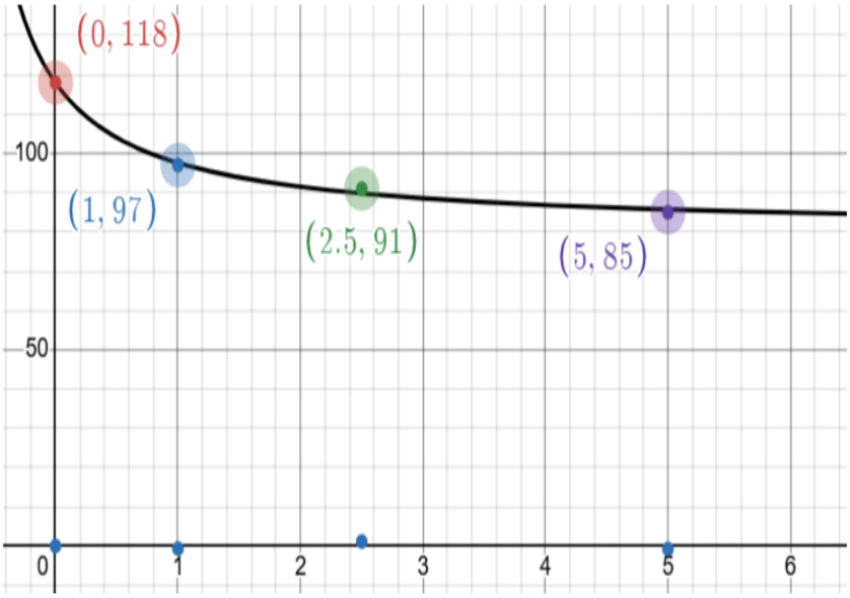
Test Tube	Fe^{3+} ion Concentration (mM)	Fluorescence Intensity (Green Channel, max = 256)
A	0.0	118
D	5.0	85



The following graph is a rationally fitted graph of the above data

Concentration of solution in millimoles >
The decrease in luminescence was found to be consistently measurable, even at relatively low Fe^{3+} concentrations.
These results support the use of tea-derived CQDs as a sensitive and selective fluorescent sensor for Fe^{3+} ions. Although the current setup demonstrated effective detection down to 10^{-1} mM concentrations, literature suggests that with chemical doping or surface modification, detection limits may be further reduced to the 10^{-3} mM range. This highlights the potential for further optimization and application of such CQD-based systems as low-cost alternatives to conventional iron detection techniques such as AAS or ICP-MS, especially in point-of-care diagnostics and field-based water monitoring.

2. RESULTS AND INFERENCE

The study demonstrated the successful synthesis, characterization, and application of carbon quantum dots (CQDs) derived from Camellia sinensis (tea) extract for the selective detection of iron ions through fluorescence quenching.

1. Synthesis and Optical Properties

CQDs were synthesized using a rapid, microwave-assisted method without the need for additional carbon sources or stabilizing agents. The prepared CQD solution exhibited strong green fluorescence when exposed to ultraviolet (UV) light at 365 nm, which was attributed to quantum confinement effects and the presence of functional surface groups such as hydroxyl, carboxyl, and amine groups—known to contribute to emissive behaviour.

2. Selective Fluorescence Quenching by Fe^{3+} Ions

The CQDs exhibited pronounced fluorescence quenching upon exposure to Fe^{3+} ions. This quenching effect was found to be both significant and concentration-dependent. Test solutions with Fe^{3+} concentrations ranging from 0 mM to 5.0 mM showed a measurable and progressive decrease in fluorescence intensity. In contrast, other metal ions such as those of magnesium (Mg^{2+}), zinc (Zn^{2+}), and copper (Cu^{2+})—when tested at 50 mM concentrations—produced negligible changes in fluorescence. This confirmed the high selectivity of the synthesized CQDs for Fe^{3+} ions.

3. Quantitative Analysis and Dose-Dependent Response

A quantitative analysis was conducted by exposing the CQDs to a series of $FeCl_3$ solutions at varying concentrations (0 mM, 1.0 mM, 2.5 mM, and 5.0 mM). The fluorescence intensity was recorded under UV illumination and analysed through digital image analysis. The green component of the emitted fluorescence was found to decrease from 118 (1 byte, i.e. 256 being max) at 0.0 mM to 85 at 5.0 mM, showing a clear dose-dependent behaviour. This linear response established the potential of tea-derived CQDs as a reliable fluorescence-based probe for the detection and estimation of Fe^{3+} ion concentration in aqueous media.

4. Minimal Interference and Environmental Compatibility

Control experiments with other commonly occurring metal ions confirmed that these did not interfere significantly with the CQD fluorescence. Additionally, the colour of the salt solutions did not visibly alter fluorescence output under UV illumination, suggesting minimal matrix interference. This specificity is likely due to the strong coordination affinity between Fe^{3+} ions and the oxygen/nitrogen-containing functional groups present on the CQD surface.

Overall Inference

The results of this investigation suggest that CQDs synthesized from Camellia sinensis offer a sensitive, selective, and environmentally sustainable approach for Fe^{3+} ion detection in water samples. The simplicity of synthesis, combined with measurable and reproducible quenching behaviour, supports the application of such CQDs in low-cost field detection kits or portable fluorescence-based sensing systems. Further enhancement through doping or surface modification may extend detection limits into the micromolar or nanomolar range, enabling their use in environmental monitoring and biomedical diagnostics.

3. APPLICATIONS AND FUTURE SCOPE

The tea-extract-based carbon quantum dots (CQDs) developed in this study demonstrate broad applicability across environmental, agricultural, biomedical, and analytical domains.

Environmental Monitoring:

Iron contamination from industrial discharge or natural leaching threatens ecosystems and public health. The CQD-based fluorescence probe offers a low-cost, sensitive, and portable solution for real-time Fe^{3+} detection in water. With further surface modifications, this platform can be adapted to detect other heavy metals such as Hg^{2+} and Pb^{2+}.

Agriculture:

Iron levels in soil significantly influence plant health and yield. A CQD-based sensor can assist farmers in monitoring iron concentrations rapidly, supporting precision agriculture and minimizing fertilizer misuse.

Biomedical Applications:

Fe^{3+3+} dysregulation is implicated in conditions like Parkinson’s, Alzheimer’s, and cancer. These CQDs may be engineered for non-invasive bioimaging and early diagnosis or used to monitor iron supplementation therapies.

Analytical Advantages:

Compared to conventional techniques like AAS or ICP-MS, CQD-based detection is inexpensive, user-friendly, and field-deployable. Its scalability makes it particularly suitable for low-resource settings.

Future Directions:

These CQDs could be further tailored to detect ions like Cd^{2+}, As^{3+}, or NO_3^-, expanding their utility in food safety, healthcare, and environmental science. Their eco-friendly synthesis and versatility position them as promising candidates for sustainable sensor technologies.

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